CHARACTERIZATION OF SHALLOW SUB-SURFACE SEDIMENTS OF THE SALTON SEA

PREPARED BY

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Project Information

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The project was administered and managed by Carla Scheidlinger. Field work including all sampling was performed by James Kulpa and Dr. Stephen Crooks. Jesus Montano collected selected shoreline samples. Laboratory analysis of the soil samples was performed by the Soil Laboratory at Brigham Young University in Provo, Utah under the direction of Dr. Bruce Webb. Data management and spatial analyses were done by John Chesnut. The report was prepared by Stephen Crooks, Carla Scheidlinger, and John Chesnut. Logistic and overall managerial support was handled by Frank Stradling.

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Executive Summary

The Salton Sea was surveyed for the nature of sediments that would be exposed if the level of the Sea were to drop by approximately 25 feet. The survey consisted of grab samples and core samples, and a generally unfruitful acoustic survey. The samples were analysed for particle size and for organic content, and the results were mapped onto Salton Sea base maps in a GIS format. Nine morpho-sedimentary districts were recognised in the Salton Sea covering an area of 68,304 acres. These include open shore districts (East Shore, Bombay, Test Base and Sandy Point), transitional districts (North Shore, Niland and Desert Shores) and deltaic districts (Whitewater and Delta). Open shore districts are subject to high wave energy creating sandy (or barnacle rich) beaches and transporting fine muds to quiescent offshore areas. Deltaic sequences are subject to high sediment loading from river point sources and show evidence of limited reworking by storm waves. Transitional districts reflect open shore deposits subject to sedimentation from proximal delta outflow. Deltaic sequences typically consist of muddy sand channel deposits flanked by organic-rich sandy- and silty muds back-delta deposits. Districts to the southern region of the lake are underlain by a platform of firm former desert soils.

The bed of the Salton Sea consists of a range of sediment types from barnacle beds, and clean sands through to fine silts and muds. The bulk of the sediment falls within the clay loam, sandy clay loam, and clay, as defined by NRCS soil classification. Across the study region average sand, silt, clay contributions are 47.9%, 23.9% and 27.2% by weight, respectively. The distribution of these sediments is very much dependant upon a balance between supply from adjacent sources and reworking action by waves and currents with sediments becoming finer grained with increasing water depth.

Barnacle beds blanketing surface sediments were a significant feature across many parts of the Lake-bed. These beds may form an ‘armouring’ to covered sediments possibly protecting them from erosion should lake levels fall. The distribution and integrity of barnacle beds is not clear but were commonly found on ‘sandy’ units along the eastern and western shore and to a lesser extend on the ‘muddy’ southern shore of the lake.

Calculations were made for the amount of area that would be exposed in each of nine morpho-sedimentary districts around the Sea, and for the nature of the sediment that would be exposed at each of five elevational increments. A decline in Sea level of three feet from an elevation of –227 feet to –230 feet would expose **11,252 acres** of sediment, most of it characterized as sandy loams, with a sand fraction of 53.3 percent, silt of 21.1 percent, and clay of 21.7 percent. Shells make up 3.9 percent of the exposed sediment at this level. A further decline of five feet, to -235 feet or eight feet down, would expose an additional **6,501 acres**, most of it continuing to be sandy loams, with a sand fraction of 53.7 percent, silt of 21.9 percent, and clay of 22.7 percent. Shells make up 1.7 percent. A decline of an additional five feet, to the –240 foot level or 13 feet down, would expose an additional **14,626 acres** of sediment, which would be predominately sandy clay and sandy clay loam. Composition of this increment is 46.9 percent sand, 25.0 percent silt, and 28.1 percent

clay, with no shell composition. A decline to the –245 foot level, or 18 feet down, would result in an additional **18,941 exposed acres**, consisting largely of sandy clay loam with a composition of 42.0 percent sand, 26.0 percent silt, and 32.0 percent clay. A final decline to the –250 foot level, or 23 feet down, would produce an additional **16,984 exposed acres**, primarily consisting of sandy clay loam with 42.5 percent sand, 25.5 percent silt, and 32.0 percent clay. A total of **68,304 acres** would thus be exposed with a decline of 23 feet from the current Sea level.

The amount and nature of the surface exposed at each of the nine districts is highly heterogeneous spatially due to sediment depositional patterns and wave re-working. The Salton Sea is an energetic system and the current sediment mosaic reflects the distribution of that energy. Falling water levels are expected to result in a reworking of lower shore sediments in open shore and transitional districts. As water levels recede sediments will be suspended by waves with a proportion of the fines transported further off shore leaving a 'lag' deposit of coarser material. Deltaic sequences are less subject to wave attack and so these muddy sediments are less likely to be reworked as water levels fall leaving expansive areas of dried mud.

These sediments bear some resemblance to the exposed sediments at the Owens Lake playa, which have been a source of severe PM_{10} emissions. The information suggest, however, that sediment data are necessary, but insufficient alone, for air quality specialists to predict the severity of a dust problem that may be caused by these exposed sediments at the Salton Sea.

Introduction

Project background

The Salton Sea is the largest body of water in California, encompassing 376 square miles (240,640 acres) with a maximum depth of 51 feet (Figure 1). It is a hypersaline lake located in a closed desert basin east of Los Angeles and San Diego. The Sea was initially formed in 1905-1907 by flooding on the Colorado River, which breached an irrigation control structure allowing virtually the full flow of the river into the Salton Basin. The Sea is now sustained primarily through irrigation return flows from the Imperial, Coachella, and Mexicali Valleys. Rainfall and small volumes of municipal effluent and storm water runoff help supplement the agricultural drainage.

The proposed transfer of Colorado River water from the farmlands of the Imperial Irrigation District (IID) to the urban areas of coastal California will almost certainly result in lowering water of the Salton Sea. As the lake water level falls, subsurface sediments will become exposed, potentially causing wind erosion and dust emission that would threaten health and trigger violations of air quality standards. This project is designed to identify and describe the nature of the material that would be exposed by declining lake levels. These data will provide a critical tool for the future evaluation of the potential for dust emissions from the exposed playa surface. The data will also suggest logical measures for dust mitigation and the placement of these control measures on the exposed surfaces. Where sediments would provide suitable substrate for surface restoration, these data will suggest the optimal locations for such restoration activities.

Previous studies

A number of previous studies have been undertaken to describe the physical, geochemical and biological processes within the Salton Sea (see symposium proceedings: Barnum et al. 2002). Specifically related to this project is a preliminary sedimentological study involving the collection of samples for geochemical and textural analysis from 73 locations across the lake (Vogl and Henry, 2002). Only 12 of these samples fall within the survey area of this current study.

Project Goal

The project was initially funded to map the lake-bed surface sedimentology down to a depth of the 15 ft contour to determine the surface nature of the area that would be at risk from atmospheric exposure should water levels falls. The project was expanded to cover the area to a depth of about 25 feet, although no physical sediment sampling was to be done past the depth of 15 feet. This exposed area could rival the exposed playa surface of the Owens Lake, which is currently the largest source of PM-10 (particulate matter less than 10 microns in diameter) in the United States. Every water body is unique, however, so Salton Sea sediments are not expected to conform in any significant way to the sediment surfaces of other exposed playas.

Specific requirements of this project are:

1. A classification of types of bottom sediment existing in the Sea;
2. Mapping of the sediment types; and
3. An estimate of the extent of each sediment types.

The resulting data must be of quality that it can be used for developing a predictive model for determining if the air quality will worsen as a result of receding water level and the degree to which this will occur.

Methods and materials

Approach

The approach adopted was to undertake, where possible, direct grabs sampling of lake-bed surface sediments at 0, 5, 10 and 15 ft depth intervals along shore normal transects around the circumference of the Salton Sea, at 1 km spacing (Figures 2 and 3). This surface information was supplemented with a series of short cores collected at 2 km stepped intervals along 5 and 15 ft contours using a Split Side Russian Peat Corer (max sample length 20 inches) to investigate near-subsurface sedimentology. This analysis was crucial in helping to place the collected surface samples into a geomorphic context based upon an increased the understanding of the dynamic nature of the Salton Sea and it interactions with the lake-bed sediments. Additionally, a geophysical textural mapping system (QTC Impact V) was deployed as a trial in an effort to assist in the interpretation of sedimentology between sample locations and to water depths of 25 ft.

The digital maps produced of sediment grain size and organic content are intended to provide information to air quality experts for the evaluation of the extent of possible air quality problems should the lake-level drop to as much as 23 feet below current levels.

Field procedures

For the purpose of this study "surface sediments" are considered to range from 0 to 6 inches in depth with "subsurface sediment" found below this depth interval. Collection of surface sediments was undertaken directly by Grab Sampler as well as the upper portion of a shallow core collected using a Russian Split-Side Peat Corer. Grab samples were collected at 0, 5, 10 and 15 ft contours (determined by a calibrated onboard depth finder) along shore normal transects spaced 1 km apart. All equipment was cleaned before going into the field as well as between sample sites to prevent contamination of retrieved sediments. Procedures followed the guidelines of the Quality Assurance Protection Plan (QAPP) that had been prepared for this project prior to the initiation of field work. Locations of the samples collected were recorded on a Garmin 76s DGPS (WAAS) with horizontal resolution of less than 10 ft.

Surface sediment sampling

Sampling of surface sediments was undertaken using a Ponar-type Grab Sampler (6" x 6" stainless steel jaws with a sampling area of 36 square inches). The jaws are triggered when the sampler impacts the lakebed, resulting in sediment collection upon retrieval of the instrument. Grab sampling at any given location was repeated until 0.5 to 1.5 kg of sediment was collected. The sediment was placed in the mixing container and manually homogenised for 2 minutes. Approximately 200-300 grams of sediment was then sub-sampled and placed within a labelled airtight sample bag and stored within a cooler. A null sample was recorded at sites where after 10 subsequent attempts either zero or insufficient sediment was retrieved. Location and characteristics of grab samples are in Figures 4 and 5.

Sub-surface sediment sampling

It is not uncommon for the texture of lake and marine surface sediments to reflect recent depositional processes, but for the main bulk of sediment just a few centimetres below the surface to be texturally different.

Short cores (maximum length 20 inches) were collected using Russian Split-Side Peat corer. Unlike end-filling corers this side-filling sampler collects uncompressed samples from wetlands and shallow lake and sea beds. The corer with extension rods was deployed in up to 15 ft water depth. Once the surface was penetrated the corer was rotated clockwise 180 degrees so that the sharpened edge of the chamber cuts a sediment core, which is contained by the cover plate. During retrieval, the cover plate's counter-clockwise rotation extrudes the undisturbed sample. The corer measures 5 cm in diameter and 55 cm in length with a sample volume of 10 ml/cm.

Each core was logged in an undisturbed state noting features including lithology, texture, lamination structure, consistency and colour (with reference to a standard soil color chart) before being divided into subsamples (top 0”-6”, middle 6”-12” and bottom 12-18” depth intervals). Core locations and characteristics are in Figure 6. Core logs and core texture data are found in Appendix 1.

Acoustic textural mapping

Acoustic textural mapping was undertaken using a Quester Tangent Corporation (QTC) View 5 system (constituent hardware: Echosounder complete with transducer (50kHz), QTC Sounder Interface Module (SIM), Laptop computer with docking station and GPS system**)**. Raw data outputs were downloaded daily during sampling events, and were analysed using QTC IMPACT software before depiction within a GIS system. The theory of how acoustic sampling is accomplished is described below.

The amplitude and shape of an acoustic signal reflected from the sea floor is determined by the sea bottom roughness, the contrast in acoustic impedance between water and sea floor, and perturbations caused by non-homogeneities in the substrate’s volume. Remote seabed classification requires an acoustic data acquisition system, an algorithm set to analyze the data, an implementation method to determine the seabed type, and ground truth to relate the acoustic classification to seabed features.

The QTC VIEW^{TM} seabed classification system typically uses the signal from a normal incidence, single-frequency echo sounder (Collins et al., 2002). The system is connected in parallel with the echo sounder transducer and digitally extracts the echo trace. Pre-processing involves identification of the sea floor in the echo trace and filtering to suppress noise.

Echo description is accomplished using several algorithms to extract 166 echo shape features, known as full feature vectors (FFVs), from each trace. Multivariate statistical analysis then identifies the best feature combinations to distinguish groups of echoes representing different seabeds. The feature combinations are reduced to three primary values, known as Q-values.

Classification is accomplished using the three Q-values; it is assumed the acoustic response from like seabeds will be similar. When the principal components originating from each echo are plotted in Qspace, seabeds with similar acoustic responses will form clusters. An echo is classified using its position in Q-space with respect to the clusters generated from calibration data; the echo being classed the same as the closest cluster. Information on the features used and the clusters identified as suitable for the classification scheme are stored in a catalogue. New echoes are captured and analyzed by the catalogue and a class is determined.

Laboratory analysis

Sediments were analysed to determine sand, silt and clay ratios and organic content by standard laboratory techniques.

Grain size analysis

The grain size analysis and organic content analysis were performed in the Soils Laboratory at Brigham Young University, directed by Dr. Bruce Webb. Salton Sea samples were washed before analysis to remove salts that induce flocculation of clay particles in suspension. In the washing, 40 grams of soil was mixed with 250 ml of distilled water. The samples were then shaken for 5 minutes and centrifuged. The clear liquid was poured off and new water was added. The process was repeated eight times or until the soil would not centrifuge out.

Grain size analysis followed the established procedure outlined in Black (ed) (1965) involving 40 grams of sediment mixed with deflocculant (calgon: sodium hexametaphosphate) and stirred. The slurry is transferred to a litre cylinder, homogenised and then the particles are allowed to settle. Measurements were made by hydrometer at 40 seconds and 8 hours to determine sand (2mm-62.5μm), silt (62.5μm-2μm) and clay (<2μm) weight ratios.

Organic Carbon Content

Organic carbon content was determined by the standard Walkley-Black dichromate oxidation technique (Walken and Black, 1934).

Data analysis

GIS documentation and methods

1. GIS documentation and methods

The Salton Sediment GIS layers were created using ArcView 3.3, ArcMap 8, and GRASS 5.0.2. Paper maps are Acrobat .pdf files exported from ArcMap 8.

The base map for the GIS is adapted from the Salton Sea Digital Atlas (beta 0.91) [SSDA]. The SSDA base map is projected into UTM Zone 11N using the NAD 1927 datum. This projection and datum has been maintained in new sediment layer files. Several files from the SSDA were essential including the "l_bath5F" shape file. This file has 5 foot interval bathymetry in mean sea level (MSL) elevation in feet. The SSDA "l_shohi" shape file (detailed shoreline) was used as a basis for the creation of a Sea shoreline for this project.

The location of grab and core samples were recorded at the time of collection using a Garmin 76s DGPS (WAAS) model GPS in a WGS 1984 Latitude and Longitude coordinate system. Locations were given a unique waypoint ID (1 to 714), as well as a descriptive transect name and depth position. Analysis data of samples were cross referenced to the location data using the recorded waypoint or transect information. The 1984 WGS location data were transformed to the UTM Zone 11N NAD 1927 projection using the WGS84_NAD27_V6 transformation matrix available in ArcToolbox 8. This matrix is the ArcMap implementation of the “CONUS, western US” transformation. Throughout the report, GIS data are reported in UTM Zone11N, NAD 1927 projection and datum.

The QTC track data was recorded similarly in WGS 1984 Latitude and Longitude coordinates using the DGPS unit networked to the data acquisition computer. The classified QTC track was also transformed to UTM NAD 1927 projection using the WGS84_NAD_V6 transformation matrix. The 1999 LFR sediment data were received as a digital shape file from the SSDB office in Redlands. The LFR data set consists of 71 locations with sediment fraction data.

Location data were verified using a BLM cadastral control point file downloaded from the USGS data site. The high detail shoreline shape file “l_shohi” in the Salton Sea Digital Atlas (beta 0.9) has severe topology problems that caused system freezes in both ArcView and ArcMap. We used the GRASS command “v.prune thresh=1” to eliminate redundant points within a 1 meter tolerance. This "pruning" produced a much more stable shoreline file. The shoreline and -250 foot contour line from the l_bath5f shape file were used to create a binary mask file containing the donut shoreward of the main -250 foot contour.

Two grab sample collections were missing waypoints: SCS 10/15 and SCN 23/ 10. The position of these samples were interpolated along their transect lines. Three samples were duplicated as replicates for QA/QC purposes.

The data set consists of 3 master database files that are related by unique waypoint and lab control number keys. The data set is summarized in Table 1 below.

1) MasterSedimentAnalysis has 621 lab results. This database is keyed by the unique lab control number (“Lab_num”) given individual lab samples. It is cross referenced to waypoint, and for cores samples, to the core segment sequence. The top core segment is given sequence number 1.

2) Master_Sediment_location has 586 valid waypoints. Lab control numbers have been keyed to this table, and the lab analysis associated with each waypoint is appended to this table. Waypoints are coded by type (C = core, G = Grab, Shore Grab = G1). The top core sequence analysis were assigned core waypoints, so these values could be used in surface interpolation.

3) Core_data reports 68 Core locations. Separate columns are maintained for each core segment, keyed by the lab analysis control number.

No sample recovery locations are included in the database records. These records must be filtered prior to analysis, as null values are reported as 0 (zero).

The Grab data set consists of the analysis of grab samples taken at approximately 1 km intervals along shore normal transects at the depth of 0, 5, 10, and 15 feet. There were 142 transects required to complete the lake periphery. The Core samples were taken at depths of 5 and 15 feet in an alternating pattern midway between grab transects.

The Grab sample data were combined with the top segment of the Core sample data to generate a sediment analysis database with 586 locations. There were 85 locations that were scored as null samples, with bottom class of Shell (barnacle beds), concrete, or rip-rap, or are missing from the laboratory data for unexplained reasons (1 sample).

A. Valid waypoints

DEPTH	TYPE: Core	Grab	Zero	Grand Total
0			103	103
5	32	143		175
10		138		138
15	33	137		170
Grand Total	65	418	103	586

B. Null data, No Sediment Recovery, or lab results with organic fraction only

DEPTH	TYPE: Core	Grab	Zero	Grand Total
0			16	16
5	3	29		32
10		16		16
15	5	16		21
Grand Total	8	61	16	85

C. Valid lab numbers

Depth	Core	Grab	Zero	Grand Total
0			105	105
5	59	126		185
10		132		132
15	71	128		199
Grand Total	130	386	105	621

Table 1. Summary of Data set by depth, type, and recovery

2. Interpolation of sediment surfaces

It was observed that the Null sample recovery zones were frequently associated with high sand areas. Packed clays, and submerged constructions were also responsible for “no sample recovery”. Null locations were excluded from the interpolation of surface data. An edited database, (Seds_noNull.dbf), of 501 samples with valid analysis was used for interpolation.

It was hoped the 1999 sediment data collection made by LFR in the Vogl and Henry (2002) study could be used in conjunction with the current data to extend the interpolated surface over the whole of the lake. Comparison of 12 points where 2003 sediment data and 1999 LFR data were recovered within a 200 meter radius revealed that incomparable methods were being used for the Sand-Silt-Clay estimation. Clay fraction was a linear function with LFR= 0.46 * 2003 data. Silt fraction was high in the LFR data set without a discernable linear pattern, and sand showed scatter. (Figure 7). The LFR data set was not used in combination with the 2003 data, the data sets re not comparable.

Three interpolation techniques were tested: 1) Inverse Distance Weight (IDW) 2) Regularized Spline with Tension (RST) 3) a three dimensional RST interpolation (Grass module: s.vol.rst) using depth as the third spatial variable (Mitas, 1999). Interpolations were performed using the ArcView 8 Spatial Analyst extension and GRASS site modules.

Interpolation of sediment surfaces was limited to the lakebed zone between the shoreline and the –250 foot MSL bathymetric contour. The -250 foot contour is approximately 23 feet below the lake surface at the time of the survey. This contour represents an extrapolation beyond the set of 15 foot depth data points in the sample database.

A grid cell size of 25 m x 25 m was selected to provide reasonable resolution to the interpolation. The extent of the interpolation was 1955 x 1866 cells, yielding a grid with 3.668,556 pixels.

Individual sample results can strongly affect the interpolation due to the relatively sparse distribution of samples. Fortunately, virtually all samples showed predictable and continuous pattern of variation in comparison to other nearby points. Variation between points was highest in the diverse delta environment. No editing or selective removal of unusual values was attempted. Inspection of the dataset strongly indicates that depth of water was the strongest local variable.

IDW interpolation was done using the default conditions of power=2 and neighborhood of points=12. Results appeared generally consistent with expectations. Shorelines showed scalloping due to increasing influence of offshore data between the transect lines.

Regularized Spline with Tension interpolate surfaces as a continuous flexible plate. The surface's fidelity to the sample point data and the flexibilty of the plate are controlled by the smoothing and tension parameters. RST interpolations were parameterized interactively to produce a smooth and non-negative surface. However, the RST interpolations tended to produce irrational negative fractional composition in between sample areas unless the tension was greatly increased from default values (Grass default tension=40, smoothing=0.1). Increasing tension and smoothing to avoid negative proportions produced a map that was essentially identical to the IDW interpolation by making the "plate" surface stiff and responsive to local sample values.

The 3d RST interpolation method (s.vol.rst in GRASS) included a third spatial component to account for variation produced by the depth of water. A digital elevation model (DEM) representing bathymetric contour of the lake is introduced as the source of this third variable. The GRASS module transforms the 2d cell representation into a 3d "voxel" representation of the volume and calculates a RST surface for the three dimensions. The z depth dimension of the lake was represented in 2-foot increments, producing a voxel dimension of approximately 90 million cells. The specific command set in GRASS was:

```
g.region rast = bathymap
   #sets region and cell size to bathymap  raster
s.vol.rst Site_pts cellinp=bathymap cellout=SAND_RST  field=2  \
zmult=41.0104987 maskmap=MASK
    # z dimension multiplier  of 41 is used to scale the
    #2foot depth increments with the 25 meter  x and y dimension
```

#Maskmap is -250 contour "donut" binary map to restrict interpolation to region of interest.

The 3d RST interpolation were run using default parameters of tension=40 and smoothing=0.1. The 3d RST interpolation successfully reduced the scalloping effect on shoreline data, and the erroneous offshore influence of the 5 foot core samples. The 3d RST interpolated maps were adopted as the master interpolated surfaces. There are four maps showing the interpolations conducted for sand, silt, clay, organic content, and a clay-silt ratio presented in Appendix 2.

Error in interpolation was be tested by comparing the actual sample data to the coincident cell value of the interpolated surface (Table 2, below). This analysis was performed for the sand fraction data. Total mean error in sand fraction was 0.04 % (a low value is expected, since the heart of the RST process is to minimize total error). Comparison by depth and region indicate that, the interpolated surface in comparison to the actual data underestimated the sand fraction at the 5-foot depth by 5% and overestimated the sand fraction at the 10 and 15-foot depths by 3 and 2 % respectively. This indicates that the beach effect (sand along the shoreline) is actually stronger than the interpolated surface indicates. Error was greatest along the steeply sloping East shore division. Error was reverse in the Delta division, where the sand gradient is actually reversed in profile.

Sand Sample Less Sand Interpolation (Error)
Average of error (percent)

	DEPTH of sample			
Division	5 foot	10 foot	15 foot	Mean
Bombay	4.9	1.5	0.1	2.3
Delta	-0.9	-0.6	0.9	-0.3
DesertShores	9.2	-2.3	-0.7	2.0
EastShore	12.4	-9.7	-7.4	-1.2
Niland	1.0	-4.5	-1.4	-1.4
NorthShore	2.8	3.6	-1.3	1.2
SandyPoint	2.2	2.3	0.9	1.8
TestBase	4.8	-1.7	-1.4	0.5
Whitewater	3.0	-2.5	-2.8	-1.0
Mean	5.0	-3.1	-2.1	0.0

Table 2. Summary of mean error (Sample less local interpolation cell value)

The three surfaces (sand, silt, clay) were interpolated independently; alternatively, one surface could be derived by subtraction of the other two from 100. Error in addition of the surfaces was concentrated in the nearshore region where the interpolated sand estimate was low.

No error-free DEM for bathymetry exists of the lake. The bathymetric shape files include a -225 foot contour inside the -227 foot shoreline contour, an impossible condition. Alternatively, the QTC track was used to interpolate mid-depth (-235 to -260) regions, but QTC data are missing in nearshore. A triangulated network (TIN) was obtained from the SSDB office, but the nearshore overrun was present in this source file. For creation of the raster DEM "bathymap" used for the 3d RST interpolation, we deleted the -225 foot contour from the bathymetric shape file, and recreated a DEM using the other contours and the GRASS module v.surf.rst, which interpolates a surface from vector contour lines.

No effort was undertaken to populate un-sampled regions with mean data, or to increase the density of shoreline sediment samples with representative data. Shoreline samples immediately east of the Alamo River indicate that the location of the shore in the " l_shorhi" basefile may be incorrect in this region.

The interpolated surface was divided into larger 40 acre (402.336 meter square blocks). These larger pixels (actually individual polygons) were sampled for mean cell characteristics of the 256 25 m pixels that make them up. The 40 acre blocks were placed on UTM baselines, and do not correspond to State Plane township and range grid. In order to assign sediment and soil class membership to points or regions, data were projected onto the NRCS Sand-Silt-Clay ternary diagram, and points were assigned membership by polygon overlap on the ternary diagram using ArcMap intersect and union commands. Data was placed on the equilateral ternary diagram by transforming the x-axis to x = 100-(clay% + sand/2). Thus, the silt interpolation value was not used for classification, but only the sand and clay interpolations. The three surfaces (sand, silt, clay) were interpolated independently; alternatively, one surface could be derived by subtraction of the other two from 100. Error in addition of the surfaces was concentrated in the nearshore region where the interpolated sand estimate was low compared to the sampled data value.

Bathymetric areas of the lake divisions were calculated using bathymetry derived from the SSDA “l_bath5f” shape file (stripped of the –225 contour) and the ArcView X-Tools extension. Data collected by this study indicates some error exists in the contours, especially in the delta nearshore zone. The published –250 contour and an interpolated contour derived by RST using the QTC data set are essentially identical lakewide.

Lake divisions were prepared after surface interpolation. Surfaces were displayed in a classified pattern, and boundaries were hand digitized by tracing pattern edges. Divisions were created for a variety of sedimentary, morphological, and administrative reasons

Major lake divisions (identified in the text as morpho-sedimentary districts) were further subdivided into smaller sub-units using the same technique of hand digitizing along class boundaries. Delta sediments which overlay other sediments were separated (eg. San Felipe Delta in the SW and Salt Creek Delta on the East Shore). The Alamo and New River delta were separated into sandy and muddy (nearshore) units. North and South halves of the lake were divided along the presumed, proposed drill corridor, even though sediment type is continuous across this division. The proposed drill points were obtained as a Lat-Long shape file from URS, and a line hand digitized through these points.

Data are sorted in this report and accompanying databases clockwise from Bombay. This starting point was chosen because 1) sediments shift abruptly at this boundary, and 2) it is roughly coincident with the proposed lake division placing data from the north and south halves of the lake together.

Profiles were generated by hand digitizing a presumed transect line running near data points from the shoreline to the –250 contour. Actual points had been field located using magnetic bearings and GPS coordinates. Several transects (notably BBS 22 to 26) have several alternative placements, a single transect was selected to avoid redundancy. Distance along the digitized transects were calculated using a cosine transform of the location data to find the perpendicular intersection along the transect line for points not exactly collinear. Transects are not mathematically perpendicular to the local bathymetry, so gradient slope and distance is approximate rather than exact. Transects at the Alamo delta start on the seaward extension of the delta rather than at the backwater shore (i.e. near Red Hill Marina).

Results and discussion

Evaluation of Survey Methods

Based upon 521 surface grab samples and 65 core samples (core samples providing 130 surface and subsurface samples) the distribution of sand, silt, clay and organic matter has been mapped in detail.

It had been intended that acoustic textural mapping would provide a means to increase the degree of certainty between direct sediment sample locations and to extend the data in to 15-25 ft depth range. This extended acoustic mapping proved unfruitful within this large and complex lake for a number of reasons:

1. The technique involves correlation of direct sample textural data with the remotely sensed acoustic signature of the sediment as the boat passes over the location. In part of the lake, particularly in the southern districts, a firm basement topography underlies shallow sediments of various thickness. In places this basement material was recognised by the sonar system and incorporated within acoustic signature. This inclusion of a mixed surface/subsurface signature reduced the correlation with directly collected surface sediment samples.

2. Algal and zooplankton blooms within shallow water regions interfered with the systems ability to differentiate ('pick') the true sediment surface from the clay- and sand-sized plankton in the water column.

3. Post-storm season sedimentation of algae and fine muds produced a 'patchy' thin blanket across surface sediments that was locally detected by the sonar system so reducing the correlation between acoustic signature and bulk sediment analysis.

For these reasons, we have elected not to present the acoustic data, as we were not satisfied with its accuracy. The analysis following was performed with the mapping techniques described above, and is based solely on the physical data. The bulk of the survey involving direct grab and core sampling is more than sufficient to provide a detailed map of the sedimentology within the 0-15 ft contour range, and to provide the ability to extrapolate down to the 25 ft depth contour.

Grab samples and core results

The location of the grab samples, and a visual summary of the textures in them, are in Figures 4 and 5. These figures show for each sampled point the volume percent of clay, silt, and sand in that sample. Darker pentagons indicate a smaller amount of sand; darker squares and triangles indicate higher percentages of silt and clay. These figures clearly show the “beach effect”, of higher sand content close to the shoreline. The presence of a high percentage of sand near the shore does not predict the nature of the sediments further out along the sampled transect. The location of samples that contained quantities of barnacle shells is also shown in these figures. Most of the barnacles were found along the west shore of the Sea, although significant coverage was found on the eastern shore and to a lesser extent on the southern lake margin. An interactive data base that charts the grab samples for all areas is provided electronically as Appendix 3.

The location of the core samples, and some descriptive information regarding the differences found in depth increments, is in Figure 6. The map shows the texture of the sediments, expressed in fraction of sand, at each depth interval of the core. It can be seen that some of the cores were texturally homogeneous (e.g., had the same sand fraction at depths of the core), others were highly heterogeneous (e.g. interbedded sands and muds of varying thicknesses). The degree of heterogeneity was spatially variable (see next section) but this finding indicates that the sediments found in the top several inches of an exposed area may not accurately reflect what might be underneath.

Identification and description (quantitative and qualitative) of morpho-sedimentary districts

A diverse range of sediment textures is found around the shallow margins of the Salton Sea. After examining several classification schemes, including the Folk (Folk 1954) and the Ocean Drilling Program (ODP) (Mazullo et al. 1988), we have adopted for use in this report the NRCS soil classification (NRCS 1999), as it is the most commonly used and understood system for most terrestrial practitioners. We are aware that, strictly speaking, these sediments are not “soils”, but as it is anticipated that they will be exposed and potentially may be the site of plant growth for dust control, we are presenting the data with the NRCS classification.

The bulk of the sediment lies within the clay loam, sandy clay loam, and clay types (Figure 8). As well as these mineral sediments, barnacle shells and shell fragments are locally present. The surface sediment and sub-surface stratigraphic data together with topographic data suggested a division of the bed of the Salton Sea into nine morpho-sedimentary districts, that are defined geographically. These include open shore districts (East Shore, Bombay, Test Base and Sandy Point), transitional districts (North Shore, Niland and Desert Shores) and deltaic districts (Whitewater and Delta). Open shore districts are subject to high wave energy creating sandy (or barnacle rich) beaches and transporting fine muds to quiescent offshore areas. Deltaic sequences are subject to high sediment loading from river point sources and show evidence of limited reworking by storm waves. Transitional districts reflect open shore deposits subject to sedimentation from proximal delta outflow. Deltaic sequences typically consist of muddy sand channel deposits flanked by organic-rich sandy- and silty muds back-delta deposits. Districts to the southern region of the lake are underlain by a platform of firm former desert soils.

These districts are listed in the following table, starting from the mid-eastern shore f the Sea, and progressing clockwise to the south. The distribution of each district is mapped in Figure 9.

District	Character	Comments
Bombay	Open shore	Wave exposed region underlain by a terrace of firm former desert soils. Sandy beaches and nearshore give way to muds below wave base.
Niland	Transitional	Shallow sequence of muddy sediment derived from Alamo River and transported north east by prevailing local counter-clockwise currents overlying a terrace of firm former desert soils. Southward transition of sandy beaches muddy shores.
Delta	Deltaic	Sandy channels with muddy organic rich flanks. Shallow sediments underlain by a terrace of firm former desert soils.
Test Base	Open shore	Shallow silty sediments underlain by terrace of firm former desert soils to the south.
Sandy Point	Open shore / sand spit	Sand spit derived from reworked local soil formation. Possible topographic spur supporting spit but not detected within cores.
Desert Shores	Transitional	Principally open shore increasingly dominated by white water delta fine sediments to the north.
Whitewater	Deltaic	Sandy channel with organic rich muddy flanks.
North Shore	Transitional	Relatively steep shore with sand and barnacle shell beaches and near shore giving way to muds below wave base. Becomes increasingly muddy towards delta.
East Shore	Open shore	Wave exposed relatively steep shore with sandy beaches and near shore giving way to muds on lower shore below wave base.

Table 3: Morpho-sedimentary districts

Figure 10 shows a slightly different presentation of the data from Figure 8, including the division of the sampled area into districts. Figure 10 has divided the sampled area in to 40 acre blocks for ease of determining areas. The ternary diagram is again shown, indicating where sediments of each classification were encountered. Figure 11 is presented to show the location of each grab sample on which the maps were based, and its classification. This figure also includes the data for shells, which were encountered frequently on the west regions (Desert Shores and Sandy Point), as well as on the eastern area of Bombay.

We also present quantitative data to describe the distribution of sediment types in Tables 4-9. Each table is derived from a GIS database based upon existing bathymetric data source with surface of the lake represented by the -227 foot contour. Table 4 shows each district, divided into 5 contour intervals extending down to the -250 foot contour, which is to a depth of about 24 feet. Examination of these tables shows the distribution of the various sediment types both in region and in depth, with the mean textural fraction shown. For each district and each contour, Table 4 indicates the percent of each of three mineral types: sand, silt, and clay. The table is color coded for the major soil divisions. Thus, in the area between –230 and –235 feet in the Bombay district (upper limit –230 feet), the sediment is 67% sand, 11 % silt and 19 % clay. The remaining fraction is shell. The soil type is a sandy loam.

		Depth MSL					
Division	fraction	-227	-230	-235	-240	-245	Mean
Bombay	Sand	66	67	62	54	51	60
	Silt	13	11	11	15	18	14
	Clay	18	19	27	32	32	25
Niland	Sand	41	38	27	21	28	31
	Silt	31	34	38	37	32	34
	Clay	26	28	36	44	41	35
Delta	Sand	38	36	37	42	46	40
	Silt	31	30	28	25	24	28
	Clay	31	33	35	32	28	32
TestBase	Sand	47	47	42	39	40	43
	Silt	18	18	22	23	23	21
	Clay	29	31	36	37	36	34
SandyPoint	Sand	58	62	63	58	52	58
	Silt	14	15	16	16	18	16
	Clay	19	18	18	23	27	21
DesertShores	Sand	57	55	51	47	47	51
	Silt	22	23	26	26	25	24
	Clay	18	20	23	28	29	24
WhiteWater	Sand	43	38	30	26	34	34
	Silt	33	38	41	39	33	36
	Clay	23	24	31	36	34	29
NorthShore	Sand	61	59	57	50	48	55
	Silt	20	21	22	27	29	24
	Clay	18	18	21	23	25	21
EastShore	Sand	69	65	55	45	38	55
	Silt	10	14	21	27	28	20
	Clay	14	18	27	34	37	26
Lake Mean		53	54	47	43	43	48

Class Key
NRCS Soil Class
- Sandy Loam
- Sandy Clay Loam
- Loam
- Sandy Clay
- Clay

Table 4. Sand, silt, and clay fractions at the different districts at the depth contours examined. Soils are identified as NRCS classes.

Table 5 provides additional quantitative information based on district and depth. The upper table shows the number of acres contained in each district at each depth interval. At Niland, for example, between the –235 and –240 foot depth (upper limit –235 feet), there are 2,646 acres that would be exposed, consisting of sandy clay. If the level of the Sea were to fall to –250 feet, there would be a total of 8,982 acres of sediment exposed, in three different classes.

Area In each division (Acres)	Upper Limit 5 foot contour					
Division	-227	-230	-235	-240	-245	Grand Total
Bombay	402	290	528	533	695	2,449
Niland	915	827	2,646	2,183	2,411	8,982
Delta	4,180	1,907	5,566	8,845	6,407	26,906
TestBase	1,165	1,053	1,960	2,326	2,276	8,780
SandyPoint	714	414	852	1,136	1,158	4,274
DesertShores	1,022	610	771	1,056	1,132	4,592
WhiteWater	1,745	606	1,122	1,300	1,173	5,946
NorthShore	445	326	517	667	760	2,715
EastShore	664	467	666	895	971	3,662
Grand Total	11,252	6,501	14,626	18,941	16,984	68,304

Class Key
NRCS Soil Class
Sandy Loam
Sandy Clay Loam
Loam
Sandy Clay
Clay

Table 5. Acre calculations for area exposed at each depth interval in each district. Area is coded for sediment class exposed.

Table 6 shows the same information for organic content of sediments exposed. High organic content is found at all levels at Whitewater, and is concentrated at deeper levels at the Test Base and the North Shore. Organics are higher near the shore at Delta.

Mean Organic Percent	Upper Limit 5 foot contour Depth MSL					
Division	-227	-230	-235	-240	-245	Grand Total
Bombay	1.1	1.2	1.4	2.0	2.1	1.6
Niland	1.8	1.9	2.3	2.9	2.9	2.4
Delta	5.2	3.3	2.6	2.2	1.9	3.0
TestBase	2.6	2.9	2.9	2.9	3.1	2.9
SandyPoint	1.9	1.5	1.3	1.6	1.9	1.6
DesertShores	2.5	2.7	3.1	3.4	3.4	3.0
WhiteWater	5.6	5.3	6.0	5.9	5.7	5.7
NorthShore	2.2	2.4	2.8	3.7	3.7	3.0
EastShore	1.6	1.7	2.0	2.5	2.8	2.1
Grand Total	2.7	2.4	2.7	3.0	3.1	2.8

organic

> 3%

Table 6. Organic contents at depth contours for the different districts.

Finally, we present an overall view of the sediment classifications at depths and districts in Tables 7. Clays are found only at deeper level at Niland, and sand areas are concentrated at shallower levels in all locations except Niland, Delta, and Whitewater.

Division	-227	-230	-235	-240	-245
Bombay	Sandy Loam	Sandy Loam	Sandy Clay Loam	Sandy Clay Loam	Sandy Clay Loam
Niland	Loam	Clay Loam	Clay Loam	Clay	Clay
Delta	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Sandy Clay Loam
SandyPoint	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Clay Loam	Sandy Clay Loam
TestBase	Sandy Clay Loam	Sandy Clay Loam	Clay Loam	Clay Loam	Clay Loam
DesertShores	Sandy Loam	Sandy Loam	Sandy Clay Loam	Sandy Clay Loam	Sandy Clay Loam
WhiteWater	Loam	Loam	Clay Loam	Clay Loam	Clay Loam
NorthShore	Sandy Loam	Sandy Loam	Sandy Clay Loam	Sandy Clay Loam	Sandy Clay Loam
EastShore	Sandy Loam	Sandy Loam	Sandy Clay Loam	Sandy Clay Loam	Clay Loam

Table 7. Sediment classifications of districts at the contours examined.

Tables 8 and 9 provide data identical to that in Tables 4 and 5, but for more finely divided areas within each district.

	Contour Interval (upper limit)																	
	-227			-230			-235			-240			-245			Average		
SUBDIV	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
Bombay	66	13	18	67	11	19	62	11	27	54	15	32	51	18	32	60	14	25
NilandShore	49	24	24	47	25	27	44	22	35	32	22	46	41	22	37	43	23	35
Niland	29	43	28	27	45	29	23	41	37	20	37	44	27	32	41	26	43	32
AlamoDeltaSh	39	34	27	34	41	25	30	39	31	35	32	32	45	26	27	36	35	28
AlamoDelta	50	24	21	59	19	19	50	24	24	53	22	21	50	23	25	52	23	22
SouthShore	42	34	24	41	34	24	42	32	25	46	29	24	46	26	25	44	31	24
OldRiverShor	34	41	25	33	43	25	33	42	26	41	38	22	46	39	15	37	40	23
NewRiverDelt	41	28	31	42	27	29	51	20	26	48	19	30	46	24	29	45	24	29
NewRiverMud	33	27	40	29	28	43	28	26	46	31	25	45	39	25	35	32	26	43
SWshore	51	18	28	52	16	29	47	20	32	44	22	33	43	23	33	47	20	31
SanFelipeDel	43	21	34	42	21	36	35	24	41	32	25	43	31	26	44	36	23	40
TestBase	46	15	23	47	18	29	43	21	35	39	22	39	42	21	35	43	19	31
SandyPointS	57	13	20	66	13	17	65	16	15	61	15	19	57	15	23	62	14	19
SandyPointN	63	12	16	66	13	16	65	15	17	62	14	21	55	17	25	62	14	19
SaltonCity	42	25	25	41	26	30	37	27	35	33	27	40	33	26	41	39	26	31
WestShore	60	18	18	57	21	19	50	26	25	44	26	31	42	24	35	52	23	25
DesertShoreS	54	25	19	52	26	20	50	27	22	44	30	26	51	24	25	50	27	23
Oasis	59	20	18	57	22	19	51	27	23	47	27	27	45	26	29	51	25	24
Whitewater	43	33	23	38	38	24	30	41	30	26	39	36	34	33	34	42	33	24
NorthShore	58	22	18	56	24	19	54	25	21	47	30	23	45	31	24	49	27	24
Canal_Overfl	64	17	18	64	16	18	63	16	20	60	18	23	55	21	25	48	14	16
StatePark	68	10	17	64	14	20	58	22	25	51	29	29	44	31	30	57	21	24
EastShore_No	60	11	20	54	18	24	47	27	30	38	35	35	31	37	35	46	25	29
SaltCreekDel	76	6	10	71	11	14	61	20	24	49	25	32	42	27	35	57	20	26
EastShore	68	11	15	63	14	20	54	21	29	43	25	37	37	26	41	53	20	28
EastShoreSou	70	9	14	62	16	19	50	25	29	39	31	36	34	30	38	51	22	27
Average	45	30	22	49	26	23	46	25	29	45	27	30	44	26	31	45	28	25

SCS Soil Class
- Sandy Loam
- Sandy Clay Loam
- Loam
- Clay Loam
- Clay

Table 8. Sand, silt, and clay in the sub-districts at the contours examined.

The “Delta” district, in these tables, is divided into six sub-districts: Alamo Delta Shore, Alamo Delta, South Shore, Old River Shore, New River Delta, and New River Mud. The district subdivisions can be seen in Figure 8. This sub-division permits a more detailed account of the sediment distribution by sub-district and by depth.

Sum of AREA	Contour Interval (upper limit)					
SUBDIV	(227)	(230)	(235)	(240)	(245)	Grand Total
Bombay	402	290	528	533	695	2,449
NilandShore	550	441	387	105	177	1,661
Niland	365	385	2,259	2,078	2,234	7,321
AlamoDeltaSh	1,813	329	579	564	124	3,408
AlamoDelta	43	181	505	1,295	1,858	3,883
SouthShore	354	180	601	1,685	1,404	4,224
OldRiverShor	79	61	436	463	46	1,084
NewRiverDelt	773	276	1,119	2,337	2,104	6,609
NewRiverMud	1,118	880	2,327	2,502	871	7,698
SWshore	508	403	712	1,026	852	3,500
SanFelipeDel	348	257	632	556	563	2,356
TestBase	309	392	616	744	862	2,924
SandyPointS	316	122	187	271	378	1,274
SandyPointN	307	226	586	708	589	2,415
SaltonCity	91	66	79	157	191	585
WestShore	345	191	230	329	301	1,397
DesertShoreS	536	320	392	554	639	2,441
Oasis	142	99	148	173	192	754
Whitewater	1,745	606	1,122	1,300	1,173	5,946
NorthShore	244	192	356	486	573	1,852
Canal_Overfl	201	134	160	181	187	863
StatePark	67	42	56	83	89	337
EastShore_No	54	37	51	66	78	285
SaltCreekDel	116	83	171	269	270	908
EastShore	306	220	268	341	379	1,514
EastShoreSou	121	85	119	137	156	618
Grand Total	11,252	6,501	14,626	18,941	16,984	68,304

SCS Soil Class
Sandy Loam
Sandy Clay Loam
Loam
Clay Loam
Clay

Table 9. Area calculations by sub-district and depth contour.

Overall, there are 68,304 acres of sediment that would be exposed by a water level drop from –227 ft NAD to –250 ft NAD. The bulk of this area, 50,551 acres (or 75%) falls beneath the -235 ft contour, leaving 17,753 ft above (or 25%) within the margins of the lake no deeper than 8 ft. Of the total lake area above the –250 ft NAD contour sand, silt and clay make up 47.9%, 23.9% and 27.2% of the mineral sediment by mass, respectively. While the average sand content decreases with depth (from c. 53% to c.43%) the sediments overall remain relatively sandy. Most of the sandier sediments are distributed in along of open shore areas, in the channel regions of the deltas and across all depths of the extensive Sandy Point Spit and Bombay. Muds and organic accumulations are most abundant adjacent to the major delta complexes and in more offshore regions.

Distribution of sediments and organic matter

The heterogeneous distribution of sediments around the Salton Sea lake-bed is defined by the source availability and the reworking capacity of waves and currents.

There are a number of sediment sources: principle among which are point sources of the Alamo River, the New River, the Whitewater River and San Felipe Creek. More diffuse sources are derived from reworking of the lakebed as the water levels have rise over past decades and the erosion at the lake margins of the soils units of the former Lake Cahuilla Beds as well as airborne dust from the desert hinterland.

The Salton Sea is an energetic rather than quiescent lake system, experiencing winds from all directions occasionally with speeds exceeding 50 miles per hour. Such strong gusts have the capacity to create waves up to 5-6 ft height in down-fetch regions of the lake, with a competence to regularly redistribute inshore sediment. It is this wave action, creating sandy shores and transporting fine-grained material off shore to be deposited below wave base, which defines the distribution of shoreline sediment around Salton City and Bombay Beach northwards. The sandy shorelines are supported locally be the erosion of the Carisitas-Myoma-Carrizo soil formation in the northeast region of the lake and the Meloland-Vint-Indio soil formation south of Salton City creating an extensive sandy spit know as 'Sandy Point'. Evidence from short cores of irregularly interbedded sands and muds of varying thicknesses with occasional storm lag deposits of fragments barnacle shells testify to the energetic nature of these nearshore sediment.

Deltaic sequences consisting of sandy channels with muddy flanks around the inflows of the Alamo River, New river Whitewater River and to a much lesser extent the San Felipe creek, are superimposed upon this generalised wave-dominated lake margin morphology. The rapid rate of sediment supply from the rivers exceeds the rate of removal by waves enabling the delta fronts to advance each year as silty sediments accumulate. The Delta of the Whitewater River stands alone as a discrete delta sequence spreading across silt/sandy nearshore sands. To the south combined inflows from the Alamo and New rivers of silty sediments eroded from Imperial-Glenbar-Gilman soil formation blanket the nearshore. These fine sediments merge with sands to the west but are finer to east between Red Hills Marina and Bombay Beach, reflecting a plume of muddy sediment transported by an anticlockwise circulating lake current. Apparent seasonal banding (millimetre scale organic rich horizons regularly interbedded with centimetre scale fine silts) suggest that these nearshore sediments are not frequently reworked by waves and have a high preservation potential. Coring in the region to the north east of Red Hill Marine and east of the New River Delta found evidence that of a firm platform of former desert soils locally exposed by generally blanketed beneath a thin veneer of soft silty muds.

Extensive areas of beds of barnacle shells and shell fragments (c.2" in thickness and often difficult to drive a corer through, suggesting possible cementation) blanketed regions of the lake. The true extent of this 'barnacle armour' between core and grab sample locations is unclear at present but was commonly found on sandy regions on both the eastern and western shores of the lake and less commonly on the muddy flanks of the southern deltaic shore. These beds may act as a protective layer locally reducing sediment remobilisation from the lake-bed should water levels fall.

The distribution of carbon is very much related to point source inputs from the main rivers, particularly the White Water and to a lesser extent from small agricultural drainage channels on the western shore. Overall there is a negative correlation between organics and sand content with highest organic levels being found on the muddy flanks of the three main Deltas. Close examination of sediment structure within cores finds the muddy flanks of the deltas to exhibit fine laminations of dark organic matter regularly banded with thicker layers of more mineral sediments. This suggests a pulsing of organics in to the system, perhaps seasonal.

The organic sediments on the flanks of the deltas appear to be 'varves'. Varve is a Swedish word for "cycle", and varve sequences are most commonly associated with seasonal ice cover with reduced sedimentation the summer melt and increased sedimentation. These deltaic sediments appear to reflect a layer of sediment deposited in a lake over a year. Each layer consists of two parts. During the winter, river flows carry particles in to the sea, some of the fines from which settle on the delta flank margins (1-3 cm in thickness). Over the summer, particulate organic matter (plankton) settles to the bed leaving a layer of dark matter (1-3mm thickness). Oxidation of some of this organic matter strips the oxygen from the immediate sediments below causing a change in coloration from olive to grey. So what appears to be an annual cycle in sedimentation here is reflected in couplets of dark organic laminate over clay material (the color of which is divided by redox conditions)

Finding these sediments suggests several years worth of sediment accumulation. In a complete sequence each annual varve can be counted and so the age of the sediments deduced. The importance here is that they indicate that even in such a storm prone lake there are areas which are not reworked. Not finding these sediments in other places indicates that the sediments are often reworked by the storm waves. These varves have formed an important component of our dividing the districts in to Deltaic, transitional and open shore sequences.

Globally, lakes are important sinks for the storage of organic carbon, perhaps 50 times more effective than ocean sediments (Eisele et al, 2001). In many lakes the preservation factor of the organic particles reaching the lakebed sediments has been estimated at about 10-15% (e.g. Kelts, 1988) but in modern marine sediments only an average of 0.1-0.2% of the primary production is preserved below the zone of bethic degradation (e.g. Hedges et al. 1997).

Organic and inorganic carbon that is not buried within the lake sediments may leave the water through dissolution then degassing of CO_2 (or in open lakes through outflow). Bioturbation often increases the availability of oxygen to the sediments increasing rates of organic breakdown. In principle, saline lakes can produce considerable amounts of organic matter. However, preservation or particulate organic carbon in sediments may be (c. 5% or primary production) as a result of high sulfate availability stimulating sulfate reduction, which accompanies oxidation of organic matter. Thus, in saline sediments such as those of Mono Lake organic carbon levels of only 1.1% have commonly been found (Domagalski et al 1989).

Here at the Salton Sea the organic carbon contents of the lake sediments are relatively low (district averages: 1-6%) in comparison with recorded global averages (10-15%) (Einsele et al. 2001), but comparable with other saline lakes. Carbon contents are highest on the fine-grained flanks of the major Delta regions (c. 6%) and locally at the outflows of significant drainage channels, and lowest on the distal sandy shores (c.1-3%). This reflects not only organic sedimentation proximal to the river inflows but suitable conditions for organic accumulation in the anoxic undisturbed muds of the delta flanks. Across the wave-exposed open shore districts oxygen bearing porewaters are free to circulate through the sandy sediment but more so these sediments are frequently reworked during storms providing conditions for enhanced dissolution of the particulate carbon.

An interactive data base for profiles of the sampled transects is presented electronically as one of the appendices to this report (Appendix 3). We show here two representative profiles from this data base: one for Niland, and one for the New River. At Niland (Figure 12 below), it can be seen that sand content of the sediments drops precipitously with distance from shore. Silt content remains relatively constant, and clay percent increases. The organic content increases generally with depth as well, although the total percent content remains low. The depth profile shows a regular but rather steep slope, attaining a depth of 23 feet in less than 3000 meters .

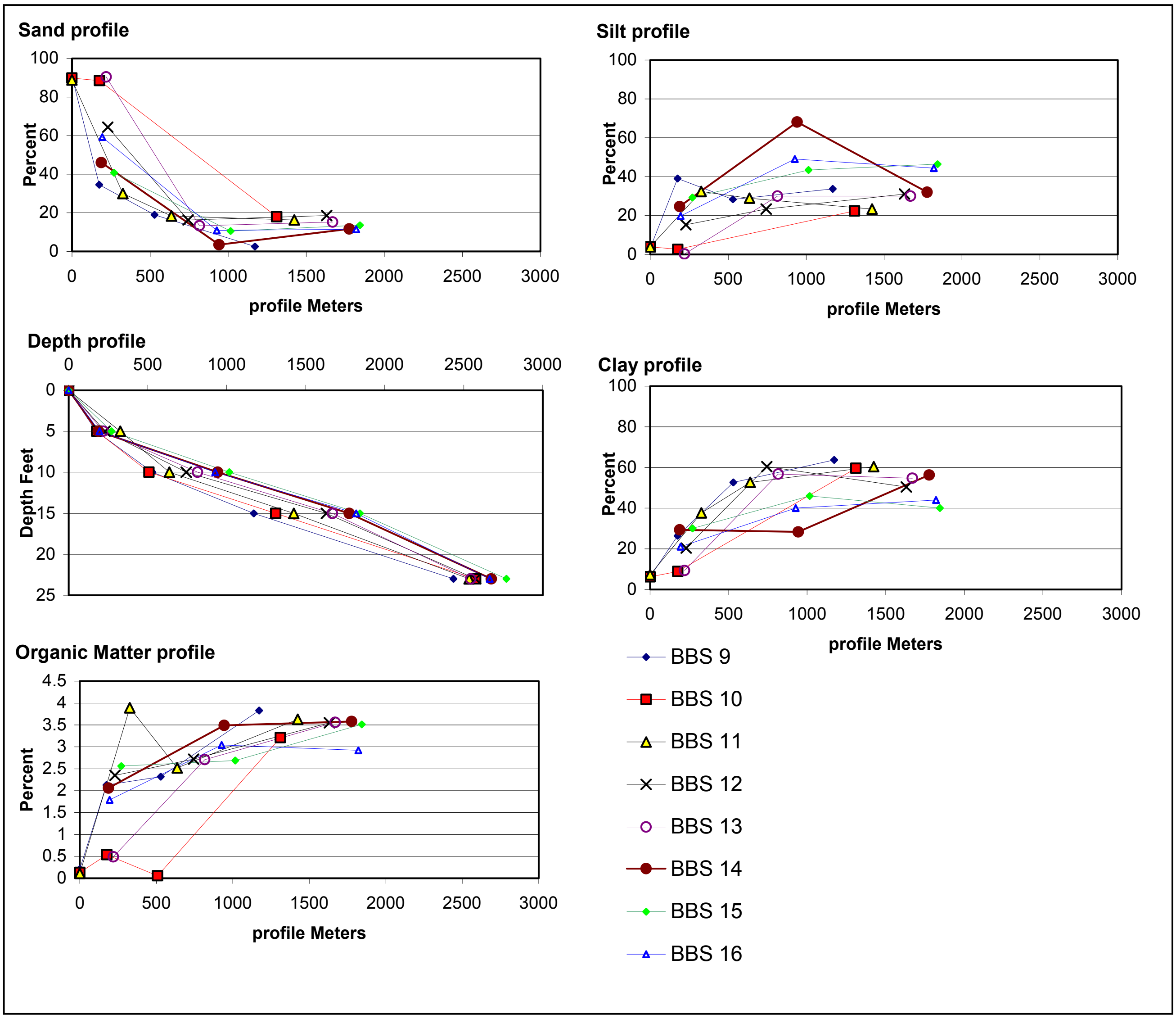

Figure 12. Sand, silt, clay, organic matter, and depth profiles for the transects sampled at Niland.

At the New River (Figure 13, below) in contrast, the profiles show that sand content tends to increase with depth, with silt being variable, and clay percent tending to decrease. Organic content tends to decrease with depth at this location. The depth profiles are variable in this district, with a slope in some transects showing attainment of 23 feet in less than 4,000 meters, and other extending to over 8,000 meters. Transects of the remaining districts can be found in Appendix 4.

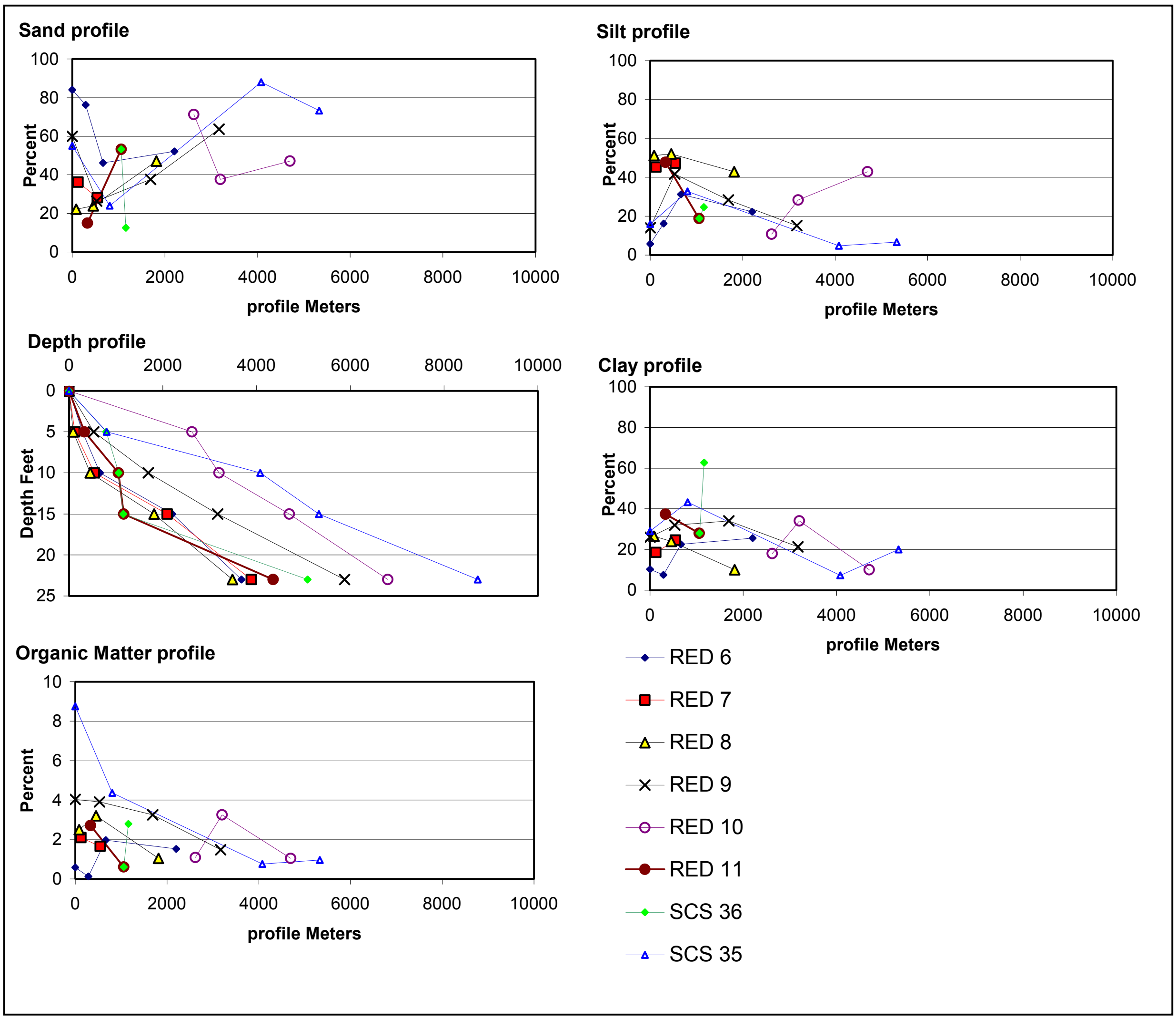

Figure 13. Sand, silt, clay, organic content, and depth profiles for the transects sampled at the New River.

We conducted some additional analyses aimed at determining the extent to which sediment type can be predicted from existing soils and land use data adjacent to the Salton Sea. Figure 14 shows an overlay of a soils map, where data are available, on the sediment data as determined from the grab samples. The data show the sediment district with their classification, and the soil series mapped by the NRCS. The map shows that the sediment zones are closely correlated with soil classifications in the soils adjacent to the sampled area of the Sea. The division between the clay loams and the loams at the south part of the Sea, for example, closely mirrors the change from the clay loams of the Imperial Glenbar soils to the sandy laoms of the Meloland-Vint-Indio soils. The sandier areas to the north and northeast of the Sea, shown in the sediments as sandy loams, are associated with the Carsita-Myoma-Carrizo and Gilman-Indo-Coachella soils, which are generally fine sands. This finding suggests that the nature and potential emissivity of sediments that might be exposed by decline in Sea level could reasonably be investigated using adjacent soils that are currently exposed.

There are, of course, some difference between recently exposed sediments and soils originating from sediments that have been subjected to weathering. The exposed desert soils will have been 'aged' to some extent, as evidenced by the armoring with rock fragments on the surface. Here the easily mobilised material has already left the surface leaving a lag deposit of cobbles which protects the underlying material from the wind. Disturbance of this lag can increase the amount of sediment released. There will be other differences as in terms of sediment fabric or structure, as well as in the effect that the chemistry will have on the behaviour of the sediments. There will be precipitation of minerals as the lake dries. Carbonates may accumulate in near surface sediments (perhaps aided by the abundance of barnacle shell carbonate source material) as will fine grained sulfate and halite mineral. The lake bed also probably contains more carbon that the adjacent desert soils. However, this material derived form plankton is unlikely to be resistant to oxidation once exposed and is likely to be lost very quickly. That said, carefully chosen soils nearby, and similar sediments from other playas, will provide a preliminary indication of possible emission potential.We also plotted the sediment data on a LandSat image of the Salton Sea to determine if sediment class and land use were related. Figures 15 and 16 show this image, in the north and south portions of the Sea, respectively. Soils that are currently used for agriculture are not associated with sediment types of clay or medium sand; rather, these cropped areas appear related to sediments classed as various types of loam (soils of mixed sediment grade). This association may provide some guidance as to which areas of the exposed sediments may be most appropriately designated as areas for vegetation for the promotion of wetland habitat or vegetative cover for dust control.

Finally, we present a map that indicates where no samples could be recovered, principally because of a high shell content. These sites were most prevalent in the Sea (Figure 17). The largest shell fractions were encounterd along the west shore, the northeast shore, and in the vicinity of Bombay.

Likely response in lake-bed sedimentation to falling water levels

So far we have described the distribution of sediments around the lake margin as they are found today, but will this distribution still exist if the lake water level falls? This is difficult to say for certain but there are some general lines of evidence that can be discussed. Wave energy is the main driving force as to whether sediments will be left in place or redistributed as water levels fall. The degree to which wave action will rework the sediments is likely to be much greater for open shore and transitional districts than for the more quiescent delta districts. The sediments of the open shore and, to a lesser degree, the transitional units are subject to frequent reworking by waves. This wave reworking is responsible for the shoaling of sandy beaches and nearshore sediments and removal of fine-grained silts and clays that are lifted in to suspension to eventually accumulate at greater water depths.

It is estimated that should all water flow into the lake cease, then the lake level could fall by up to 6.4 feet per year, based on the evaporation rate for Salton Sea water (Agrarian Research 2003). Even under this extreme case, a portion of the time that the water level is falling the open shore and transitional districts will be subject to storm generated wave action. Thus the sediments, which were once in 'equilibrium' with wave energy will now be subject to reworking. In essence, it is likely that as water level falls waves will act to reshape the shore, carrying fines out to deeper water and leaving coarser material behind. The more slowly the lake levels fall then the greater the degree to which transitional sandier beach units will develop and fines will be redistributed towards the centre of the lake.

The delta districts are expected to behave differently as water levels recede. Here, the core data suggests evidence that the delta flanks are not reworked so frequently during the storm season. Because of this, fine-grained organic rich sediments will be left stranded above the level of the receding waters. It should be borne in mind that the soft muds themselves are constituted principally of interstitial water, and so de-watering of the sediments will result in consolidation of the fine sediments, possible subsidence and/or irreversible cracking, and reshaping of the topography. Depending upon the rate of water level fall, some form of transgressive delta may appear as muds spread along the receding shoreline. A new delta will re-establish once water levels re-stabilise.

Comparison with Owens Lake

The area mapped during this study (67,530 acres) is almost three times as large as the total area of sediment that was exposed at Owens Lake, which has 22,505 acres identified in 1998 as being emissive of dust (GBUAPCD 1998). The Owens Lake playa is the largest single source of PM10 dust (aerosol particles smaller than 10 microns in aerodynamic diameter) in the United States; current estimates show that 83,000 metric tons are lofted per year (GBUAPCD 2003). Comparisons of the Owens Lake to the Salton Sea are almost inevitable. In their work on Owens (Dry) Lake, south-eastern California, Gill (1996), Niemeyer *et al.* (1999) and Reheis (1997) have demonstrated that gross changes in the hydrology of a playa (in this case human induced) can lead to extreme changes in regional dust emissions. Reheis and Kihl (1995) have also shown that changes in the frequency and extent of natural inundation occurring on large playa systems may lead to significant fluctuations in regional dust loadings. A very brief survey or what is known about the surface of the Owens Lake and its emissions is therefore in order here.

The Owens playa consists of a variety of soil types that were mapped in 2000 by Soil and Water West (SWWI 2000 and 2002). The areas identified as "clay" occupy the largest portion of the playa, encompassing 8,412 acres. The areas identified as "sand" are the next most prevalent, occupying 4,296 acres. Sand/clay occupies an additional 2,007 acres. The remaining areas, totalling 7,790 acres, are various forms of loams with variable textures. We note that the most highly emissive areas of the Owens playa are in the north and south, which are heavily dominated by sands; and the southeast, which has large bodies of heavy clays. The Salton Sea sediments, in contrast, have less area consisting of "sand", and minimal areas classified as "clay". The Salton Sea sediments, then, are somewhat more heterogeneous than are the Owens playa soils.

The extensive work by the Great Basin Unified Air Pollution Control District (GBUAPCD) has revealed, however, that sediment or soil classification is by itself a poor predictor of quantity or frequency of dust emissions. For the emission inventory conducted by GBUAPCD, the emissive areas were determined empirically by field mapping of eroded areas after storms using a GPS system. In addition, various areas of the playa were tested with portable wind tunnels to determine the emissive quality of the surfaces. These tests showed that although there are obvious surface differences across the playa, the wind tunnel-generated PM_{10} emission data showed that the highest emission rates in each area were similar for a given season. The seasonal differences are principally caused by cold weather bringing salts to the surface, which in a decahydrated condition, create a very erodible surface (GBUAPCD 1998).

Some of the mechanisms for production of PM_{10} are well understood. Sand, or sand-sized particles, can be moved by wind so that they begin to bounce or “saltate” across the surface of the ground. The threshold wind velocity for dust emissions has been identified as 17 mph, measured on an anemometer at 10 m height. On days when air quality thresholds have been exceeded, the reported daily average wind speeds have ranged between 5 and 33 mph. (GBUAPCD 1998). These wind speeds are exceeded at the Salton Sea on about 80 days a year, as measured at the solar pond site (Agrarian Research 2003). As the moving particles impact the ground repeatedly, they can dislodge smaller particles that are lofted into the air and create dust storms. Although true mineral sand itself does not produce PM_{10}, in concert with soils that have a silt and clay content, sand is instrumental in generating PM_{10}. The other factors, such as those described above, interact to create a situation where PM_{10} is generated. Areas with shallow saline water tables can promote dust emission, as can areas with the kinds of salts that develop hydrated phases in cold and wet weather.

Other factors contributing to emissivity include the proximity to the surface of a saline shallow water table. The inclusion of salts stranded in the surface soils due to evaporation, or mobilized from precipitation, creates a situation where soil particles, especially silts and clays, are bonded in a flocculated condition. When drying occurs, the salty soils deflocculate, creating a soil surface with extremely fine, non-cemented particles that are highly subject to wind erosion.

In general, however, it has been extremely difficult to predict which areas of the playa will be emissive at any given time, although it is widely felt that most exposed, dry surfaces will become at least somewhat emissive at some time (Duano Ono, pers. comm.). Informed opinion from air quality experts is that the location and size of dust source areas on clay dominated areas of the Owens playa are dependent on the annual weather patterns, including timing of precipitation events (which are more frequent and more intense in the Owens Valley than at the Salton Sea), high wind speeds, and diurnal temperatures (which are colder than at the Salton Sea). The sand areas, however, are more predictable, as the saltation action of the sand is more certain to generate dust events. Overall, the opinion is that salt chemistry and climate are large determinants of erosion potential, with actual soil type taking a secondary role (Cox and Holder, 1997).

Salt chemistry in particular distinguishes the Salton Sea and the Owens Lake surface environments. The following discussion, although not strictly speaking related to sediments, is included here for further insight into the emission potential for the Salton Sea.

Marked differences between Owens Lake and the Salton Sea exist in the salts that would form on the surface of exposed sediments. Owens Lake is a sodic environment. Sediment pore water at Owens Lake is saturated in sodium carbonate/bicarbonate and sodium sulfate (Mirabillite) at wintertime temperatures. Calcium and magnesium ions are virtually absent from the system, as an excess of carbonate has previously precipitated all available calcium and magnesium. Sodium carbonate and sodium sulfate form decahydrate crystals at very dilute brine concentrations when temperatures drop below the phase limit near 60 degrees F. Recurrent winter low temperatures induce the formation of efflorescent decahydrates salts on the surface of the sediment from pore water brines, which were under-saturated at higher temperatures. Surface crusts formed by capillary evaporation of groundwater spontaneously convert to decahydrated forms when exposed to elevated wintertime moisture and relative humidity. These decahydrate salts form fragile needle-like crystals and are easily dislodged by high winds and/or blowing sand.

The Salton Sea is similar to saline marine brine in composition, rather than to a sodic brine lake. It is at or very near saturation for calcium carbonate, so excess calcium and magnesium are abundant. The excess calcium and magnesium encourages the early formation of very stable calcium carbonates and dolomites ($CaMgCO3$). No excess carbonate exists to crystallize with the sodium present. Excess calcium ions will also form sulfates (anhydrite and the dihydrate gypsum). Gypsum may dehydrate and erode from the surface of the exposed sediments.

Mirabillite (sodium sulfate decahydrate) will form from Salton Sea brine or pore water when temperatures fall below 60 F, just as it does at Owens Lake. The warmer wintertime temperatures and lower total available sulfate concentration in the Salton Sea brine, however, mean that this crystal will form less abundantly than at Owens Lake.

Halite (sodium chloride) forms from evaporation of both Owens and Salton Sea brine. At Owens Lake, halite forms in conjunction with trona. Trona has the much greater volume due to its lower density, and dominates the physical characteristics of the combined salts. In comparison, halite will form the predominate volume of all salt forming from Salton Sea brine, just as it does in typical marine systems. Salt formation on exposed Salton Sea sediments should resemble marine or saline playa evaporation. Northern Baja's Laguna Salada, due to its similar chemistry, may provide a better model of exposed Salton Sea sediments than does the Owens Lake, although the presence of sand in the Laguna Salada sediments would be crucial for any meaningful air quality extrapolations.

The current study provides a solid basis for understanding the potential for dust emission from Salton Sea sediments, but cannot by itself reliably predict the amount of emission that could result from the exposed sediments. It does, however, indicate clearly that a problem could exist, and that proactive planning is indicated. We suggest further studies in the sections below.

Recommended further work

1. **Extend grab sampling to 20 and 25 ft contours.** With water levels anticipated to fall below the 15 ft contour it would be beneficial to increase the sedimentological data down to the 25 ft contour. Trials with the acoustic mapping system were not successful in extending the grab samples survey results to this greater depth.

2. **Develop a set of standard operating procedures for the future collection and processing of sediment samples for texture and organic content.** This will enable all future data sets to be used with each other, dramatically improving the quality and value of the data.

3. **Initiate a program of testing exposed areas for the potential to support vegetation as an emissions control measure.** Prior experience indicates that not all areas are equally suited for the introduction of plants for surface stabilization. An early program of pilot projects on exposed soils close to the current Sea margin would put a mitigation program

4. **Initiate a program of testing sediments for potential for emission of PM10.** This can be done readily with portable wind tunnels on soil areas that are already exposed. Selection of testing sites should be done in close collaboration of sediment, soils, and air quality experts. On-site field testing for emission has been conducted at the Owens Lake, and this experience has proved very valuable in air quality modelling.

5. **Investigate how sediments would respond to drainage**. Saline soils with some sodicity are prone to sealing when irrigated with fresh water in the phreatic zone for vegetation establishment. Examination of such changes in other playa environments such as Laguna Salada would reveal some issues surrounding “natural” playa reclamation.

6. **Chart barnacle bed distribution.** Thick beds of encrusted / cemented barnacles shells blanket areas of the shallow lake-bed. These beds may protect underlying sediments from wind erosion should lake-water levels fall. It would be advantageous to have a clearer understanding of the distribution and integrity of these barnacle beds.

7. **Sediment grain size.** Further grain size analysis should be done at ½ phi intervals. This would give us a much clearer picture, and a better statistical representation, of the particles present, including the amount of PM_{10} for instance, and would increase the precision of emission models. The analysis would not require a change in the field procedure, although it would involve a more time consuming lab analysis.

8. **Further research on how the sediments would be re-worked by wave action.** There are several ways that this evaluation could be done. One is to look at a time series of elevation change on the nearshore lake-bed before, during and after the storm season. Surveying along transects will give this

elevation change and the monitoring should be done before storms and immediately after. This survey should be complimented with measurements of the wave characteristics (related to depth), measurements of the lakebed sediments, and measurements of sediment in suspension. Transects should be placed to reflect the variety of districts and should encompass areas of open shore, transitional regions and delta flanks. Measurements of the wave characteristics could be supplemented with long-term data monitoring from a buoy system to help place the individual storm events in to climate context.

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APPENDIX 1

CORE LOGS

CORE DIAGRAMS

Core Descriptions

WP 37, 5 ft: No penetration (submerged parking lot).

WP 38, 10 ft: Top 2" barnacles some sand. No sample.

WP 39, 15 ft, 12": Greyish olive [5Y 5/2]Muddy sand with odour of H_2S. No indication of lamination. (0-6; 6-12).

WP 40, 5 ft, 12": 6" of dark olive [5Y 4/3] coarse sand overlying thinly-thickly laminated muds and fine sands . Isolated barnacles at 6" (0-6; 6-12).

WP 41, 15ft, 9": 8" of dark olive [7.5Y 4/3] sand/ muddy sand over becoming gray [7.5Y 5/1]. Minimal lamination (0-6; 6-9).

WP 42, 5ft, 20": Two very different sedimentological units: Grey [5Y 5/1] laminated sands (1-9") overlying olive black [5Y 3/2] mud (9-20). Sharp contact between sand and mud.

WP 43, 15ft, 10": Muddy sand, mostly dark olive [5Y 4/3] becoming grey with depth [5Y 5/1]. No lamination. (0-6; 6-10).

WP 44, 5ft, 8": Poor penetration in to dense sand with some barnacles at surface. Colour transitions from dark olive [5Y 4/3] to grey [5Y 5/1] (0-6; 6-8).

WP 48, 15ft, 20": Finely-thickly laminated olive black [10Y 4/2] with dark gray and black soft very soft muds, no sand laminations (06; 6-12; 12-20).

WP 52, 5ft, 7": Dark olive {5Y 4/3] coarse sand with storm layer or barnacle fragments at 5". No other apparent lamination (0-6; 6-7).

WP 59, 15ft, 20": Thickly (c.5 mm) laminated olive grey [7.5Y 4/2] and grey [7.5Y 4/1] soft muds (0-6; 6-12; 12-20).

WP 66, 5 ft, 6": Compact coarse sand no lamination but shell fragments in top 1". Bulk sediment is greyish olive [7.5Y 4/2] though lighter top 1" grey [7.5Y 4/1] (0-6).

WP 73, 15ft, 18": Laminated silty muds. Top 2" greyish olive [5Y 4/2] grading grey [5Y 5/1] with depth. Very thin bed of greyish olive [5Y 4/2] at 7 " (0-6; 6-12; 12-18).

WP 80, 5ft, 10": Top coarse granular sands with abundant spell fragments (c. 3mm dia.). No colour change: greyish olive [5Y5/2] (0-6, 6-10).

WP 87, 15ft, 18": Soft mud: greyish olive [7.5 Y 5/2] to 8", very thin bed (c.10 mm) of greyish olive at 10.5" [7.5Y 4/2] with grey [7.5Y 5/1] sediment to base of core.

WP 95, 5ft, 6": Olive black [5Y 3/2] coarse sand, no lamination (0-6).

WP 102, 15ft, 14": Laminated silty mud, greyish olive [7.5Y 5/2] with grey [7.5 Y 5/1] thin-thick laminations (3-4 mm) every centimetre or so. (0-6; 6-12; 12-14).

WP 109, 5ft, 13": Top 6" grey [5Y 4/1] coarse sand no obvious lamination overlying grey [5Y 4/1] muds thinly laminated with sands becoming yellowish grey [2.5Y 5/1] at base (0-6; 6-12; 12-13).

WP 116, 15 ft, 18": Mud becoming increasingly firm with depth. Colours leaching from apparent (not chart recorded) olive brown at surface to great . Occasionally thinly laminated. (0-6; 6-12; 12-18).

WP 124, 5ft, 15": Thinly banded grey [7.5Y 6/1] and greyish olive [5Y 4/2] muddy sand capped at surface with a thin layer of dark grey mud. Colours do not appear to reflect changes in grain size but more likely periodic influxes of organic material and oxidation changes in porewaters. (0-6; 6-12; 12-15)

WP 131, 15 ft, 18": Soft mud becoming slightly firmer with depth – surface is capped with 2" of very soft mud of recent deposition. Thinly banded hues of greyish olive [5Y 5/1] and [5Y 5/2]. (0-6; 6-12; 12-18).

WP 138, 5 ft, 16": Strongly differentiated sedimentological beds separated by a sharp erosional contact. Top 9" consisting of upper 2" of black [5Y 2/1] muddy sands over grey muddy sands [5Y 4/1] with fishbones giving way at contact to colour banded grey [5Y 5/1] greyish olive [7.5Y 5/2] muds. Sediment surface is capped with a 3 mm thick deposit of olive [5Y 6/6] organic rich material. (0-9; 9-16).

WP 145, 15 ft, 10": 6" of greyish olive [7.5Y 5/2] soft muds laminated with shell fragments overlying a unit of greyish brown [5YR 5/2] very firm basement clay (0-6; 6-10).

WP 152, 5ft, 11": Greyish brown [5YR 5/1] unlaminated sand (0-6; 6-11).

WP 159, 15 ft, 17": A spectacular very thinly banded sequence of greyish olive [7.5Y 4/2] (3mm thick) and grey [5Y 5/1](5 mm thick) muds. Top of many of the grey layers marked by a thin (1mm) thick black horizon of likely organic rich material. Interpret the sequence to reflect continued sedimentation with regular periodic influx of organic material leading to redox reduction in below sediments.(0-6; 6-12; 12-17).

WP 166, 5 ft, 12": Thinly bedded muds and sands (0-6") over a short sequence of bedded muds (6-10") and basement clay (10-12").

WP 173, 15 ft, 17": Very soft mud. Olive black [10Y 3/1] at surface (top 2") becoming increasingly grey [10Y 5/1] with depth. Below 9" regular banding with greyish olive [7.5Y 5/2]. (0-6; 6-12; 12-17).

WP 180, 5ft, 12": Olive Black [7.5Y 3/1] laminated sand (0-4") over olive black [7.5 3/1] and grey [7.5Y 4/1] banded silty clays (4-9") and greyish red [2YR 5/2] basement clay material.

WP 187, 15ft, 15": Grey [10y 4/1] muds becoming slightly lighter and greyish olive [7.5 4/2] with depth and banded every 2 cm with dark olive [5Y 4/3]. Surface capped by 2" of olive black soft mud [10y 3/1]. (0-6; 6-12; 12-15).

WP 194, 5ft, 12": Grey [5y 5/1] silty mud overlying firm basement at 9" depth. (0-6; 6-9; 9-12).

WP 201, 15ft, 13": Complex colouration in solft mud. Dull orange [7.5 YR 6/4] surface layer of algae or brine shrimp (2-3mm thick) over brownish black [2.5Y 3/2] and below 4" depth becoming grey [7.5Y 5/1]. (0-6; 6-12)

WP 212 5ft, 20": Regular strongly banded soft mud: olive black [5Y 3/1] and grey [7/5Y 4/1] each 2 –3 cm in thickness. (0-6; 6-12; 12-18).

WP 481, 5ft, 13": Complex banding of coloured muddy sands. Top 1" greyish olive [5Y 4/2] sandy muds over black [5Y 2/1] sandy silt (1-4") with isolated barnacle over olive black sands [5Y 3/2]. (0-6; 6-12).

WP 482, 15ft, 12": Very colourful core of sandy silts over silty sands. 0-6" of yellowish grey silty sand over 6-12" of grey [7.5 5/1] silty sand. (0-6; 6-12).

WP 483 5ft, 11": Silty sands banded (1-2cm thickness) in colour greyish olive [7.5Y 5/2] with grey [7.5Y 5/1] with barnacle fragments at 4".(0-6; 6-11).

WP 484 5ft, 16": Soft bedded muds colour banded at the cm scale greyish olive [5Y 4/2] at the top becoming increasingly grey with depth [5Y 5/1]. (0-6; 6-12; 12-16).

WP 485, 5ft, 12": Gray [5Y 5/1] sands over sands barnacle fragments and shell lag at base. (0-6; 6-12).

WP 490, 5ft, 13": Dark olive [7.5 4/3] soft silty muds 0-8" over olive grey [10Y 5/2] firmer muds. Barnacle fragments in top 2". (0-6; 6-12).

WP 491; 5 ft, 18": Dark olive [7.5Y 4/3] soft sandy silt over lying grey [7.5 4/1] sandy slit at 16" depth. (0-6, 6-12; 12-18).

WP 529; 15ft, 9": Grey [7.5Y 4/3] muddy sands with occasional barnacle fragments. (0-6, 6-8).

WP 531, 5ft, 16": Black [10Y 2/1] sands overlying grey [10 4/1] thickly laminated sands and muds below 6" depth. (0-6; 6-12; 12-16)

WP 532, 15ft, 18": 2" of very soft dark olive grey mud [2.5GY 3/1] overlying soft dark greenish grey [10GY 3/1] mud (0-6; 6-12; 12-18).

WP 533, 15ft, 18": 2" of very soft dark olive grey mud [2.5 GY 3/1] overlying soft brownish black muds [2.5Y 3/2] At 11" there is a sharp transition to multiple thinly laminated grey [2.5GY 5/1]. (0-6; 6-12; 12-18).

WP 534, 15ft, 16": All soft mud. Uniform grey mud (0-6") overlying thinly laminated olive grey mud which then gives way to thin beds of olive black and grey mud.

WP 535 15ft, 14": Very soft black mud (0-2") over uniform grey [5Y 6/1] becoming firm with barnacle fragments and small concretions at 12" depth. (0-6; 6-12).

WP 536, 15ft, 11": Shallow (10") of soft mud over grey firm base [5Y 4/1]. Top 2" dark greenish grey [5GY 4/1] transitioning sharply to olive grey [5GY 6/1].

WP 537, 5ft, 19": Sandy dark olive grey [5 GY 3/1] unit with small concretions towards base of sequence. (0-6, 6-12; 12-18).

WP 539, 15ft, 8": Top 1" black [10Y 2/1] sandy silt with barnacle fragments over firm grey [5Y 4/1] sandy clay. Barnacles at base. (0-6; 6-8)

WP 540, 5ft, 16": 4" of very soft black mud [7.5GY 2/1] over soft dark grey [2.5GY 3/1] mud which becomes dark greenish grey [7.5GY 4/1] with depth.

WP 571, 5ft, 16": 8" of dark olive grey [5GY 4/3] sandy silt overlying dark bluish grey [5BG 3/1] muddy sand (0-8; 8-16)

WP 572, 15ft, 19": 3" of very soft black [10Y 3/2] mud overlying soft greyish olive [10Y 4/2] sandy clay with slight indication of lamination below 14" depth. (0-6; 6-12; 12-18).

WP 574 15ft, 15": 7.5" of black [N2/1] soft sandy mud sharply transitioning to underlying grey [10y 5/1] muddy sands. (0-7.5)

WP 576, 15ft, 1.5": Poor penetration into compact muddy sand with possible barnacle armoring.(0-1.5).

WP 578, 15ft, 8": Brownish black [10YR 3/2] sand becoming dark olive grey below 6" depth. (0-8)

WP 579, 5ft, 19": Top 1" barnacle covering overlying muds mixed with barnacle fragments. Firm dark olive grey [2.5GY 3/1] muds below 7.5"

WP 580, 15ft, 12": Soft muds, black [7.5 YR 5/2] in upper 6.5" transitioning sharply to dark grey green [5GY 3/1] slightly firmer muds. (0-6; 6-12).

WP 591, 15ft, 6": Barnacles at surface. Dark grey mud over red basement clay (no colour chart).

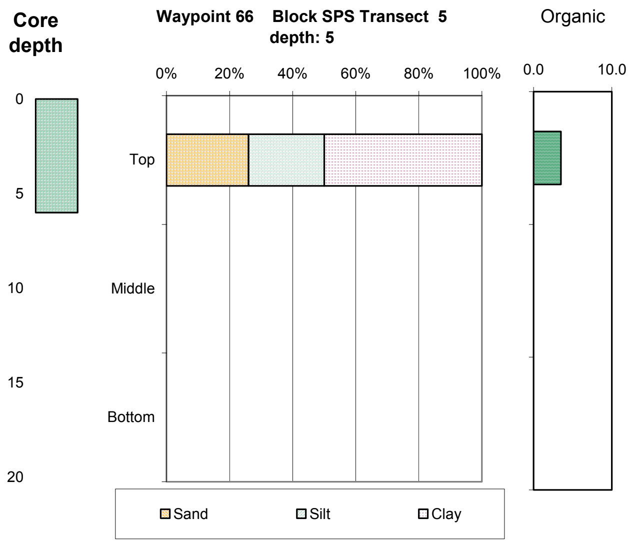
WP 596, 5ft, 14": 2" layer of barnacles at surface. Grey uniform soft mud (no colour chart) (2-6; 6-12).

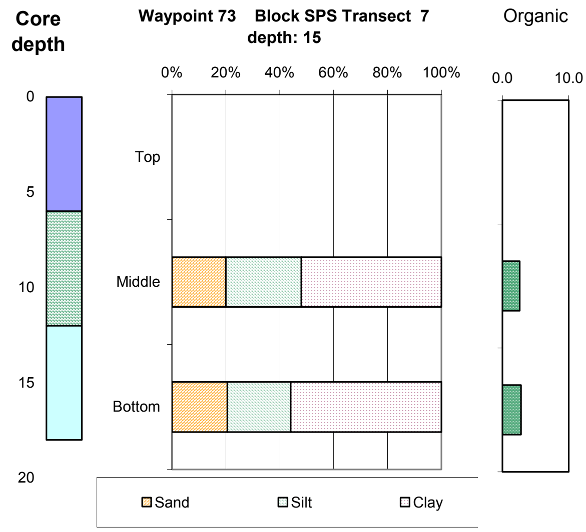
WP 601, 5ft, 3": Very firm red basement clay (no colour chart) (0-3)

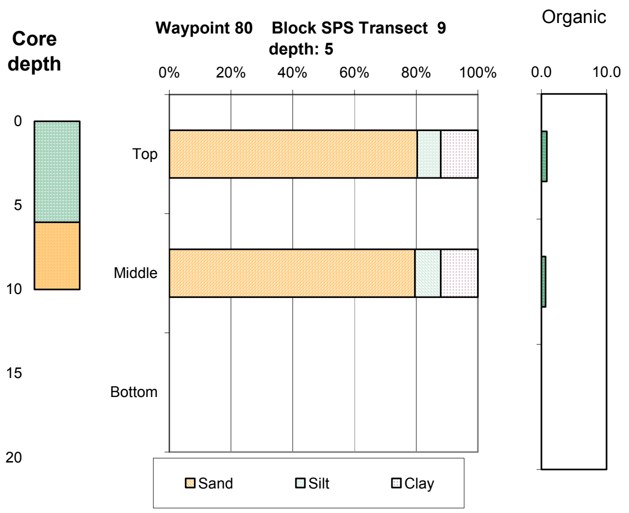
WP 602, 5ft, 2": Compact black sand (no colour chart) (0-2)

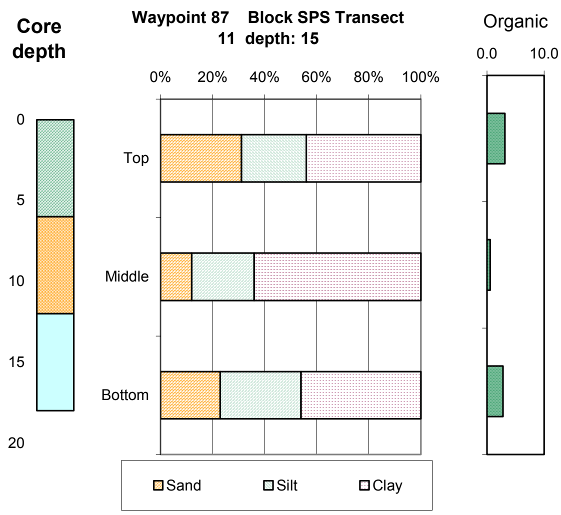
Mis- numbered core

WP 535, 5ft, 19": Mud differentiated only by colour. Top 6" brownish grey [10 Y 4/1] over a 4" thick dark layer of brownish black [7.5Y 3/1] becoming light dark olive grey with depth [2.5 GY 4/1]. (0-6; 6-12; 12-18).



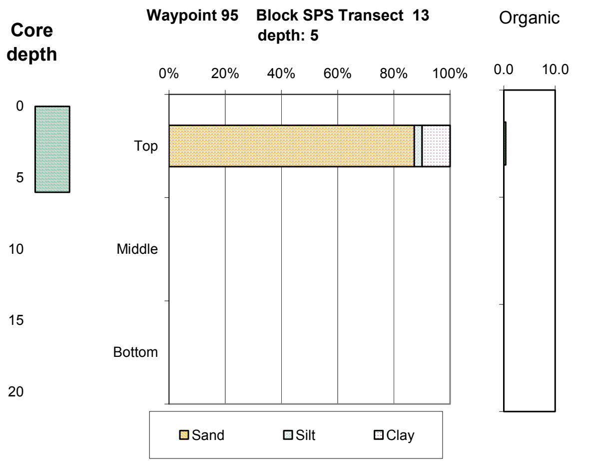


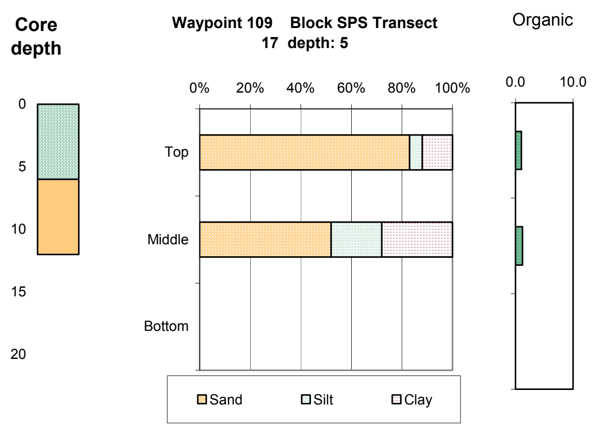




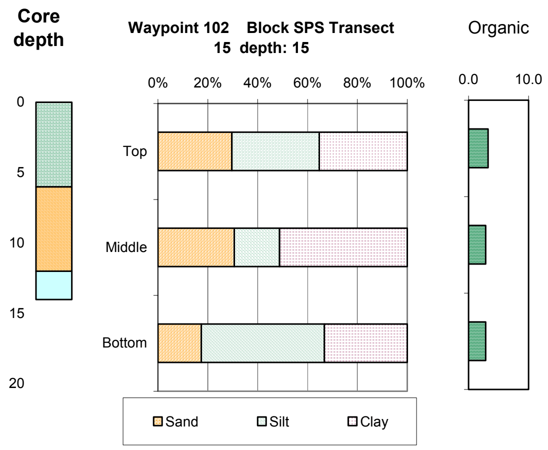
Five foot cores

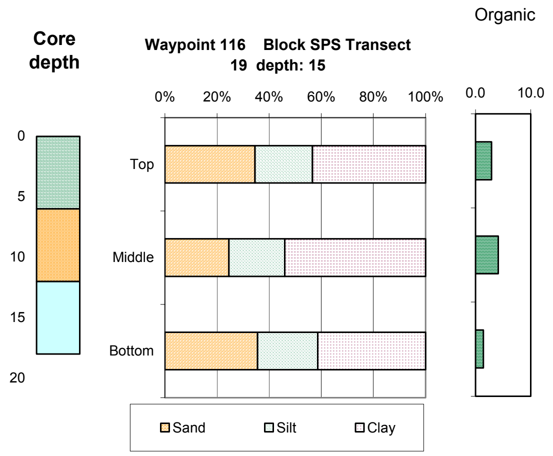
Fifteen foot cores





Five Foot Cores





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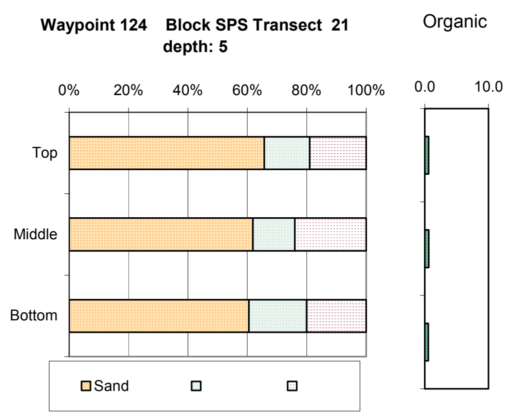
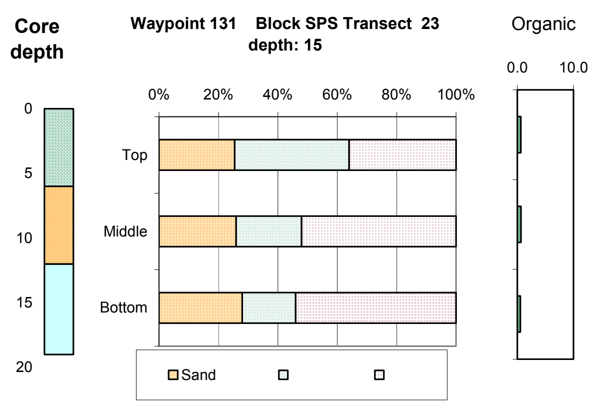


Five Foot Cores



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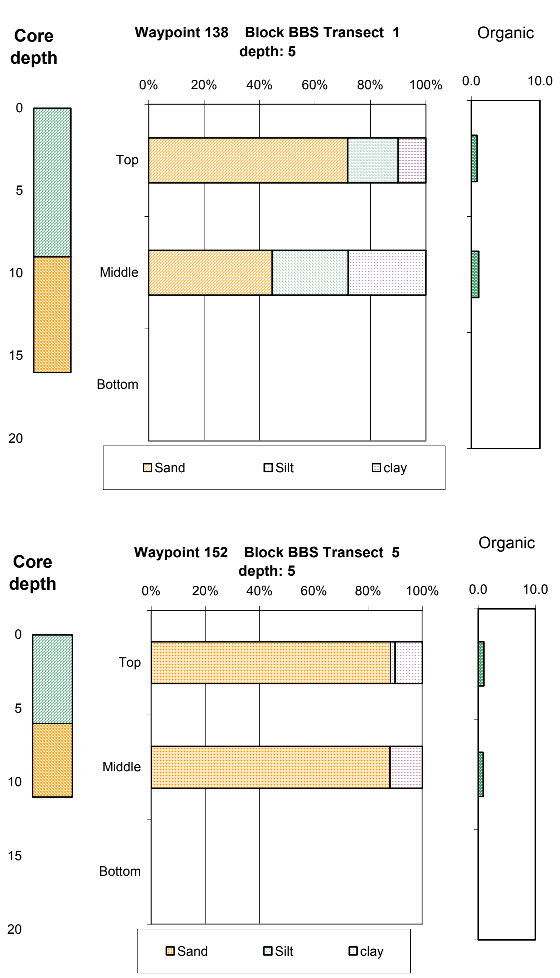

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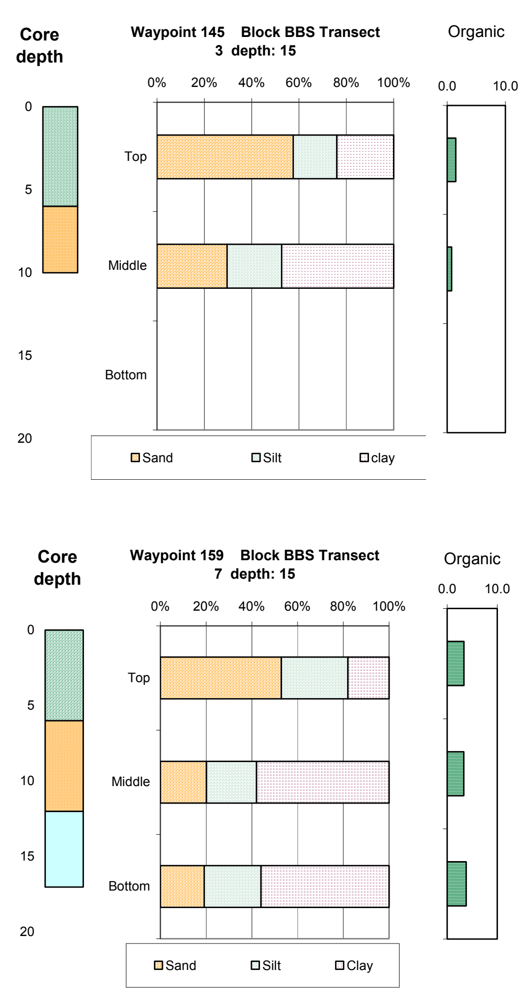

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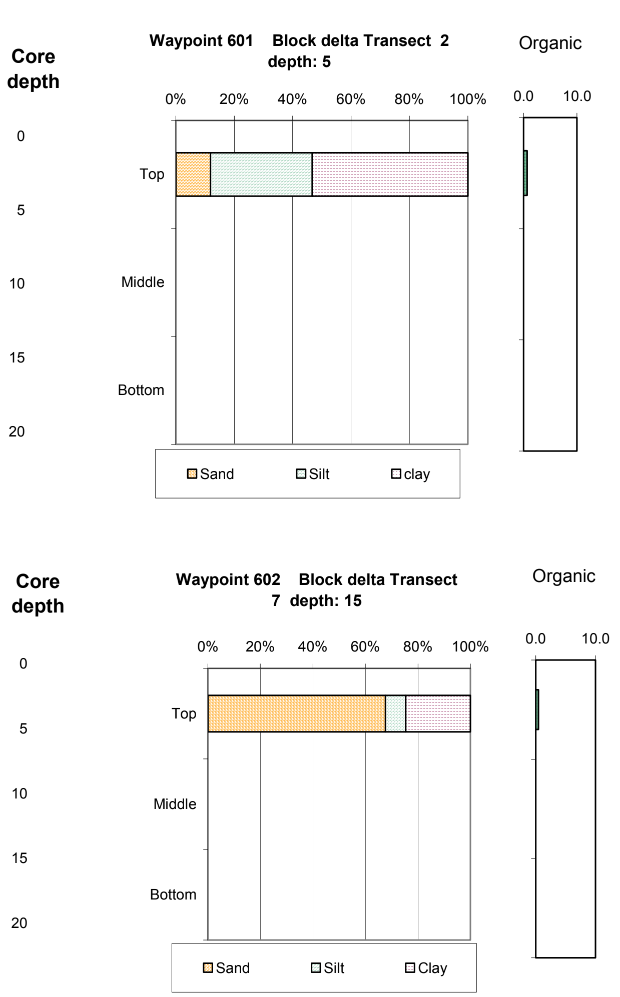

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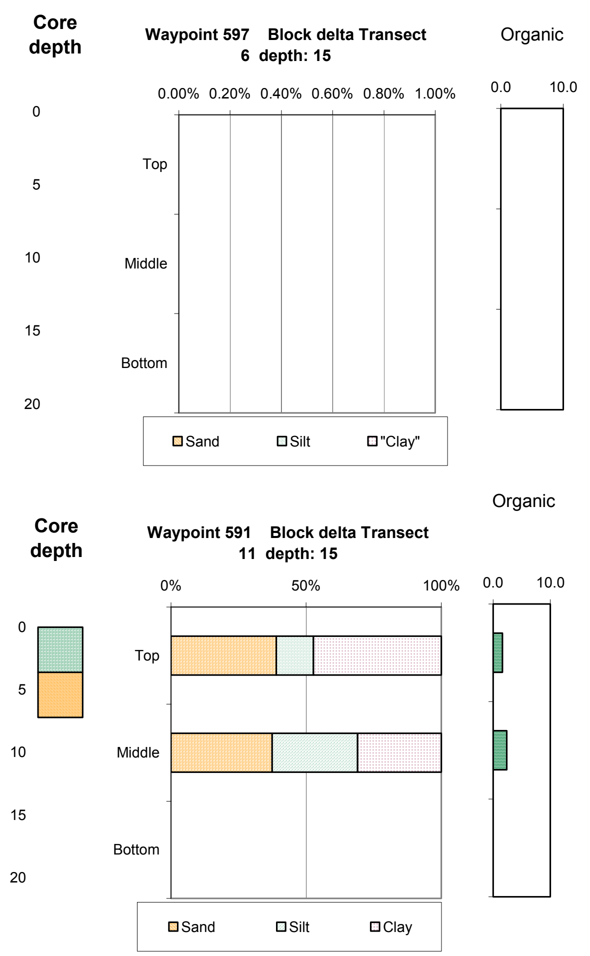

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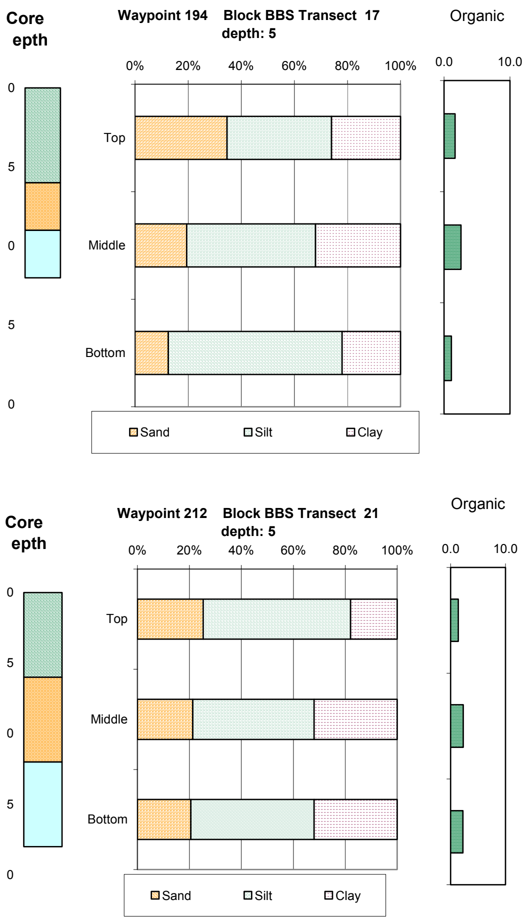

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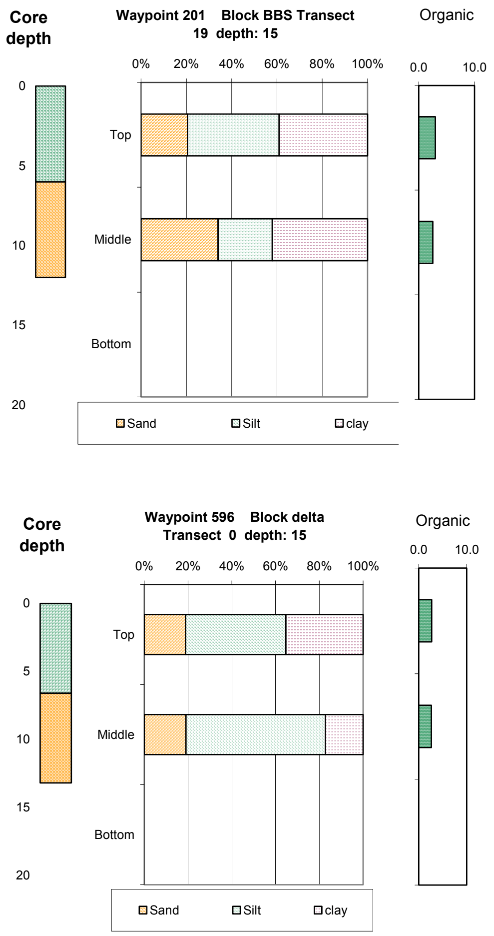

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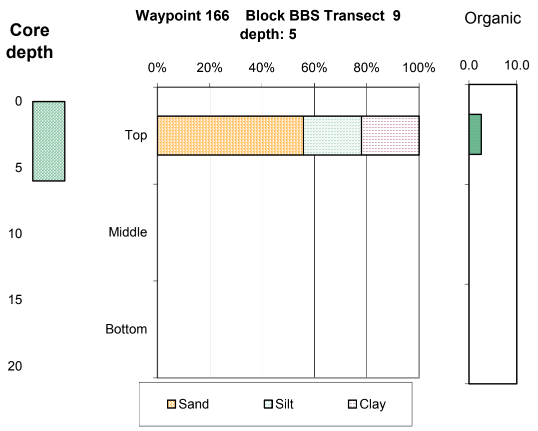

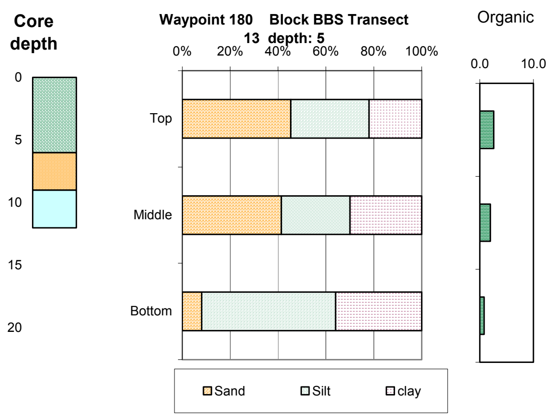

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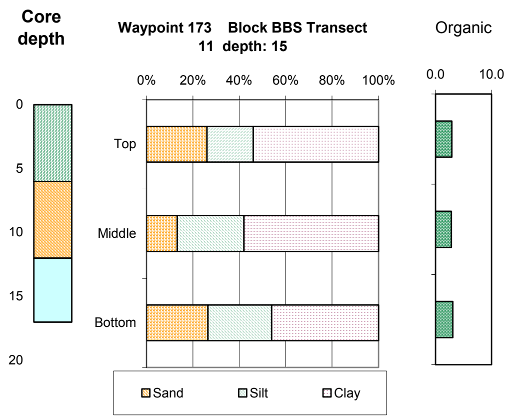

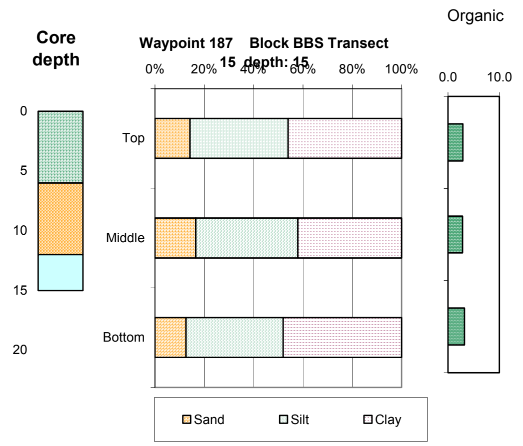

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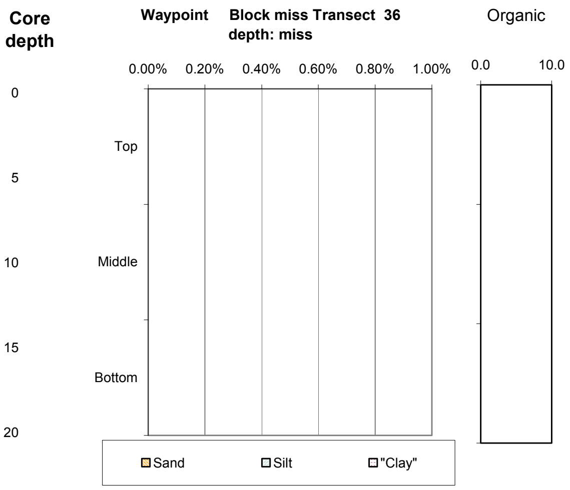
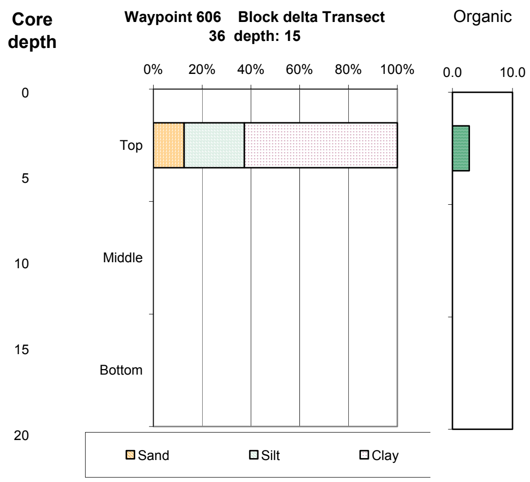
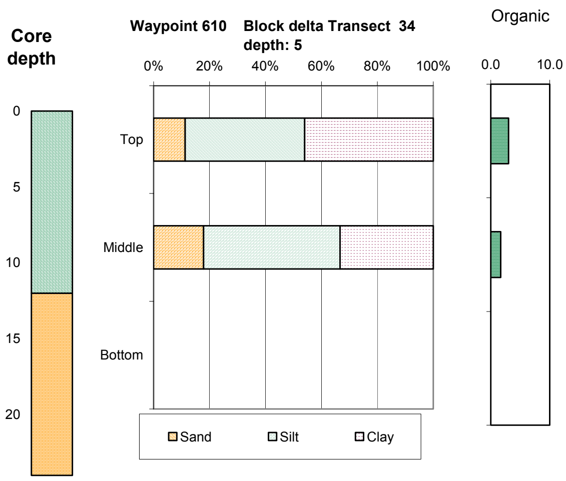
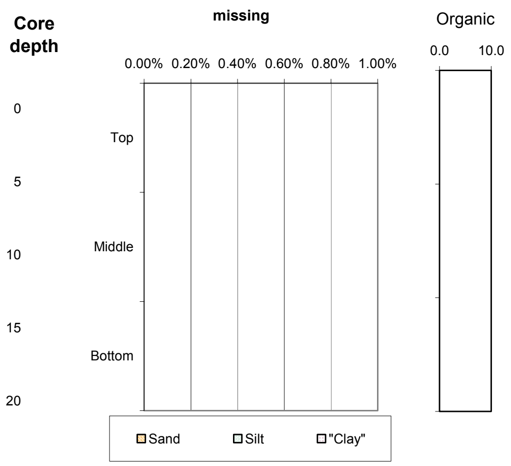


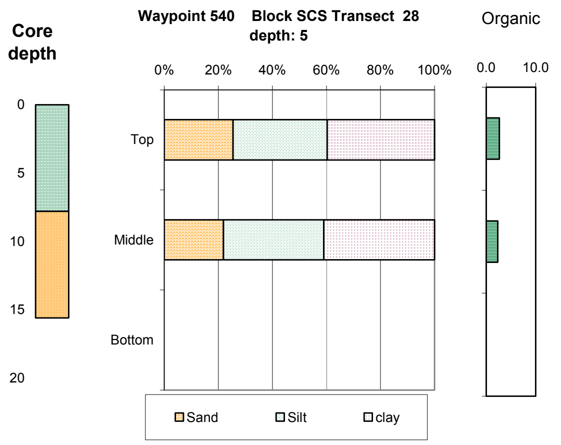


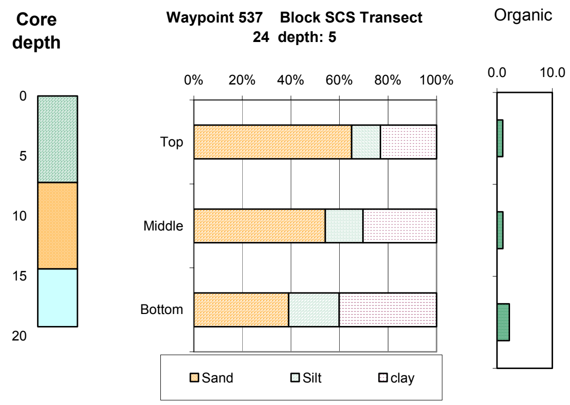




Five foot cores

Fifteen foot cores





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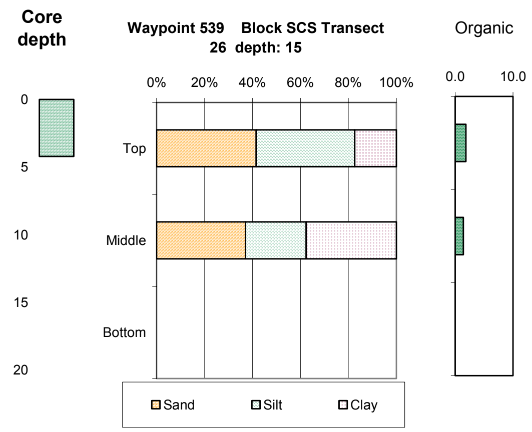

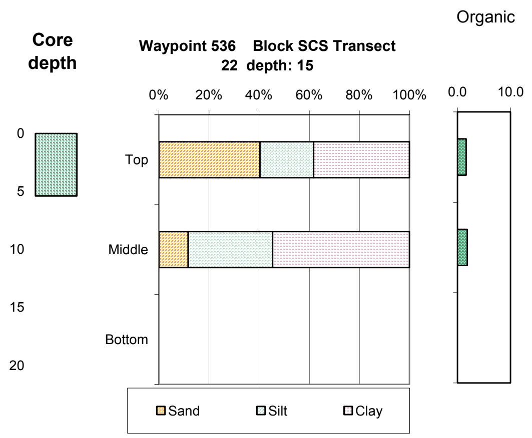

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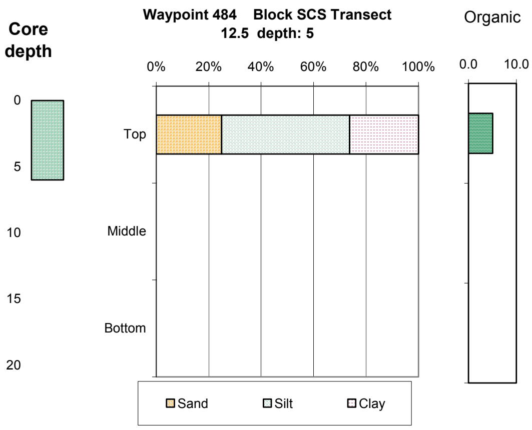

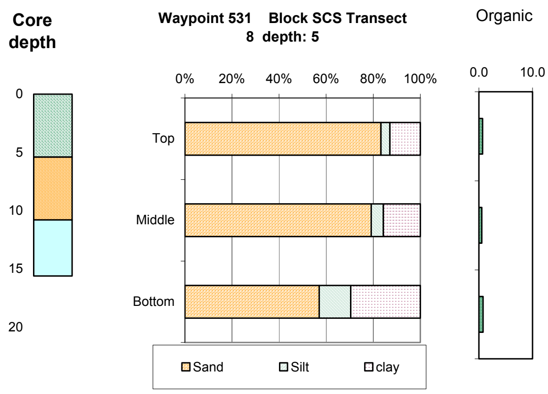

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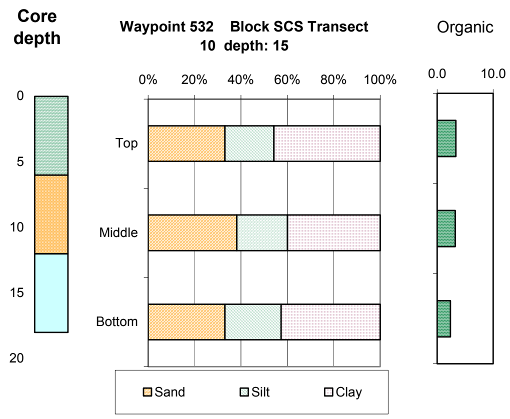

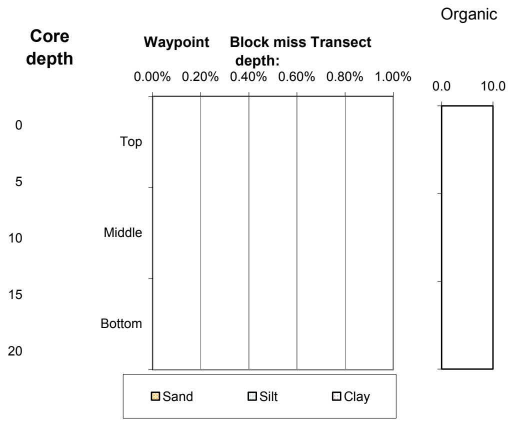

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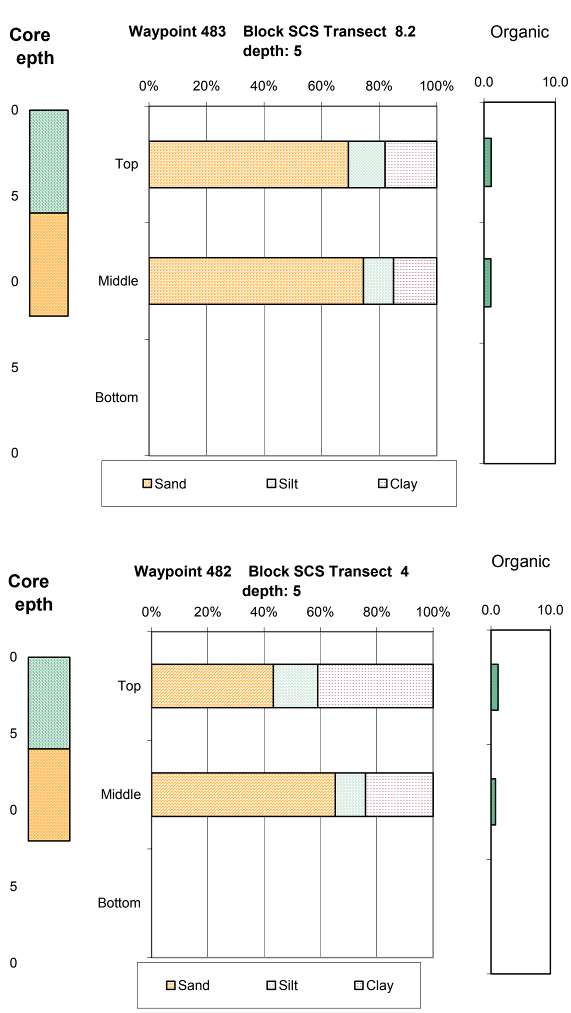

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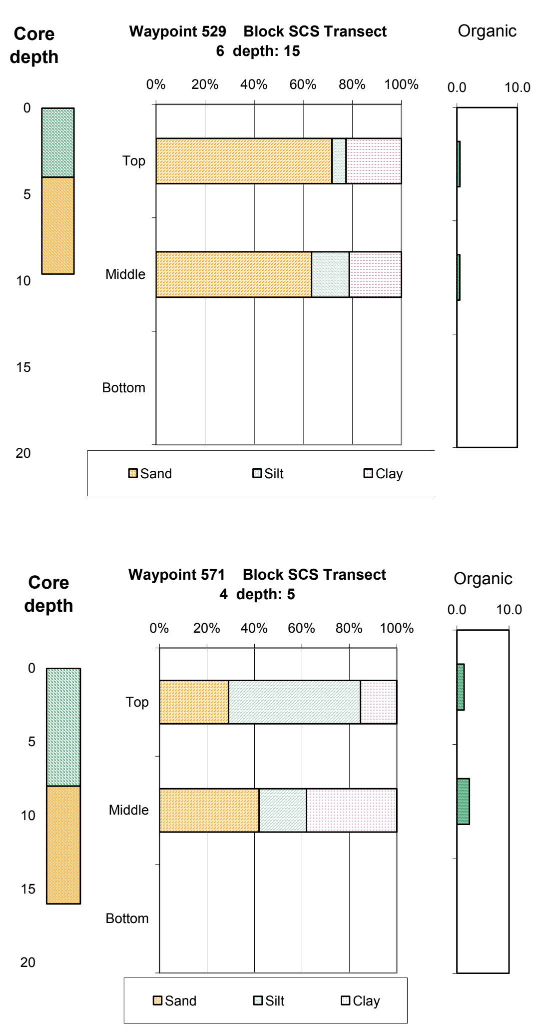
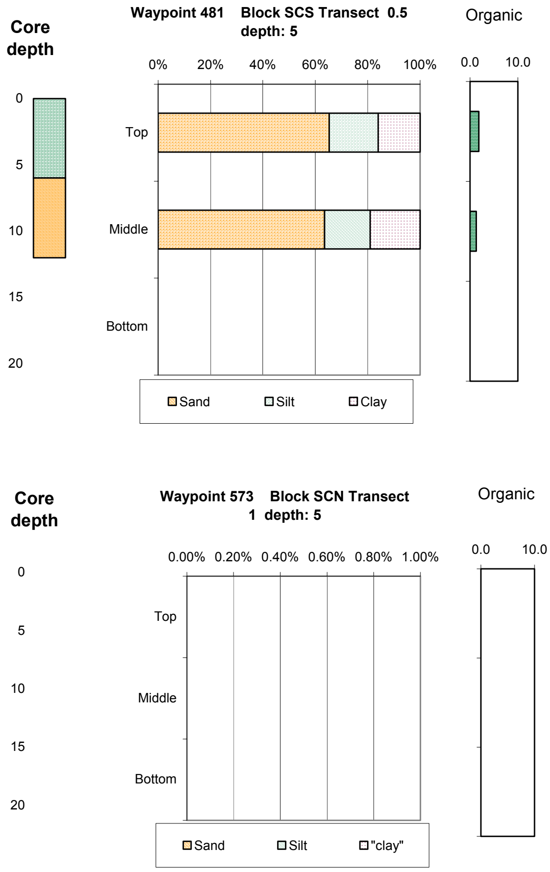
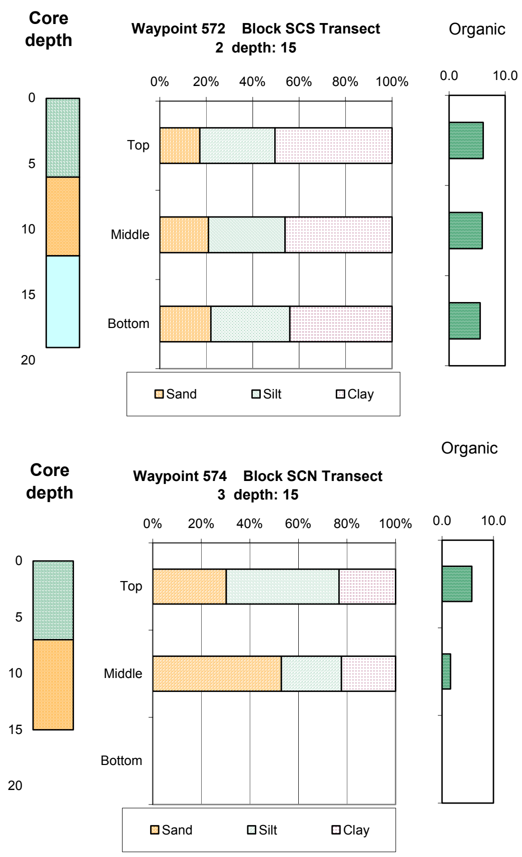


Fifteen foot cores



Five Foot Cores



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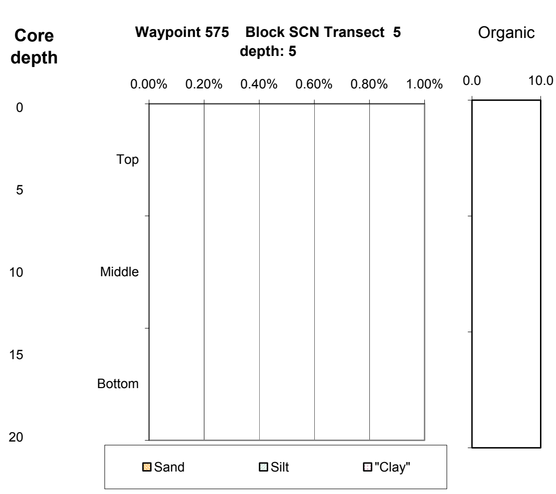
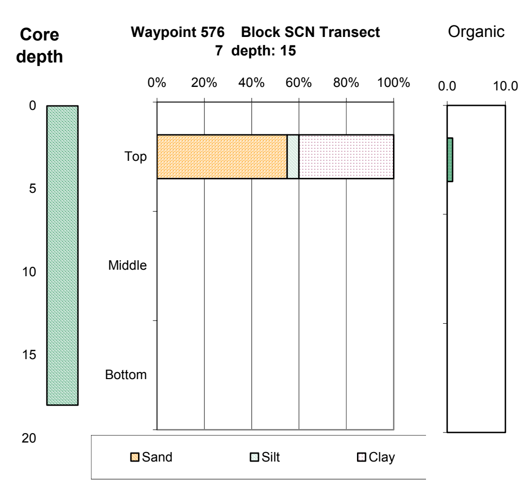
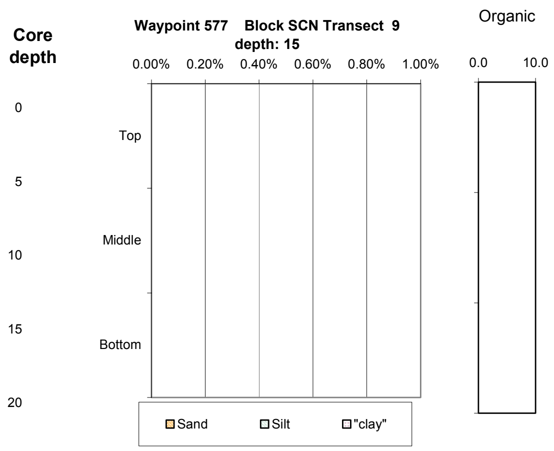
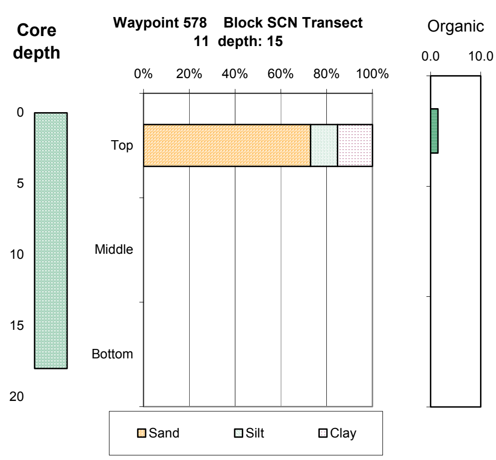


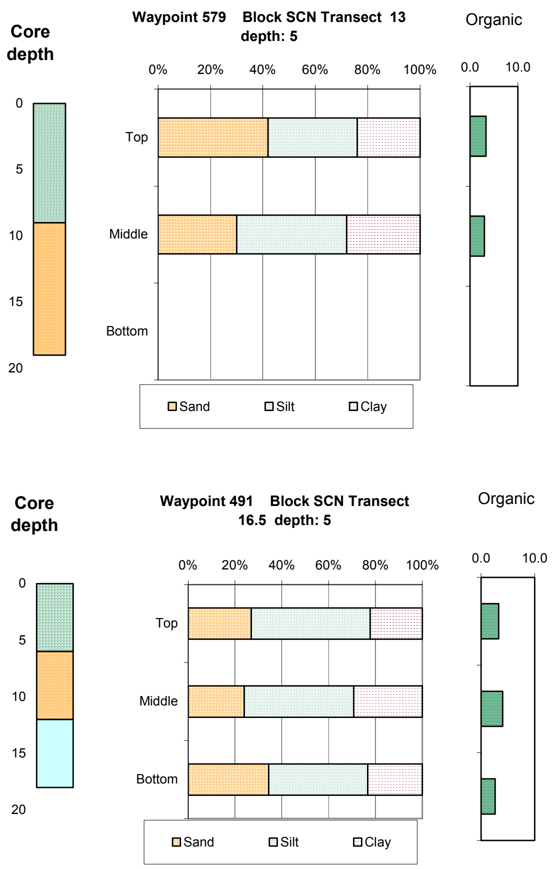




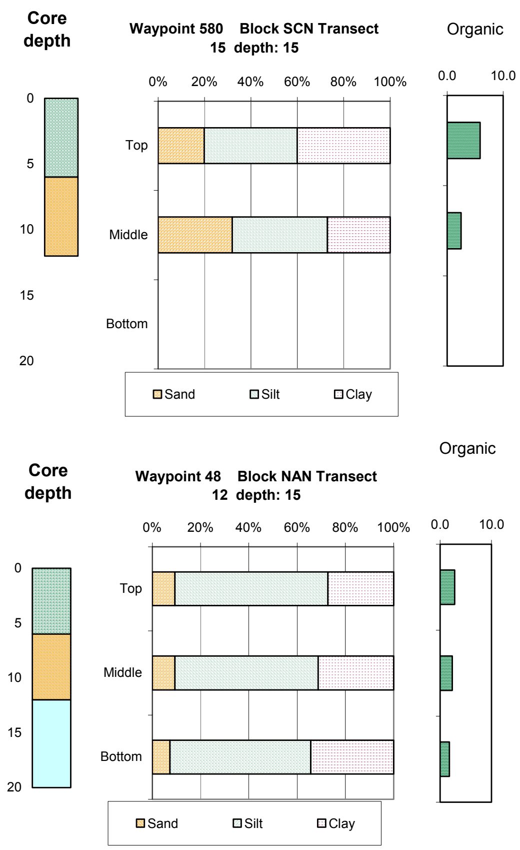


Five foot cores

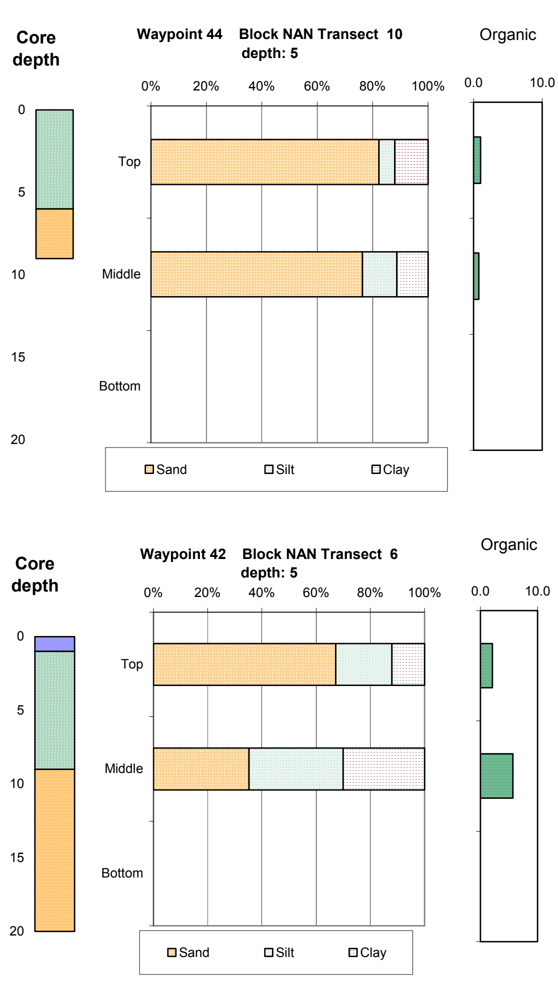
Fifteen foot cores



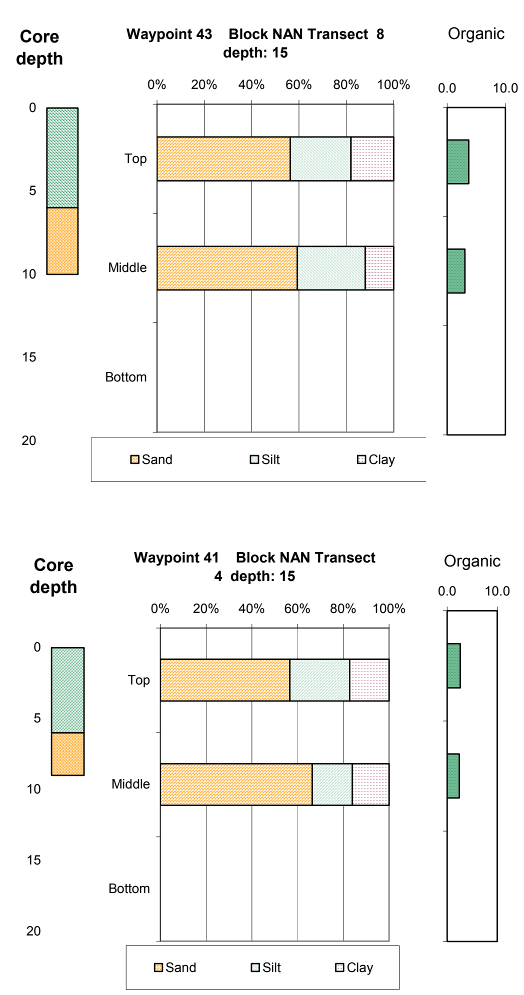
Five Foot Cores



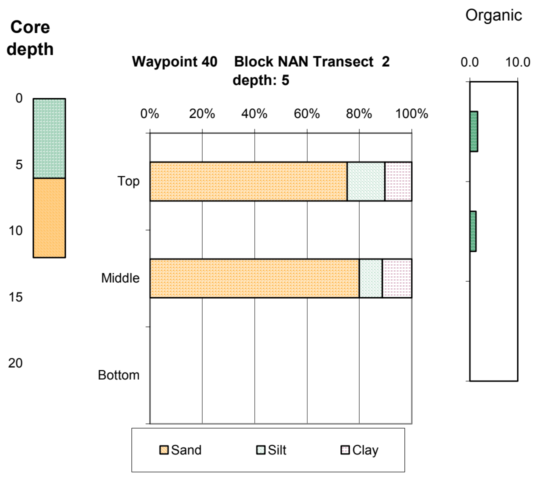
Fifteen foot cores

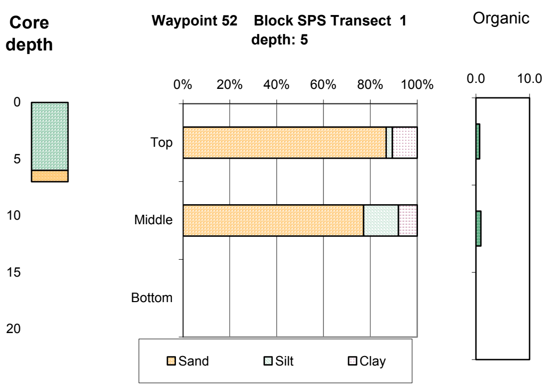


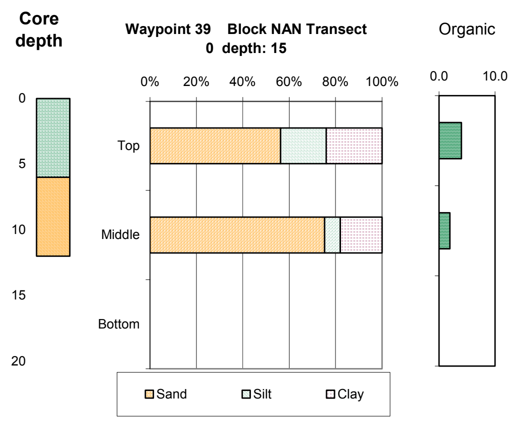
Five foot cores

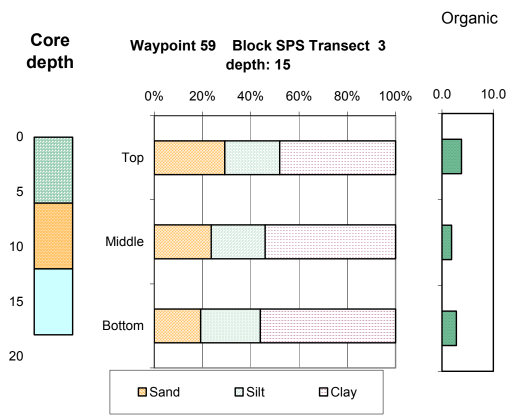


Fifteen foot cores









Five Foot Cores

Fifteen foot cores

APPENDIX 2

INTERPOLATION MAPS:

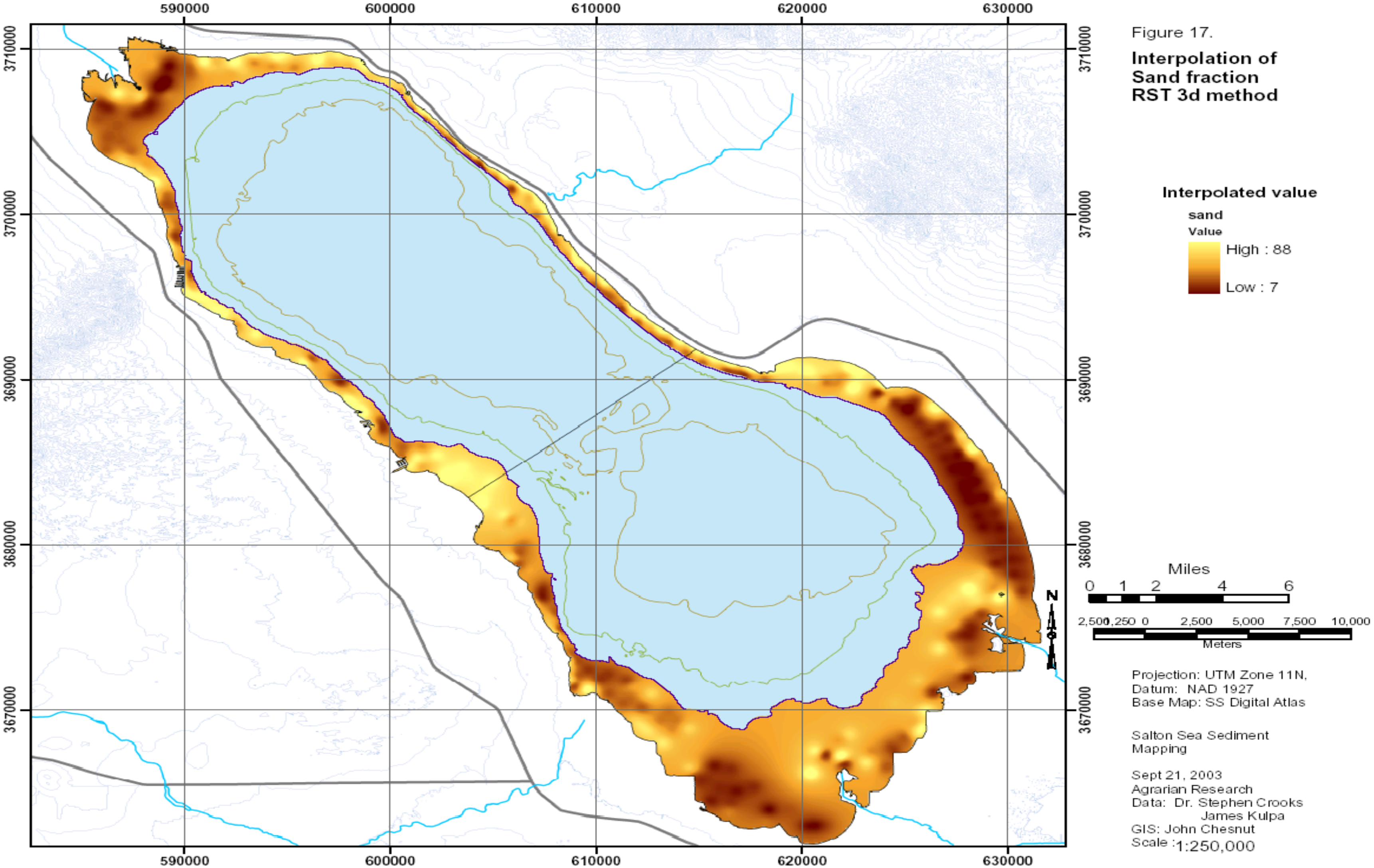
SAND: RST 3D METHOD

SILT: RST 3D METHOD

CLAY: RST 3D METHOD

ORGANIC: IDW METHOD

CLAY:SILT RATIO: RST 3D METHOD


590000
600000
610000
620000
630000
3710000
3700000
3690000
3680000
3670000
Figure 17.
Interpolation of
Sand fraction
RST 3d method
Interpolated value
sand
Value
High : 88
Low : 7
Miles
0 1 2 4 6
2,500 1,250 0 2,500 5,000 7,500 10,000
Meters
N
Projection: UTM Zone 11N,
Datum: NAD 1927
Base Map: SS Digital Atlas
Salton Sea Sediment
Mapping
Sept 21, 2003
Agrarian Research
Data: Dr. Stephen Crooks
James Kulpa
GIS: John Chesnut
Scale : 1:250,000

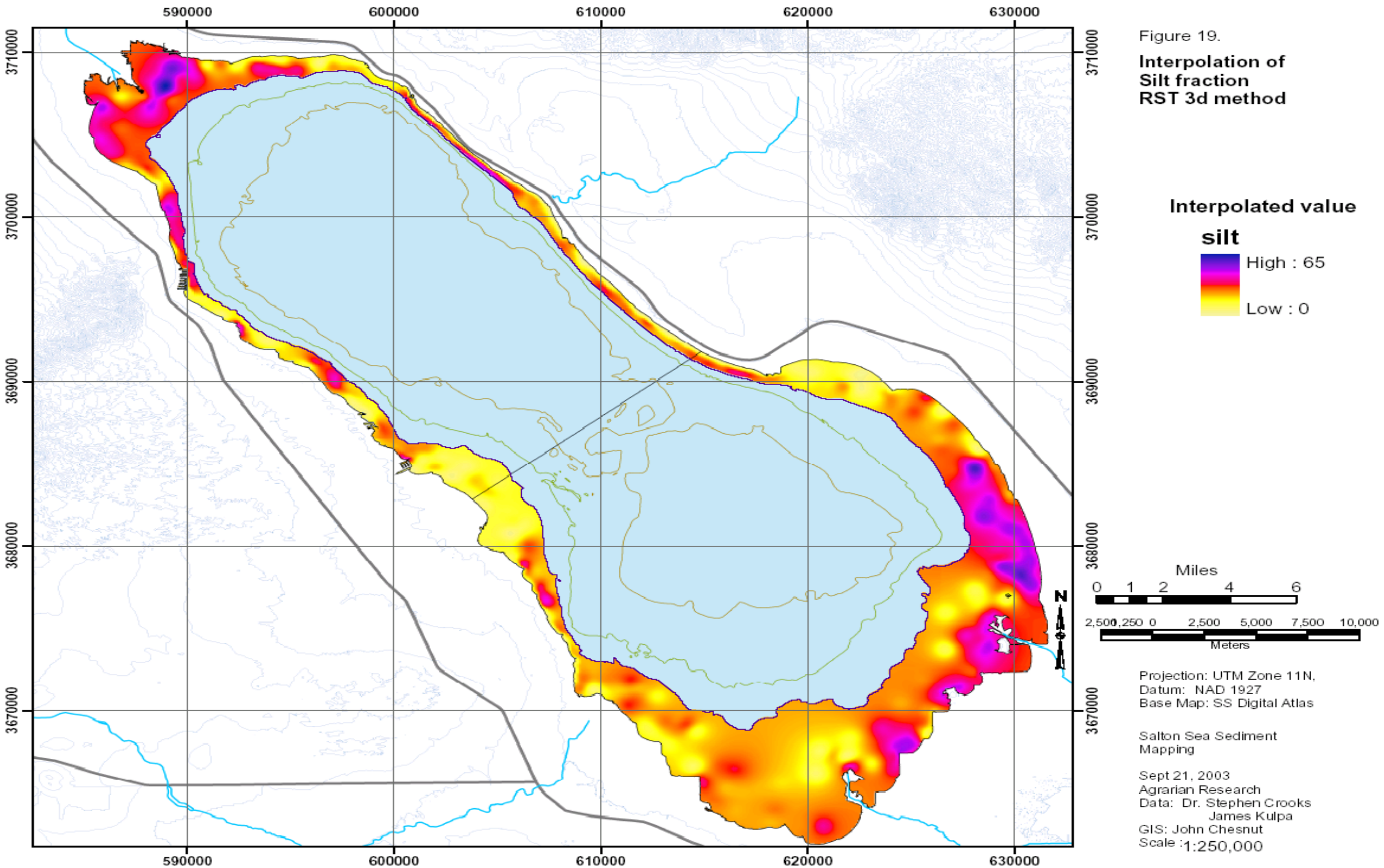
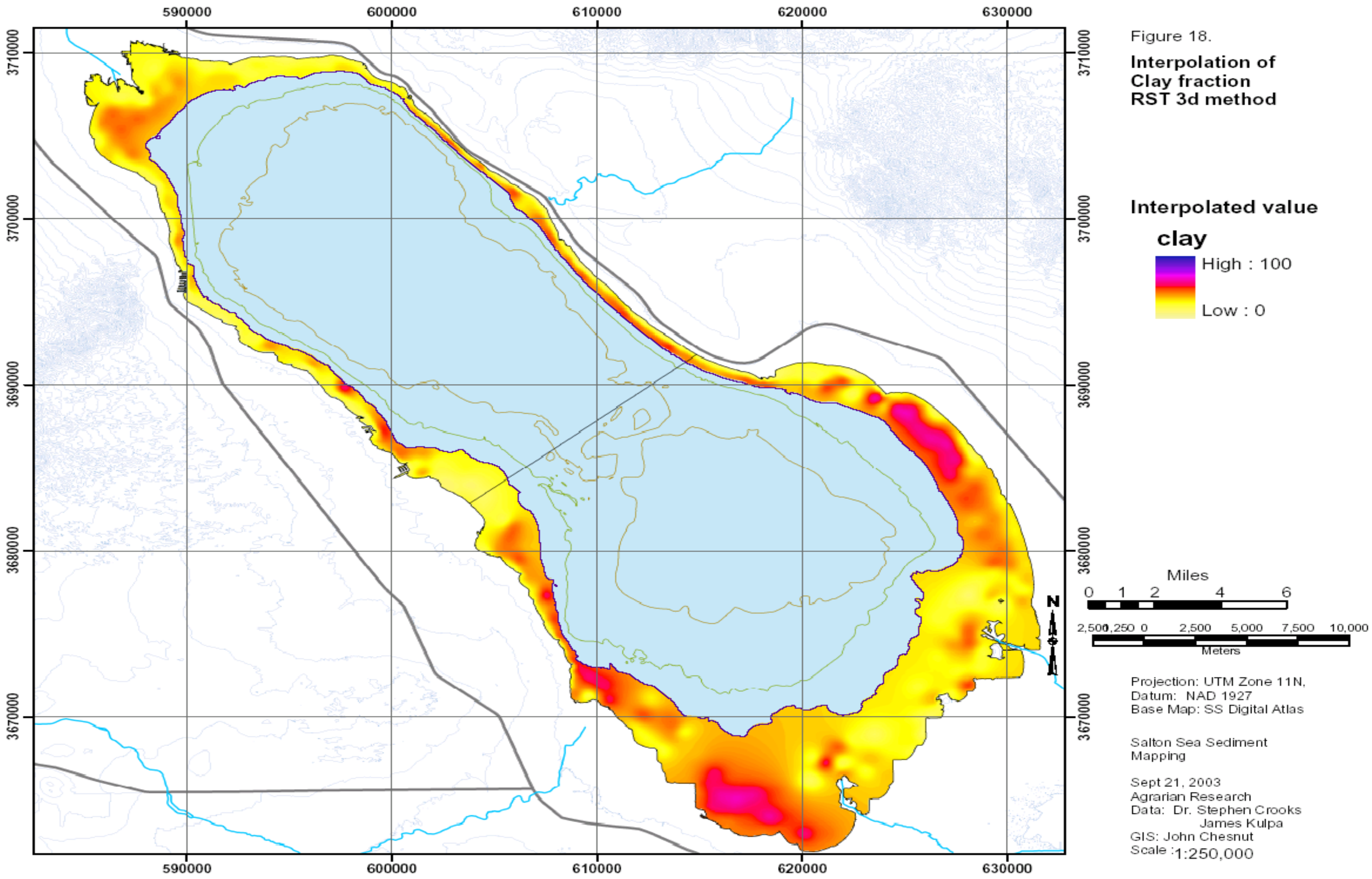

590000
600000
610000
620000
630000
3710000
3700000
3690000
3680000
3670000
Figure 19.
Interpolation of
Silt fraction
RST 3d method
Interpolated value
silt
High : 65
Low : 0
Miles
0 1 2 4 6
Meters
N
Projection: UTM Zone 11N,
Datum: NAD 1927
Base Map: SS Digital Atlas
Salton Sea Sediment
Mapping
Sept 21, 2003
Agrarian Research
Data: Dr. Stephen Crooks
James Kulpa
GIS: John Chesnut
Scale : 1:250,000

Figure 18.

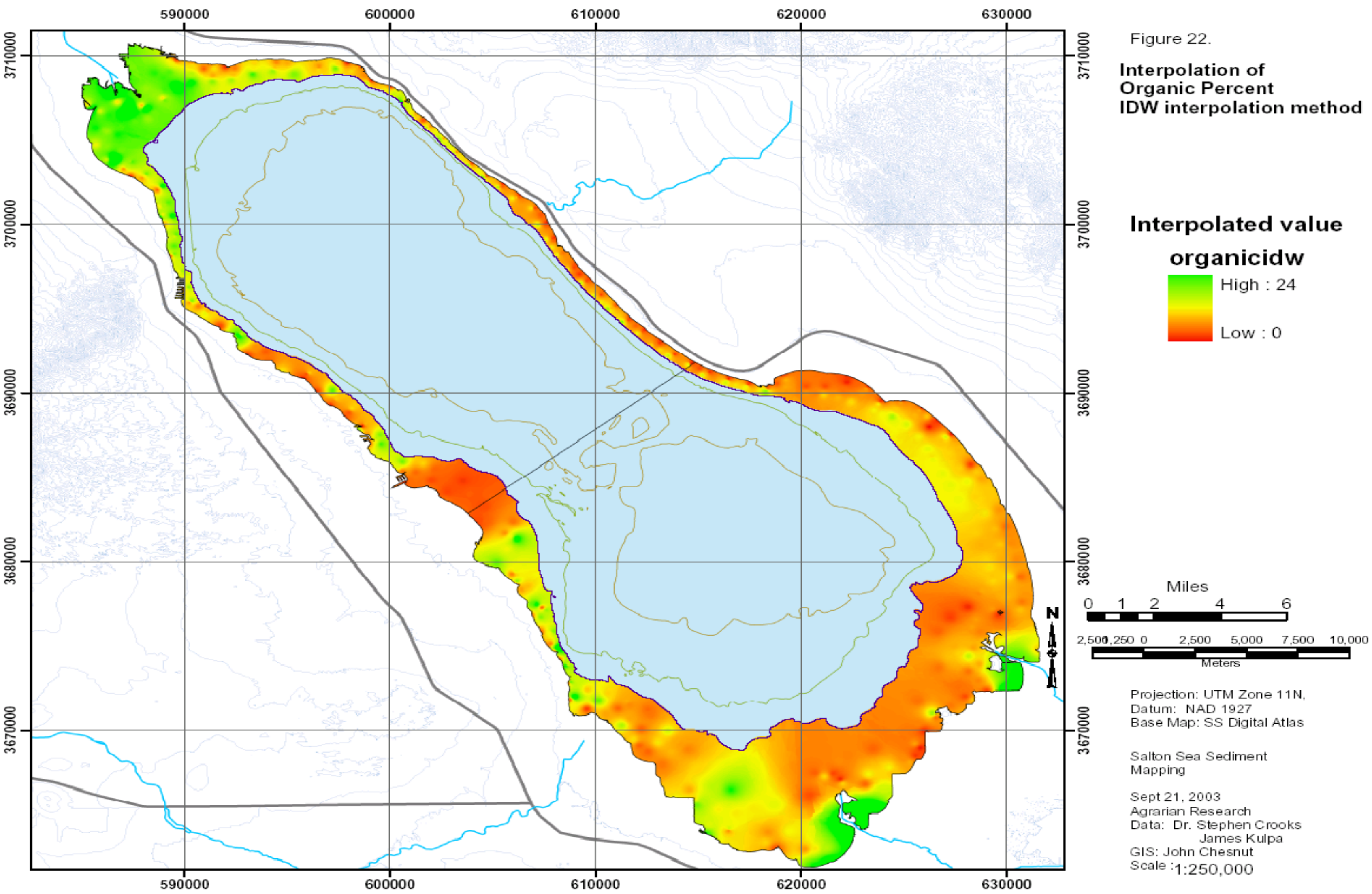
Interpolation of Clay fraction RST 3d method

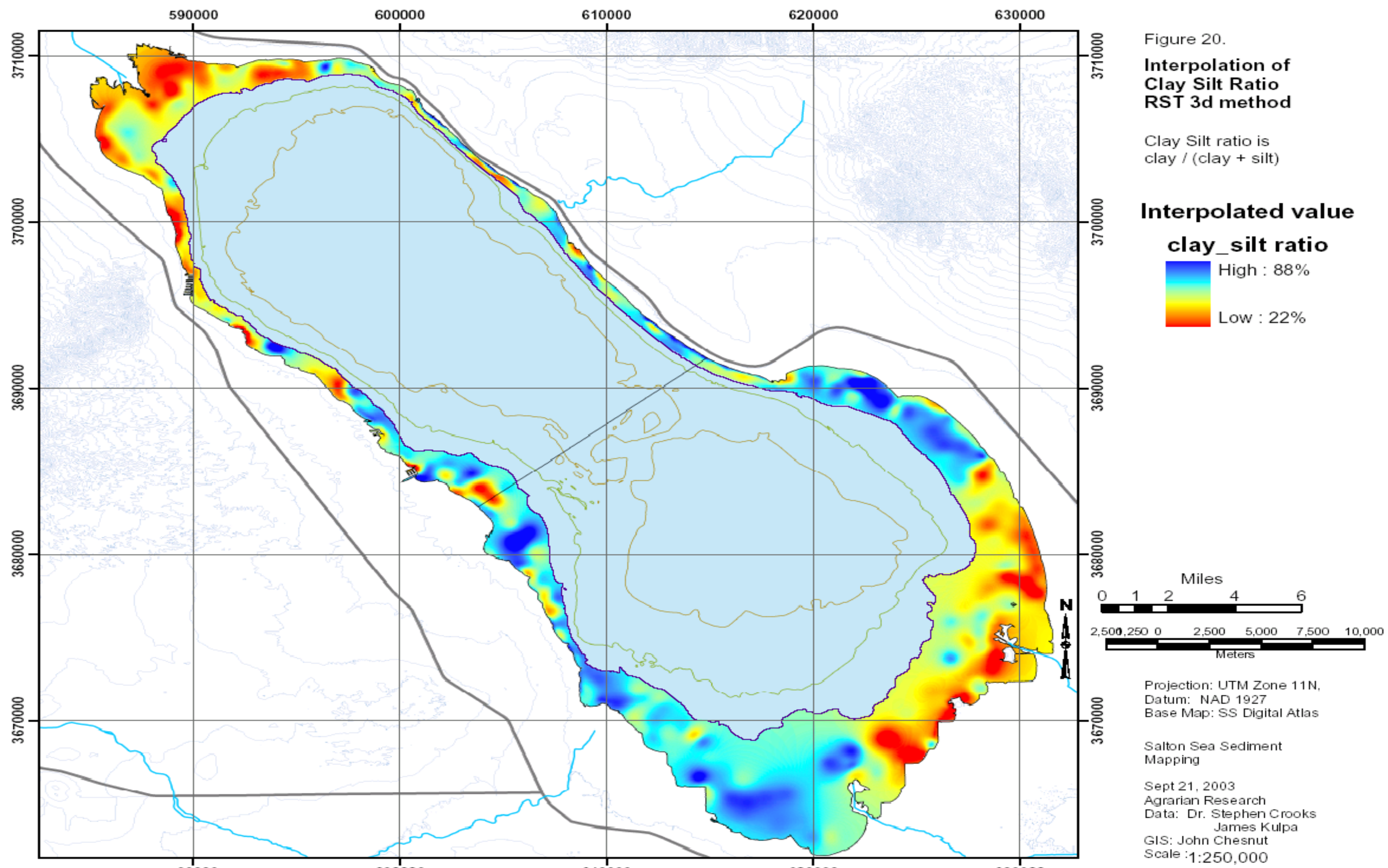


Projection: UTM Zone 11N,
Datum: NAD 1927
Base Map: SS Digital Atlas

Salton Sea Sediment Mapping

Sept 21, 2003
Agrarian Research
Data: Dr. Stephen Crooks
James Kulpa
GIS: John Chesnut
Scale :1:250,000


590000
600000
610000
620000
630000
3710000
3700000
3690000
3680000
3670000
Figure 22.
Interpolation of
Organic Percent
IDW interpolation method
Interpolated value
organicidw
High : 24
Low : 0
Miles
0 1 2 4 6
2,500 1,250 0 2,500 5,000 7,500 10,000
Meters
N
Projection: UTM Zone 11N,
Datum: NAD 1927
Base Map: SS Digital Atlas
Salton Sea Sediment
Mapping
Sept 21, 2003
Agrarian Research
Data: Dr. Stephen Crooks
James Kulpa
GIS: John Chesnut
Scale : 1:250,000



590000
600000
610000
620000
630000
3710000
3700000
3690000
3680000
3670000
Figure 20.
Interpolation of
Clay Silt Ratio
RST 3d method
Clay Silt ratio is
clay / (clay + silt)
Interpolated value
clay_silt ratio
High : 88%
Low : 22%
Miles
0 1 2 4 6
2,500 1,250 0 2,500 5,000 7,500 10,000
Meters
N
Projection: UTM Zone 11N,
Datum: NAD 1927
Base Map: SS Digital Atlas
Salton Sea Sediment
Mapping
Sept 21, 2003
Agrarian Research
Data: Dr. Stephen Crooks
James Kulpa
GIS: John Chesnut
Scale : 1:250,000