DRAFT

LETTER REPORT TO: Ms. Lynn Suer, Environmental Protection Agency, Region IX

FROM: Timothy Welp, U.S. Army Engineer Research and Development Center

SUBJECT: Lauritzen Channel Sediment Density Survey

DATE: 3 October 2005

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1. Background

The U.S. Army Corps of Engineers (USACE) District San Francisco (SPN), USACE District Seattle (NWS), and U.S. Army Engineer Research and Development Center (CEERD) assisted the Environmental Protection Agency (EPA) in conducting a study at the United Heckathorn superfund site located in the Lauritzen Channel in the inner Richmond Harbor in Richmond, California (Figure 1). Concerns related to elevated post-remediation DDT contamination levels at this superfund site had prompted speculation that fluid mud, if it existed, could provide answers to the question of contaminant causation.

The purpose of this study was to determine if fluid mud existed on the channel bottom at the time of the study, and map its spatial boundaries and density structure, in conjunction with the spatial distribution of contaminants in this sediment and overlying water. The term “fluid mud” is one of many descriptors (nepheloid layer, high turbidity suspension, fluff, colloid, flocculation layer, etc.) used to describe a high (solids) concentration suspension that can exist on the bottom of waterways with favorable mineralogical and hydrodynamic conditions. This letter report describes activities conducted to survey the channel and determine if fluid mud did indeed exist on the bottom of the Lauritzen Channel during the study duration, and map its spatial extent and density structure. The spatial distribution of contaminants in the sediment and overlying water is addressed in a data report by Mr. John Wakeman of NWS (Wakeman 2004).

As per SPN 2003, “the Lauritzen Canal is approximately 1,800 feet long (north-south) and varies in width between 120 feet near its northern end, to 350 feet near its southern end at the connection to the Santa Fe Channel. Historical water line channel depths range from –10 feet to –40 feet MLLW. Portions of the Lauritzen Canal have been periodically dredged; the most recent maintenance dredging occurred in January 1985 and reached a depth of –41 MLLW. The Lauritzen Canal continues to be actively used as a deep-water channel for LRTC operations and activities associated with Manson Construction, a dredging contractor located along the west shoreline of the Lauritzen Canal. The canal shoreline features include riprap protection (including riprap materials derived from concrete construction debris), sandy gravel fill, pile-supported docks with and without metal plating to retain upland shoreline, and fill and free-standing wooden pilings associated with former docks that in are in various stages of decay. The tidal zone within the Lauritzen Canal ranges between about -2 to +7 MLLW (Battelle, 1994).

The surfaces adjacent to the canal are mostly paved with concrete. The shallow subsurface material is fill soil that was placed over the Bay Mud and used to surcharge the area during development. This fill layer varies in thickness from approximately 5 to 15 feet below ground surface. Within the Former United Heckathorn Site, soil removal actions have resulted in shallow backfill soil. The layer beneath the fill material is called Younger Bay Mud (YBM). The majority of YBM with in the Lauritzen Canal was either removed during original canal construction or has subsequently been removed during maintenance dredging and remedial dredging. The YBM is underlain by Old Bay Mud, which is relatively more consolidated, stiffer, and laterally continuous. A relatively small amount of the upper Old Bay Mud may have been removed in conjunction with remediation dredging activities in 1996 and 1997.

Exchange of water between the Lauritzen Canal and the Santa Fe Channel occurs relatively slowly because exchange is primarily driven by tidal action. Other factors that affect the circulation into and out of the canal include wind-induced circulation and intermittent flows resulting from stormwater runoff from adjacent land features and outfall structures. Stormwater from areas to the north and west enters the canal through a concrete culvert at the north end of the canal and as sheet flow from the areas around the canal. Stormwater within the former United Heckathorn site is captured on site and managed by LRTC (Levin Richmond Terminal Corporation). Stormwater from the Former United Heckathorn Site is not directed to either outfalls or to the Canal itself.

The tidal zone within the Lauritzen Canal ranges between about -2 to +7 MLLW (Battelle, 1994). Tides at the site are semi-diurnal, with a mean tidal fluctuation of about 4.3 feet. Generally, currents within the canal are mild. As a result, the Inner Harbor Channel, Santa Fe Channel, and Lauritzen Canal all experience net deposition of sediment and require maintenance dredging to remain navigable (CH2M HILL, 1987). In addition, the bank slopes, especially in the area of the Levin Piers, are relatively steep, and it is expected that deposition from bank erosion and sloughing of upper bank sediments occur. Interstitial porewater (bank storage) at the canal margin is considered the zone where surface water and groundwater mixing occurs. The hydraulics in this mixing zone are complicated and dependent on pore pressure, water density, and hydraulic conductivity. It is expected that a relatively small net discharge or seepage of groundwater diffuse to the harbor waters."

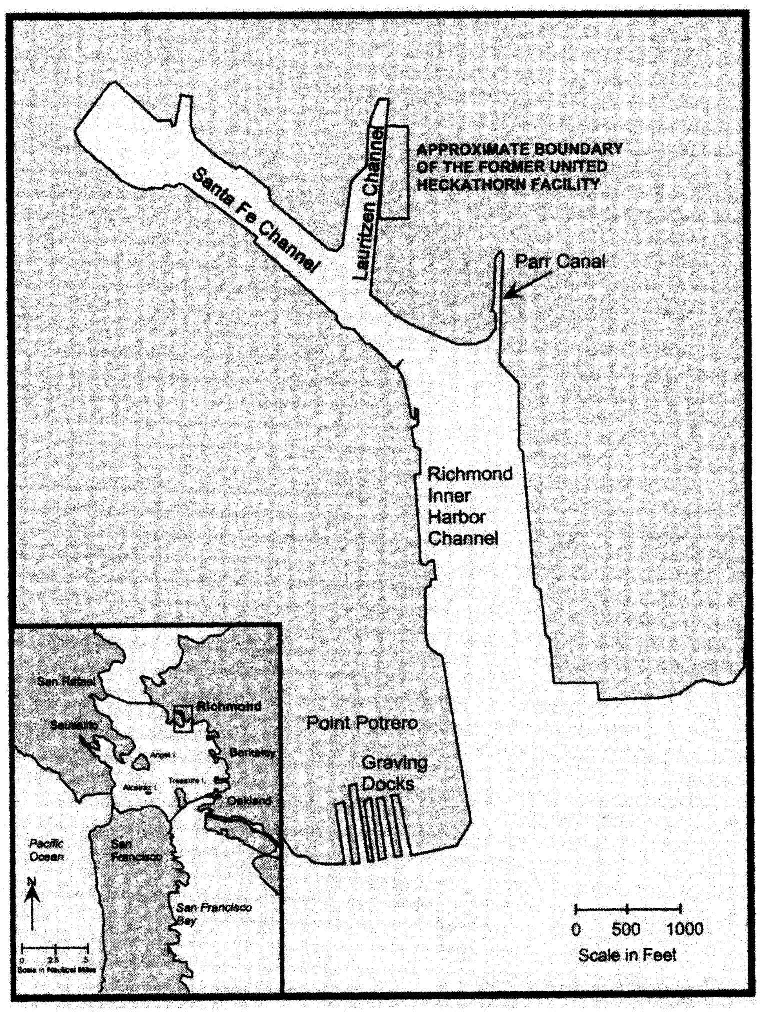

Figure 1 Location Map of the United Heckathorn Superfund Site, Richmond, California (after Kohn and Gilmore 2001)

1.1 Fluid Mud and Hydrographic Surveying Measurement Ambiguities

CEERD was involved with this study due to fluid mud surveying expertise gained from the Dredging Operations and Environmental Research (DOER) Program. A DOER work unit is currently conducting research on survey methods (acoustic, mechanical, nuclear, etc.) that can be used to characterize fluid mud as it relates to navigation issues. Fluid mud does not have a precise definition, but it is generally considered to be a cohesive fine-grained suspension with density gradations that can range from slightly greater than that of the overlying water in its upper layers, to that approaching stiffer, dense lower layers.

Although wet bulk density inversions occur in the fluid mud, the suspension's density usually increases with depth. Mehta (1994) reports that the most commonly considered upper and lower density limits for fluid mud are 1030 to 1300 g/l, although other values have been reported, primarily due to measurement under different hydrodynamic conditions and for different muds. Teeter (1997) reports that fluid mud densities can approximately range from 1050 to 1350 g/l, with concentrations ranging from 50 to 500 dry-g/l or 2 to13 percent solids by volume, and consist of silt and clay-sized material with clay minerals and organic material.

From the USACE navigation (dredging) perspective, fluid mud can be defined as a material consisting of a mixture of fine sand, and/or silt, and/or clay sediment typically found at the surface of the bottom in harbors and other areas of slow current that has a fluid consistency. "Consistency" defined as the relative ease that cohesive sediment can be deformed based on the unconfined compressive strength, and "fluid" denoting a compressive strength equal to (or approximately) zero. The navigation-related fluid mud definition will be used in the context of this report.

Kirby and Parker (1977) have studied temporal characteristics of cohesive sediment in an estuary and established a behavioral link between sediment suspended in the water column and dense cohesive sediment suspensions on the seabed (see Figure 2). Their work determined that the fine-grained material exists in three stages of an erosion-deposition cycle. High-energy events such as tidal currents or storms erode cohesive sediments and transport it into the navigation channel. Initially, this eroded material is well mixed throughout the water column in a homogenous mobile suspension. When the energy levels decrease, these mobile suspensions start to settle and form denser static suspensions (or fluid mud) that are observable on hydrographic echo sounding survey systems. If the fluid mud is exposed to another high-energy event it can be re-dispersed as a mobile suspension, but if conditions warrant continued consolidation, the fluid mud will form into settled mud. Depending on conditions, this settled mud can either remain in place, or be eroded by a subsequent high-energy event that re-initiates the cycle all over again.

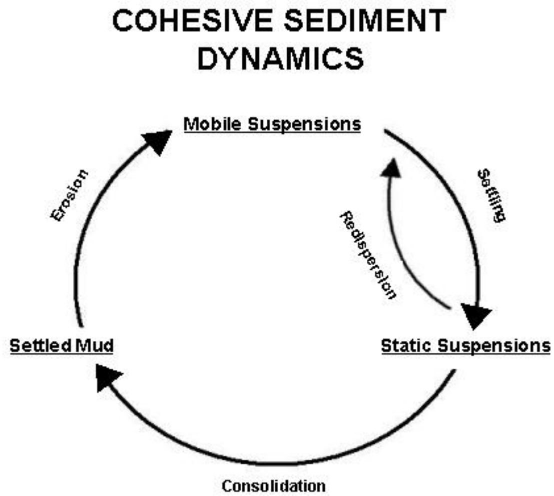

Figure 2. Relationships between mobile and static suspensions and settled mud (After Kirby and Parker 1977).

The DOER work unit is demonstrating and evaluating various fluid mud surveying methods for USACE use in reducing fluid mud measurement ambiguity. As per the U.S. Army Corps of Engineers Hydrographic Surveying Engineer Manual 1110-2-1003 (USACE, 2003), when the upper sediment layer is not well consolidated, the three major depth measurement methods used in the USACE (sounding pole, lead line, and acoustic echo sounding) will generally not correlate with one another, or perhaps not even give consistent readings from one time to the next when the same type of instrument or technique is used (see Figure 3). Depth measurement variations in unconsolidated bottom sediments (fluid mud) for sounding poles and lead lines are a function of sediment density and viscosity, probe weight, probe surface area, and probe velocity when it hits the sediment. Depth measurement variations for acoustic echo sounding in fluid mud include surface reflectivity, density, signal/noise levels, receiver sensitivity, and transducer frequency (USACE 2003).

Hydrographic surveys are usually conducted with either a high or low frequency transducer (such as 24 kHz and 200 kHz), or a combination of both frequencies (a duo-frequency system). The depth in fluid mud that an acoustic pulse reflects from is a function of the “sharpness” of fluid mud’s density gradient (or rate of change in density), not a specific density value itself (USACE 1954). Attenuation of acoustic energy is directly proportional to its frequency. The net result is that the high frequency energy will normally reflect from the upper layer of the reflective material, even a very low density one, and the lower frequency depth sounders will register a lower layer if that layer has a higher acoustic reflectivity than the upper one. In other words, the low frequency depth sounder will always penetrate to a lower depth than the higher frequency at the same transmitting power level and receiver sensitivity as shown in Figure 3 (USACE 2003).

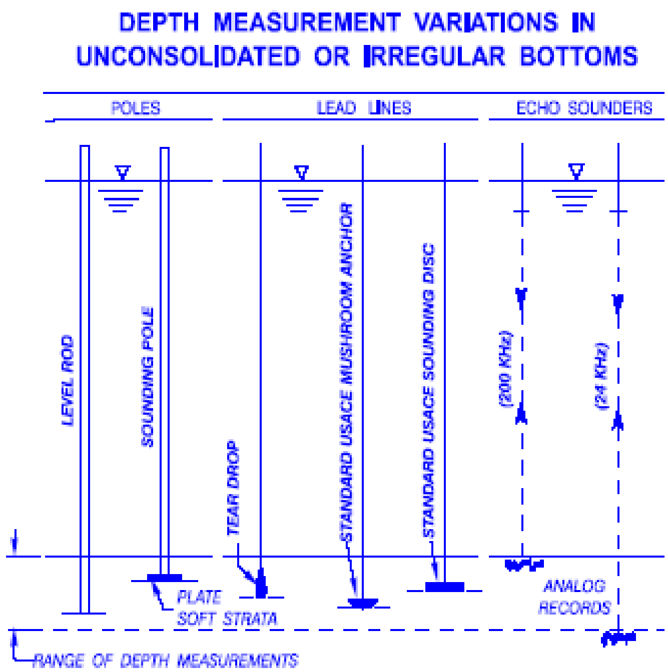

Figure 3. Depth measurement variations in fluid mud (after USACE 2003)

2. Description of Study

2.1 Study Purpose and Participants

The purpose of this survey was to determine if fluid mud existed on the channel bottom and map its spatial boundaries and density structure. CEERD, in coordination with EPA, SPN, and NWS, planned the fluid mud surveying activities and contracted Odom Hydrographics Systems Inc. (Odom) to provide the fluid mud survey system (Densitune and Silas described below), and personnel to operate it. Odom also sub-contracted for a STEMA representative to be onsite to optimize quality data recovery potential. SPN provided project management, the survey vessel, conventional hydrographic survey equipment, and crew to conduct a conventional dual frequency hydrographic survey of the Lauritzen Channel. SPN, NWS, CEERD, EPA, Odom, and STEMA personnel participated in field work activities that included mobilization, making data collection decisions, calibrating and operating survey equipment, deploying the density probe, collecting sediment samples, and demobilization.

2.2 Densitune and SILAS Surveying Equipment:

One of the fluid mud survey technologies being investigated by the DOER work unit is called the Densitune and SILAS system. The SILAS software suite samples the unaltered return signal from a low frequency hydrographic survey depth sounder and, with calibration input from an acoustical probe with a known signature, finds the variances present along the signal path and purportedly converts those changes into density information. The acoustical probe, called the Densitune silt density probe (shown in Figure 4), operates on the “turning fork” principle. One of the tuning fork legs vibrates at a specific frequency, and the other leg responds by vibrating at a frequency that depends on the density of the medium in which its inserted. The Densitune can be used to measure density of fluid mud in dredge and disposal areas and determine navigable depth in navigation channels. This probe requires calibration in a representative sediment and water sample from the survey area. In operation, it is lowered from the survey vessel and measures the density profile of overlying “clear” water and fluid mud as a function of depth (as measured by a pressure transducer).

A software package (SILAS) is provided with the Densitune that consists of four modules; calibration, data acquisition, data processing, and data export. The SILAS software was developed for the acquisition and processing of acoustic sub bottom reflection signals operating in the low frequency range of 3.5 kHz to 33 kHz to map sediment distribution and sediment characteristics. This software samples the unaltered return signal from a low frequency hydrographic survey depth sounder and, with Densitune calibration input, finds variances present along the signal path and (purportedly) converts those changes into density. The manufacturer claims that the SILAS software can be used with Densitune measurement data to compute sediment density contours.

Figure 4. Densitune density probe

This system, developed by STEMA Survey Services of The Netherlands, was first demonstrated in Gulfport Channel, Mississippi with partial funding from the DOER program. Odom Hydrographic Services, the American representative for the system, fielded the system in the Gulfport navigation channel on 13 August 2002. Densitune-measured densities in the channel compared well with the values of fluid mud samples collected from Gulfport and analyzed at CEERD (Welp, McNair, and Buchanan 2003), that Odom was invited to bring the Densitune to CEERD for further evaluation. At CEERD, fluid mud samples were prepared and respective densities measured in the laboratory. The Densitune was calibrated, and then immersed into these samples. From 27 measurements, the average relative difference between the laboratory and Densitune measurements was 1.6 percent. The Port of Rotterdam, Netherlands, has measured their channel's fluid mud density with nuclear density gages since the late 1970s (with fluid mud layer thicknesses of up to 9 ft deep). Nuclear gages are considered one of the most accurate methods to measure in situ fluid mud. The port conducted comparisons between the nuclear source probes and the Densitune, and, in 2004, decided to replace the nuclear sources with the Densitune [1].

Prior to the Lauritzen Channel study, the USACE had not evaluated the accuracy of the density values determined acoustically by the SILAS system (extensive field tests are scheduled for 2005). An objective of CEERD contributing DOER program funding (that partially funded CEERD and contractor participation) in this study was to evaluate the SILAS's accuracy in measuring acoustically-determined density. This was to be accomplished by comparing acoustically-determined density values to density values measured from sediment samples collected from the same locations and depths in the channel. The Port of Bristol, United Kingdom, reports that they compared the SILAS acoustically-determined density values with nuclear source probe-referenced values, and found the correlation good enough to decide to purchase a complete STEMA system. Bristol Port is currently using both the Densitune and SILAS to determine navigable depths based on density [2].

2.3 Hydrographic Surveying

SPN provided the survey vessel Wildcat (Figure 5) from the Technical Support and Survey Section at the Sausalito Field Office. The Wildcat was equipped with motion sensors, Hypack Max Hydrographic software, Differential Global Positioning System (DGPS), and hull mounted transducers. The echo sounder was a Mark III Dual Frequency (200 kHz and 24 kHz). Odom combined this echo sounder with the SILAS system and also provided the Densitune and a sound velocimeter (Digibar Pro). The sound velocimeter measures the water column sound velocities as a function of depth to calibrate the acoustic survey systems.

[1] Personal communication, 6 October 2004, Peter DeWit, Port of Rotterdam, Rotterdam Netherlands.
[2] Personal communication, 8 October 2004, Captain Niels Westberg, Port of Bristol, Avonmouth Docks, United Kingdom.

Figure 5. SPN survey vessel Wildcat

2.4 Ball Valve Sampler

CEERD provided a sediment sampler specifically designed to collect fluid mud samples. This sampler, called the ball-valve sampler (BVS), was designed and built at CEERD. The BVS, shown in Figure 6, consists of four pneumatically activated ball valves with attached reservoirs (200 ml or and 1000 ml) to hold the collected sample. Successive ball valve/reservoirs assemblies are separated by a distance of 1 foot in order to sample fluid mud from different depths simultaneously. When sampling, The BVS is lowered with ball valves closed and sampler reservoirs filled with air. When it reaches station depth, the ball valves are opened and fluid mud, because of the density gradient, enters the reservoir and displaces the air. After bubbles (from the displaced reservoir air) are observed at the surface, the ball valves are closed, and the BVS is hauled back to the surface and unloaded.

Figure 6. Pneumatically activated ball valve sampler (BVS)

3. Field Data Collection and Results

3.1 July 12, 2004 Activities

Equipment was mobilized and set up on Wildcat at the Sausalito Field Office. Activities included integrating SILAS software with SPN's hydrographic survey system, checking out the Densitune probe, and assembling the BVS and compressed nitrogen air source.

3.2 July 13, 2004 Activities

3.2.1 Site Conditions

A field party set up a Hazen tide gage at the Richmond Terminal Canal Industrial Park and Wildcat proceeded from the SPN Sausalito Field Office and arrived at the site to commence a conventional duo frequency survey of the Lauritzen channel. All basic hydrographic survey actions, including positioning, elevation, and water sound velocity measurements/usage, were performed in accordance with USACE 2003. An average sound velocity of 4958 ft/s was measured during a sound velocity profile conducted at the Lauritzen Channel confluence (with the Santa Fe Channel) using the Digibar Pro sound velocimeter. The project vertical control datum reference level was the TEC/NOS tidal datum diagram – NAVD 88 for MLLW (positive numbers indicate feet below MLLW), and the horizontal reference used to conduct and plot survey was California State Plane NAD83 coordinate system. A gravel barge was alongside Levin Terminal Berth B, and a crane barge and scow were tied up off the Manson dock as shown in Figure 7. Another Manson scow was anchored further north in the channel (Figure 8).

Figure 7. Photograph of study site and moored vessels on 13 July 2004 (taken from approximate midpoint of Lauritzen Channel looking south).

Figure 8. Photograph of study site and moored Manson scow on 13 July 2004 (taken from approximate midpoint of Lauritzen Channel looking north).

3.2.2 Conventional Duo Frequency Hydrographic Surveying

Objectives of the conventional hydrographic survey were two-fold, to collect the raw (unedited) low frequency (24 kHz) echo soundings required by SILAS to calculate density contours, and secondly, to gain general information on spatial distribution of fluid mud (using both the 24 kHz and 200 kHz frequency data) to optimize placement of sediment sampling and Densitune profiling stations. As previously explained in the background section, high and low frequency echo soundings will usually reflect from different depths in a fluid mud layer. When recorded simultaneously, the separation distance between these two echo traces usually indicates the presence of fluid mud and can give approximate information on layer thickness. The initial survey lines were oriented longitudinal to the channel's major axis (longitudinal survey lines) in a north/south orientation, with offset deviations necessitated by the presence of the gravel barge and Manson vessels. Next, channel cross section survey lines were conducted to provide as extensive coverage of all accessible areas in the channel as possible (see Figure 9).

During transit of these survey lines, no significant separation between the 24 kHz and 200 kHz traces was observed that indicated the presence of fluid mud, but several locations were identified as what appeared to "soft" bottom (a subtle variation between high and low frequency separation distances). Figure 10 shows the acoustic reflections from the duo-frequency (24 kHz and 200 kHz) survey system as the survey boat ran up the Lauritzen Channel approximate centerline (off the Levin Terminal). The bottom reflections consist of a relatively uniform tone of shading that undulates with small troughs and crests. For comparative purposes, Figure 11 shows a duo-frequency (24 kHz and 200 kHz) in fluid mud where both acoustic reflection horizons are clearly delineated and it can be noticed that the high frequency horizon is relatively flat (an artifact from fluid mud's lack of uncompressed shear strength).

Figure 12 consists of another Lauritzen Channel survey line oriented perpendicular to the survey line in Figure 10 (or running from one side of Lauritzen Channel to the other). Again the bottom acoustic reflections consist of a relatively uniform tone of shading that undulate with significant relief (note shading of acoustic reflections from channel side slope's look the same as channel bottom reflections). Figure 13 presents acoustic reflections from a cross section survey line (duo-frequency 24 kHz and 210 kHz) taken in Gulfport Navigation Channel with a fluid mud bottom. This figure, similar to Figure 11, shows the double reflection horizons with the relative flat high frequency (210 kHz) trace, and a distinct difference (unlike Figure 12) can be observed in the tone of shading between the channel bottom and more consistent side slopes.

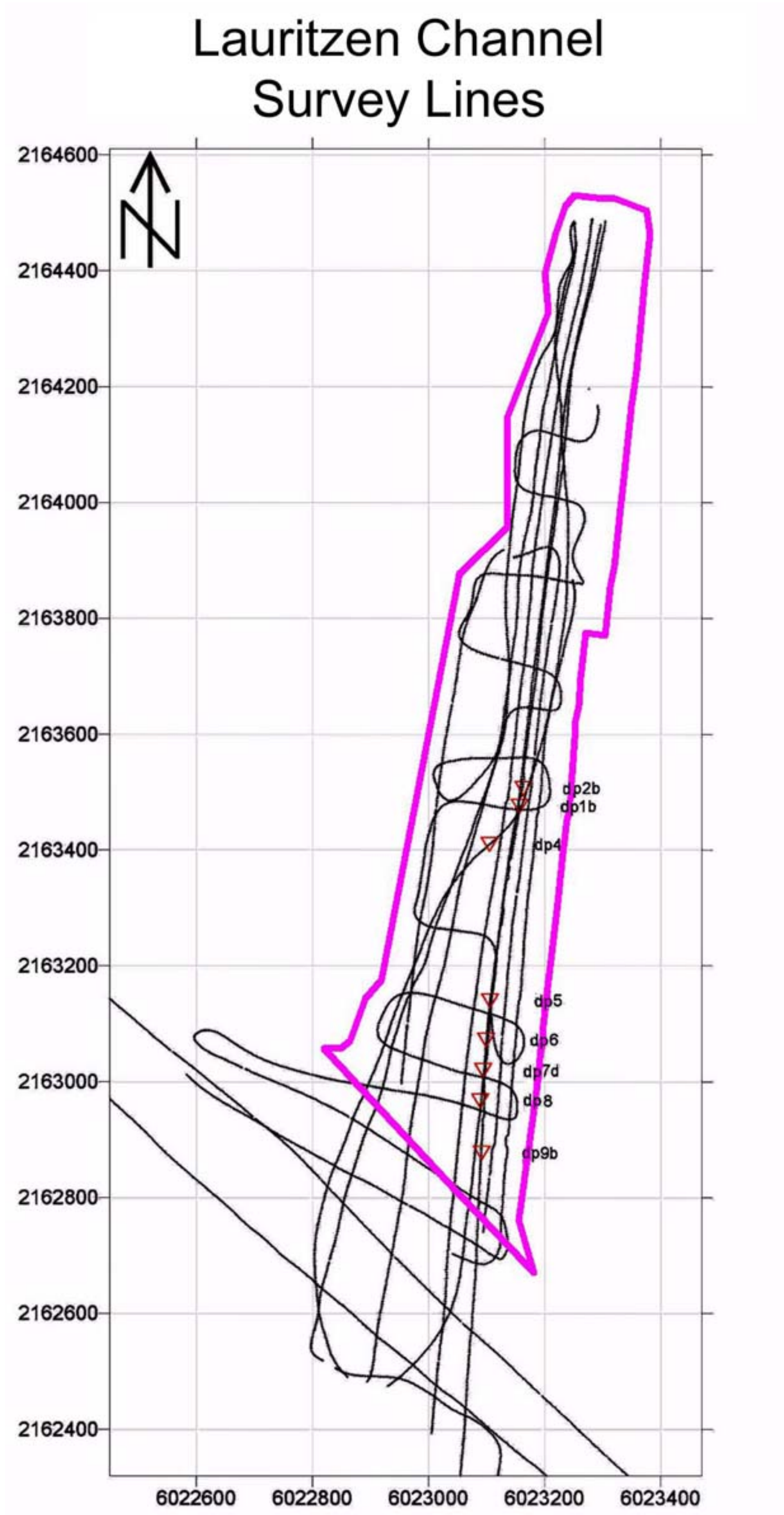

Figure 9. Study survey lines and Densitune profiling stations.

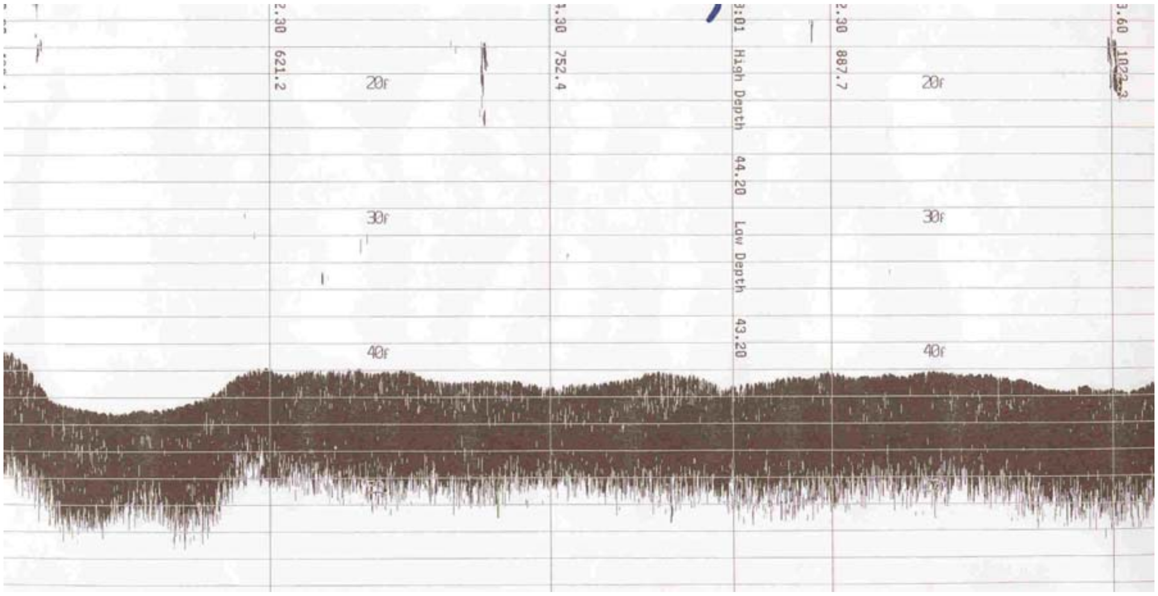

Figure 10. Survey line 227 in centerline of Lauritzen Channel off Levin Terminal with duo frequency (24 kHz and 200 kHz) survey system

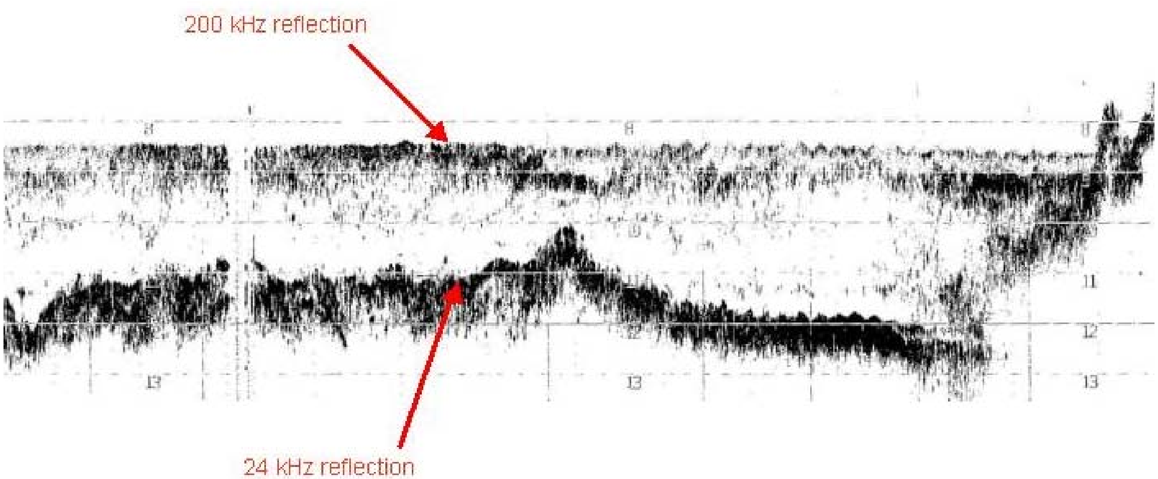

Figure 11. Acoustic reflections in fluid mud with duo frequency survey system (24 kHz and 200 kHz) (Courtesy of Odom Hydrographics Systems Inc).

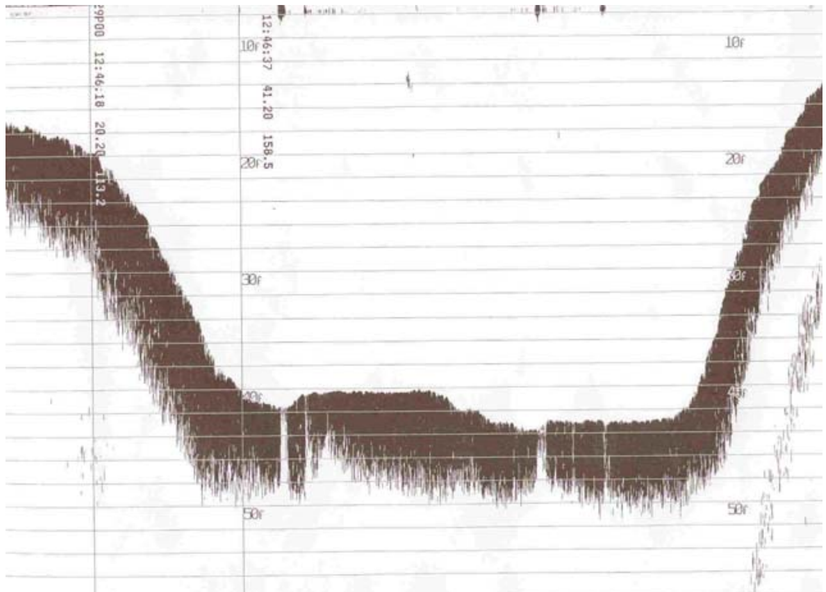

Figure 12. Lauritzen Channel cross section survey line (perpendicular to Figure 10 survey line) with duo frequency (24 kHz and 200 kHz) survey system

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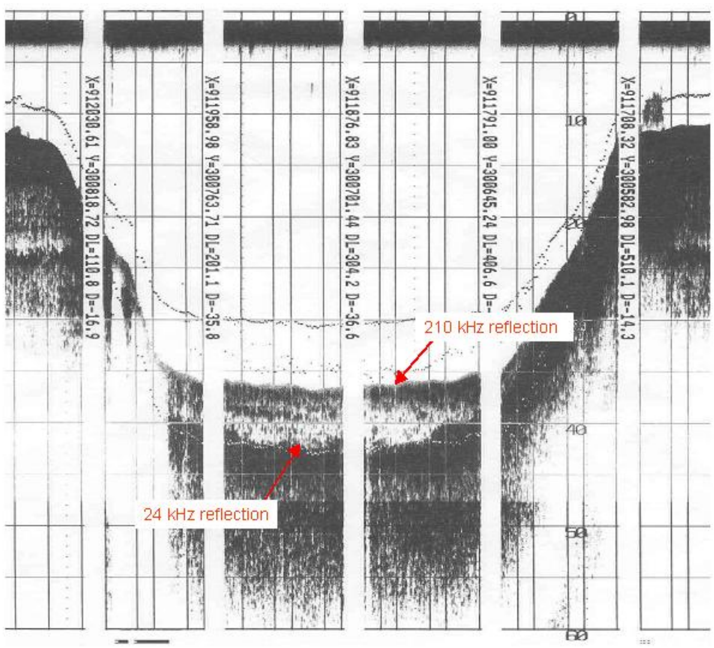

Figure 13. Gulfport Navigation Channel cross section survey line with duo frequency (24 kHz and 210 kHz) survey system

3.2.3 Densitune Profiling

The most promising areas with soft bottom material, as identified by the hydrographic (duo-frequency) echo sounding survey, were located in the vicinity off the gravel barge moored at Berth B (Figure 7), and around the moored Manson scow (Figure 8). Densitune profiles (as indicated by the stations in Figure 9) were conducted around the immediate vicinity of these two locations to collect density versus depth data. The

Densitune probe was deployed off the Wildcat and lowered by hand down though the water column and into the bottom sediment till it reached depth of refusal. At total of eight profiles were completed (several of these profiles were repeated to optimize data quality), when the probe's communications cable was damaged and its capacity to measure depth rendered inoperative. The contractor stated that while more profiles would have further improved sediment density characterization accuracy, these eight measurements were sufficient to calibrate the SILAS software/ 24 kHz echo soundings.

3.2.4 Sediment Sampling for Densitune Calibration

Next, surficial sediment samples were collected to calibrate the Densitune probe. A petit Ponar grab sampler was hand-deployed as close to the same locations that the Densitune profiles were taken. Approximately twenty casts were taken with six successfully retrieving sediment. The unsuccessful casts resulted from either premature closing of the grab sampler before it penetrated the sediment, or from the sampler not closing at all. Figure 14 is a photograph of the composite collection of several successful casts.

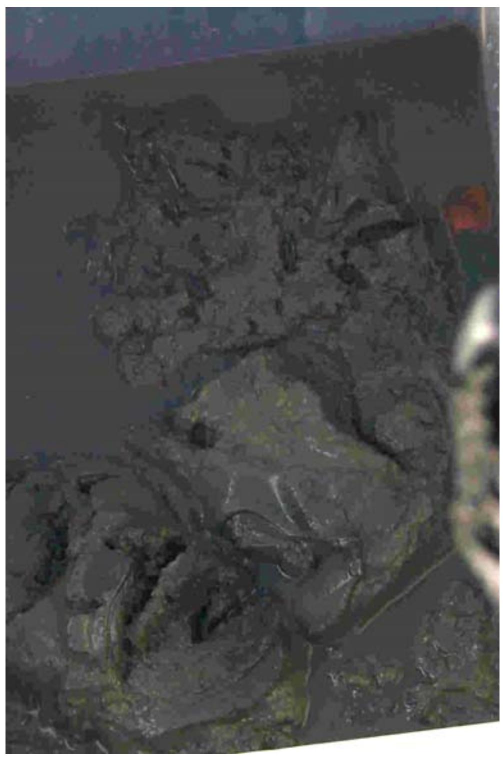

Figure 14. Lauritzen Channel sediment collected by petit Ponar grab sampler.

3.3 July 14, 2004.

3.3.1 Densitune Calibration

The Densitune probe was calibrated on site using sediment collected the day before. Stored in a 5 gallon bucket, the sediment had settled overnight forming a thin layer of supernatant overlaying the settled mud. When carefully moving this material from storage, the sediment demonstrated a propensity to readily resuspend back into the supernatant when entrained by minimal water movement.

The shear strength of this disturbed surface Young Bay Mud (YBM) was measured with a vane shear meter, after it had settled out for 13 hours. The shear meter instrument was a Geotest Instrument Company model E-286 Inspection Vane Set equipped with a model E-286.7, 50.8mm by 101.6mm vane. Raw readings were 0.95 at the top and 1.4 half way down to the bottom. Using the factors supplied by the manufacturer, these readings translate to shear strengths of 59.4 and 875 pounds per square foot respectively (2,845 and 42,000 Pascal). Shear strength values collected from field-testing can be applied to a standard load bearing formula to determine the ultimate in situ bearing capacity (pounds per square foot) of the material (q(ult)).

q(ult) = (2/3)*cu*Nc

cu = undrained sediment shear strength

Nc = bearing capacity factor for cohesion = 5.14 for purely cohesive sediment

Taking the lower value, q would be 203.5 pounds per square foot (9,750 Pascal); the upper would be 3,013 pounds per square foot (114,260 Pascal).

The Densitune calibration process consisted of the following steps:

1. Thoroughly mix sediment with agitator to ensure homogeneous mixture.
2. Measure and record sediment temperature.
3. Immerse Densitune tuning fork completely into sediment.
4. Allow measurement to stabilize and record calibration coefficient.
5. Remove and clean tuning fork.
6. Collect portion of sediment, measure precise volume and weight, and calculate density.
7. Add water (collected from site) to sediment to create lower density mixture and repeat process from step 1.

Figure 14 shows the Densitune tuning fork prior to its insertion into the initial (most dense) sediment mixture. The density of this composite sediment sample was 1281 g/l. In Figure 13, free water can be observed along with the clods of cohesive sediment retrieved with the sediment sampler. After a sufficient amount of sediment was collected during sampling, as much of this free water was poured off and returned to the Lauritzen Channel to achieve as dense material as was practical for calibration purposes. It is important to note that after this sediment was mixed the following day, it could be poured in a semi-fluid state during the calibration process of measuring volume and weight (Figure 15). While it is not know how much free water was present with the sediment clods, this sediment (after being stirred) exhibited thixotropic tendencies that allowed it to be poured as a fluid during the calibration process. Certain gels (semisolid colloids) that exhibit thixotropy can appear solid (like the sediment clods in Figure 13), but when subjected to external shearing forces such as shaking or stirring, this material will flow as a fluid (semi fluid colloid). Thixotropy is also reversible, if the semi fluid colloid is allowed to settle undisturbed, it will return back to its semisolid state.

Figure 14. Densitune tuning fork prior to immersion into sediment mixture.

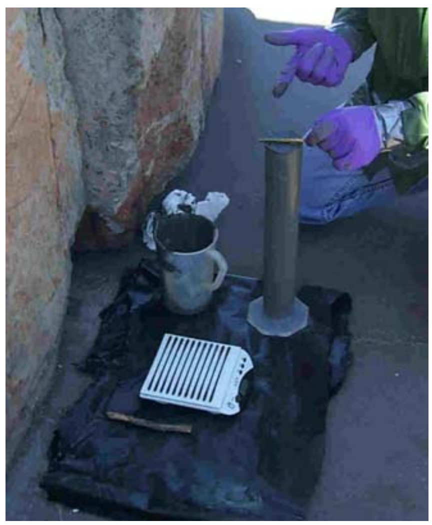

Figure 15. Lauritzen Channel sediment (after being stirred) that was poured into graduated cylinder for density measurement

Figure 16 is the calibration curve created from measuring the Densitune's response in seven different sediment mixture densities. In Figure 16, the change of slope between the 1281 g/l and 1257 g/l sample plots is significant and it is suspected that a major transition from fluid to more solid behavior occurs around a density of 1280 g/l or so. A noticeable change in material flowability was also observed when diluting from samples 6 to 5 (1257 g/l to 1211 g/l). In a qualitative sense, the mixture appeared as more of a fluid for sample 5, compared to sample 6.

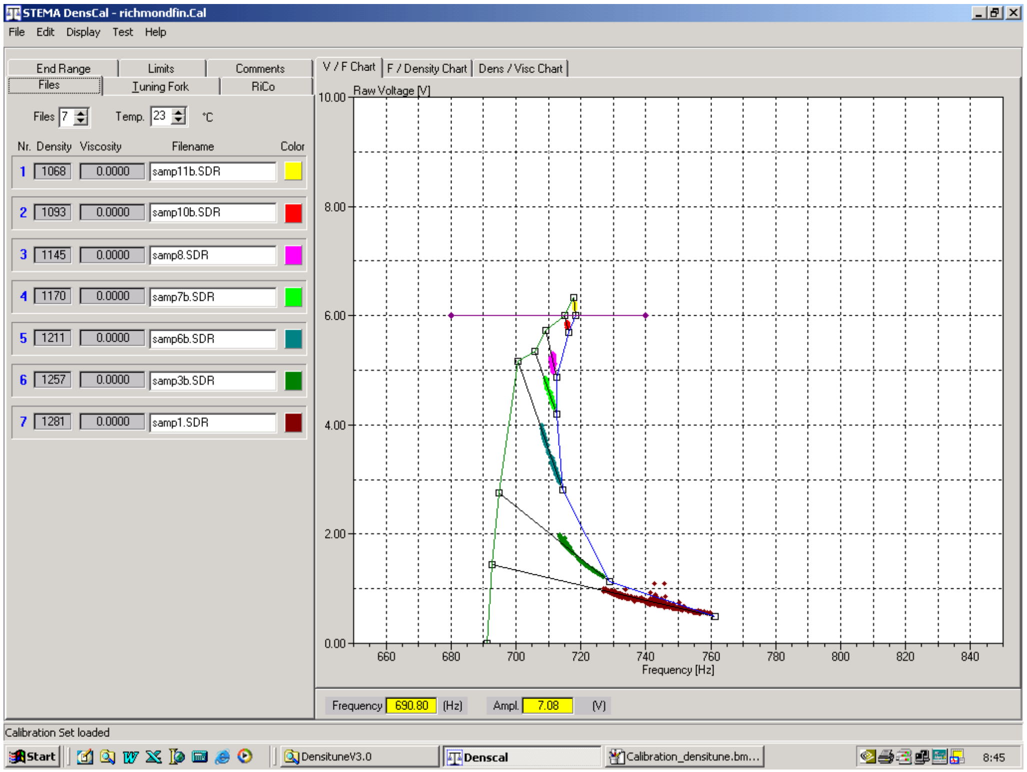

Figure 16. Densitune calibration curve

3.3.2 Calibrated Densitune Profiling Results

The calibration coefficients were applied to Densitune data collected on the previous day to generate calibrated density versus depth profiles and are presented in Appendix A. Figure 17 shows a representative profile measured during cast Dp6. This plot shows that the Densitune probe encountered sediment with a density of 1030 g/l at a depth of 38.77 ft. The sediment density gradient increased till a depth of refusal resulted at 39.54 ft with a density of 1280 g/l. Similar to a lead line, the maximum penetration depth of the Densitune is limited by the probes weight, surface area, and deployment velocity, in conjunction with sediment density and viscosity.

For comparative purposes, another Densitune profile from the Gulfport Navigation Channel, with documented fluid mud conditions, is presented in Figure 18 (this figure's units of depth are in meters, not feet as in Figure 17). The smaller range of densities plotted in Figure 18 (1030 g/l to 1200 g/l) compared to Figure 17 (1030 g/l to 1280 g/l) are more commonly seen in locations with fluid mud.

Examples of Densitune profiles tied to horizontal and vertical (bathymetric) references are presented in Figures 19 and 20. Figure 19 shows acoustic bottom reflections (in SILAS) from the longitudinal survey line that connects Densitune casts Dp1b, Dp2b, and Dp9b (from Figure 8). Figure 20 consists of acoustic bottom reflections (in SILAS) from a channel cross-section survey line aligned with Densitune cast Dp4.

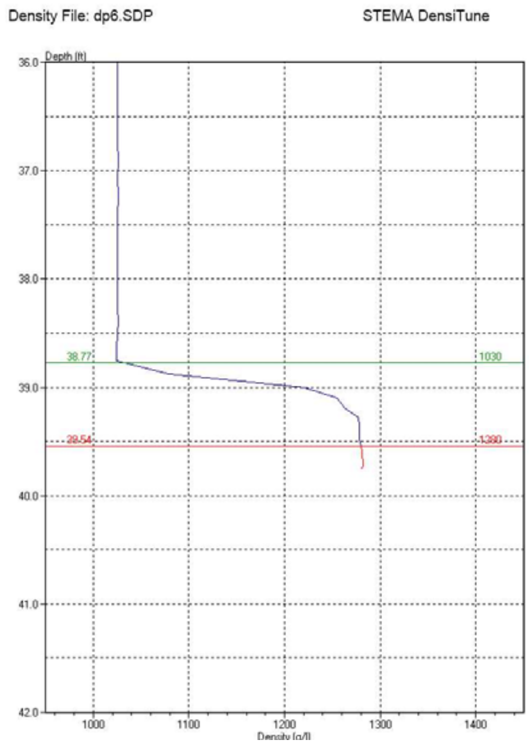

Figure 17. Calibrated Densitune density profile for Lauritzen Channel cast dp6.SDP

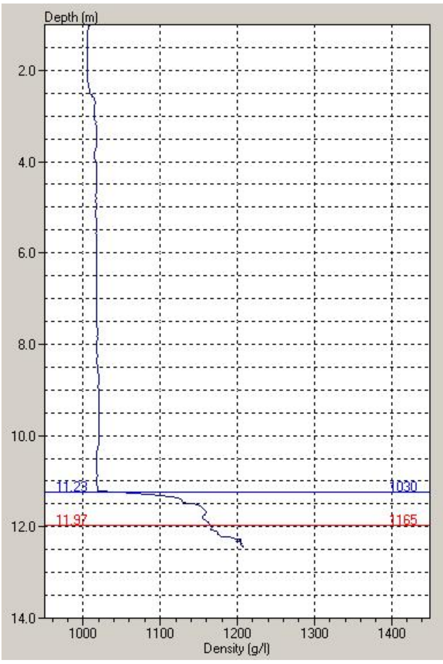

Figure 18. Calibrated Densitune density profile from Gulfport Navigation Channel, Gulfport, MS.

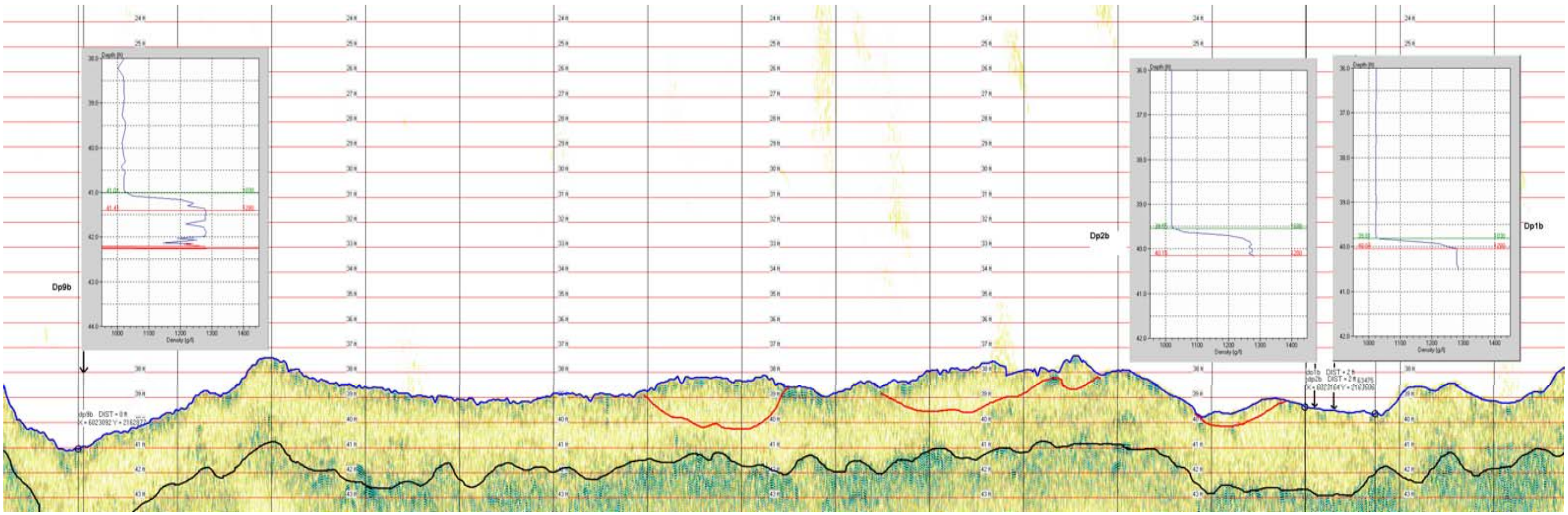

Figure 19. Example of Densitune profiles Dp1b, Dp2b, and Dp9b referenced to (channel) longitudinal survey line acoustic reflections.

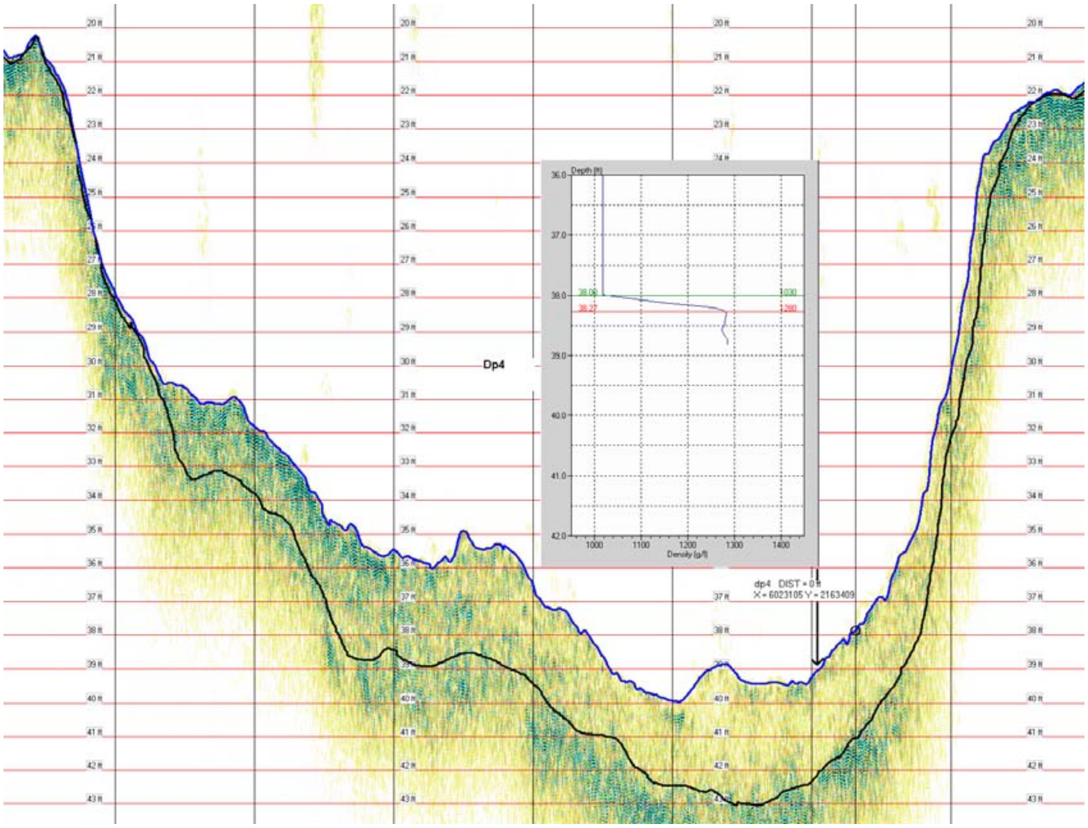

Figure 20. Example of Densitune profile Dp4 referenced to (channel) cross section survey line acoustic reflections.

After Densitune calibration and cleanup were completed, 3 additional hydrographic survey lines were conducted over channel areas made assessable after the gravel barge and Manson crane barge left the channel. These survey lines consisted of one on the west (Manson) side of channel and the other two were on the eastern side of the channel approximately 20 and 75 ft off the Levin Terminal berth C face.

3.3.3 Ball Valve Sampling Results

The final field data collection activity consisted of attempts to sample sediment with the ball valve sampler (BVS). This sampler, designed at CEERD, has been successfully used in the past to collect fluid mud samples at other USACE sites (Gulfport ship Channel, MS., Lower Atchafalaya River Bar Channel, LA, Calcasieu Entrance Channel, LA., etc.). The BVS was hand-lowered off the Wildcat till it rested (vertically) on the channel bottom, where the ball valves (as previously described) were opened, then closed. Limited time constraints allowed a total of eight casts to be conducted as close as possible to the Densitune profiling stations Dp1b though Dp9b. Even though correct BVS operation was verified by observing bubbles (caused by air escaping from opened collection reservoirs) at the water surface, no sediment was recovered from any collection reservoirs from any of the casts. The only sediment brought to the surface was cohesive sediment observed to be sticking on the BVS foot-weight after several casts. Absence of significant thicknesses of fluid mud was confirmed by this lack of sediment retrieved with the BVS. Table 1 lists Densitune profile locations, fluid mud thicknesses, and maximum penetration depths.

Table 1. Densitune profile characteristics

Measurement	Easting	Northing	Thickness Fluid Mud (ft)	* Maximum Penetration (ft)	Comments
Dp1b	6023157.03	2163475.43	0	0.75	
Dp2b	6023163.64	2163506.40	0	0.54	
Dp4	6023105.19	2163409.30	0	0.83	
Dp5	6023105.75	2163139.45	0	0.92	
Dp6	6023098.96	2163071.73	0	0.97	
Dp7d	6023093.73	2163018.77	0	0.74	
Dp8	6023088.70	2162966.40	0	0.90	
Dp9b	6023091.55	2162876.83	0	1.25	Possible debris at base

4. Post-field Data Processing and Analyses

4.1 Post-Processed SILAS Data and Definition of Sediment Density Boundaries

The un-edited digital 24 kHz echo soundings were post-analyzed with the Densitune-calibrated SILAS software by personnel from STEMA (Netherlands) and Odom Hydrographic Services (Baton Rouge, LA), in consultation with CEERD.

In SILAS, acoustic reflection amplitudes (transition points) indicate sediment density gradients (large density transitions lead to large reflection amplitudes). Comparison of acoustic reflection amplitudes of the water/sediment interface transition point and next major transition point (described as "base of mud layer") indicate that the density below this base of mud layer is expected to abruptly increase to levels over 1600 to 1800 g/l (in the density ranges for sediments such as sands and stiff clays). From the fact that small density transitions lead to small reflection amplitudes, it was deduced that the sediment density just above this base of mud layer reflector is estimated to be approximately 1350 g/l. This deduction is supported by SILAS density computations from acoustics as illustrated by the SILAS plot in Figure 21.

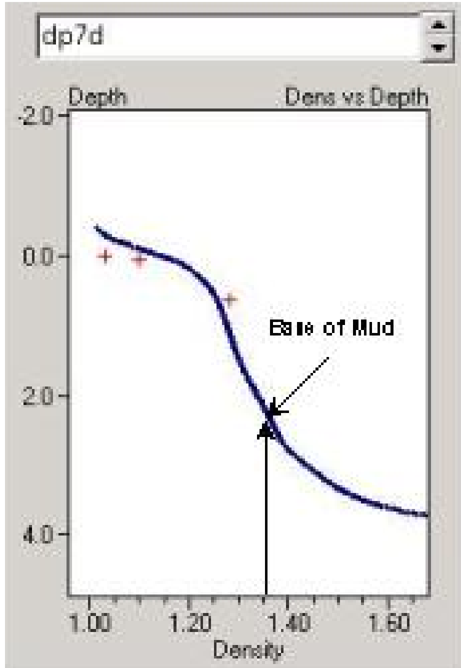

Figure 21. SILAS density calibration with two major density transitions visible, one at the water/sediment interface, and one at the base of the mud layer.

Because fluid mud was not detected in significant quantities during the study, as supported by data from the conventional duo-frequency hydrographic survey, Densitune profiles, and lack of sediment recovered by the BVS, practical determination of the upper and lower density boundary values to survey the fluid mud layer thickness was not possible. There is no universally defined critical density that relates the transition of fluid mud to more plastic sediment. Given that the major transition from fluid to more plastic behavior is expected to occur around a density of 1280 g/l (as indicated by the calibration curves in Figure 10), this value was selected as the next density boundary to characterize Lauritzen Channel sediments (the upper density boundary value being defined as the first calibrated acoustic reflection determining seabed at a value of 1030 g/l). The 1280 g/l density value (close to the initial density of the Densitune calibration sediment of 1281 g/l) is also approximately related to the maximum penetration densities obtained by the Densitune probe. The last boundary density value that was used to analyze acoustic data for characterizing Lauritzen Channel sediment was the 1350 g/l level that corresponds with the base of the mud layer.

4.2 SILAS-Generated Bathymetric Charts

Figures 22 and 23 illustrate these density boundaries as determined by SILAS recordings collected during longitudinal and cross section survey lines respectively. Figure 24 is the bathymetric chart showing depths to the water/sediment interface (depths corresponding to the blue line levels illustrated in Figures 22 and 23). Figure 25 is the bathymetric chart showing depths to the 1280 g/l density boundary (depths corresponding to the red line levels illustrated in Figures 22 and 23). Figure 26 is the bathymetric chart showing depths to the 1350 g/l density boundary (depths corresponding to the purple line levels illustrated in Figures 22 and 23). Figure 27 is a chart depicting the sediment layer thickness between the seabed and 1280 g/l level boundaries. Thickness of the seabed-to-1280 g/l layer ranged from approximately 0.2 to 1.2 ft. The calculated volume of material between these boundaries over an area of 533,300 square feet is approximately 10,000 yd^3. Figure 28 is a chart depicting the sediment layer thickness between the seabed and 1350 g/l level boundaries. Thickness of the seabed-to-1350 g/l layer ranged from approximately 0.2 to 6 ft. The calculated volume of material between these boundaries is approximately 38,000 yd^3.

4.3 Discussion of SILAS Density Measurement Accuracy

An objective of CEERD contributing DOER program funding (that partially funded CEERD and contractor participation in the study) was to evaluate the SILAS's accuracy in measuring acoustically-determined density. The BVS was to be used to collect fluid mud at random positions (not at Densitune profiling locations) and depths from the channel, then measure the respective densities with a field densitometer. These values were, in turn, going to be compared to densities (at the same locations) calculated with SILAS-analyzed acoustic reflection data. This evaluation did not occur due to lack of fluid mud at the site and lack of available sediment sampling equipment to sample the more solid-state sediment at specific depths.

But, information was available in the form of coring data collected during a 1999 study (Kohn and Gilmore 2001) that provided a basis for, at least, rough qualitative data comparisons to be conducted and generalizations to be drawn. In this study, a 6 horsepower vibracorer was used to collect samples with a 10 ft-long aluminum core barrel lined with a 4 inch –diameter butyrate sleeve. DGPS was used to log core positions (referenced to California State Plane NAD83) and water depth at each station was measured with a lead line. These depths were tide-corrected and referenced to mean lower low water (MLLW) datum. Data from this study are presented in Table 2 the form of coring station identification numbers, water depths (mud line) referenced to MLLW, core vertical segment lengths, Young Bay Mud (YBM) or Old Bay Mud (OBM) designations, and sample percent solids by dry weight.

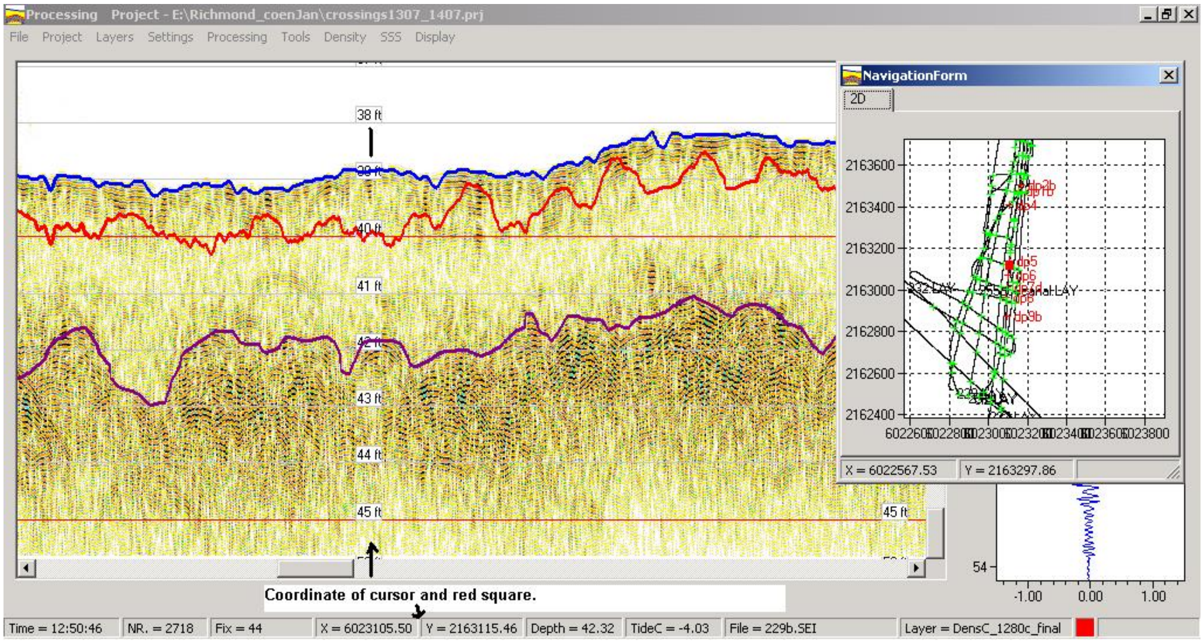

Figure 22. Example of SILAS recordings from a longitudinal survey line (blue line – water/sediment interface, red line - 1280 g/l density level, purple line - 1350 g/l density level)

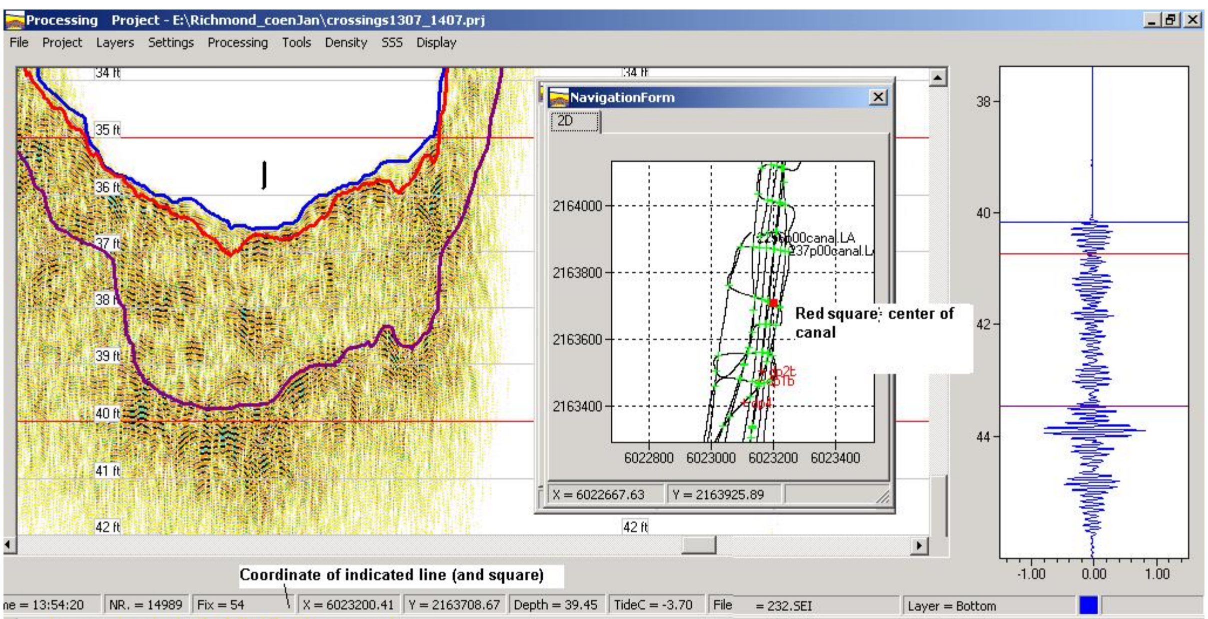

Figure 23. Example of SILAS recordings from a cross section survey line (blue line – water/sediment interface, red line - 1280 g/l density level, purple line - 1350 g/l density level)

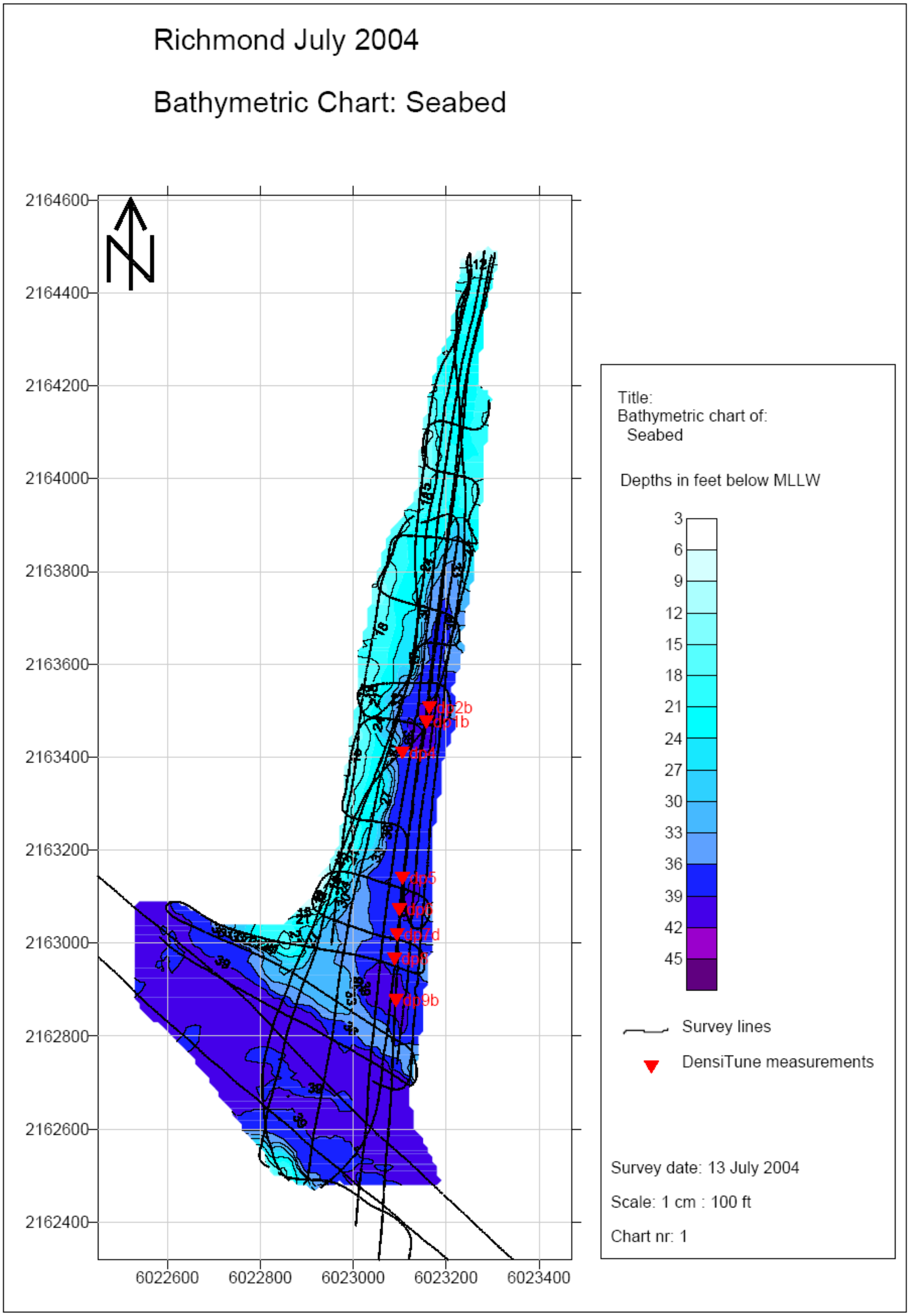

Figure 24. Bathymetric chart of Lauritzen Channel seabed

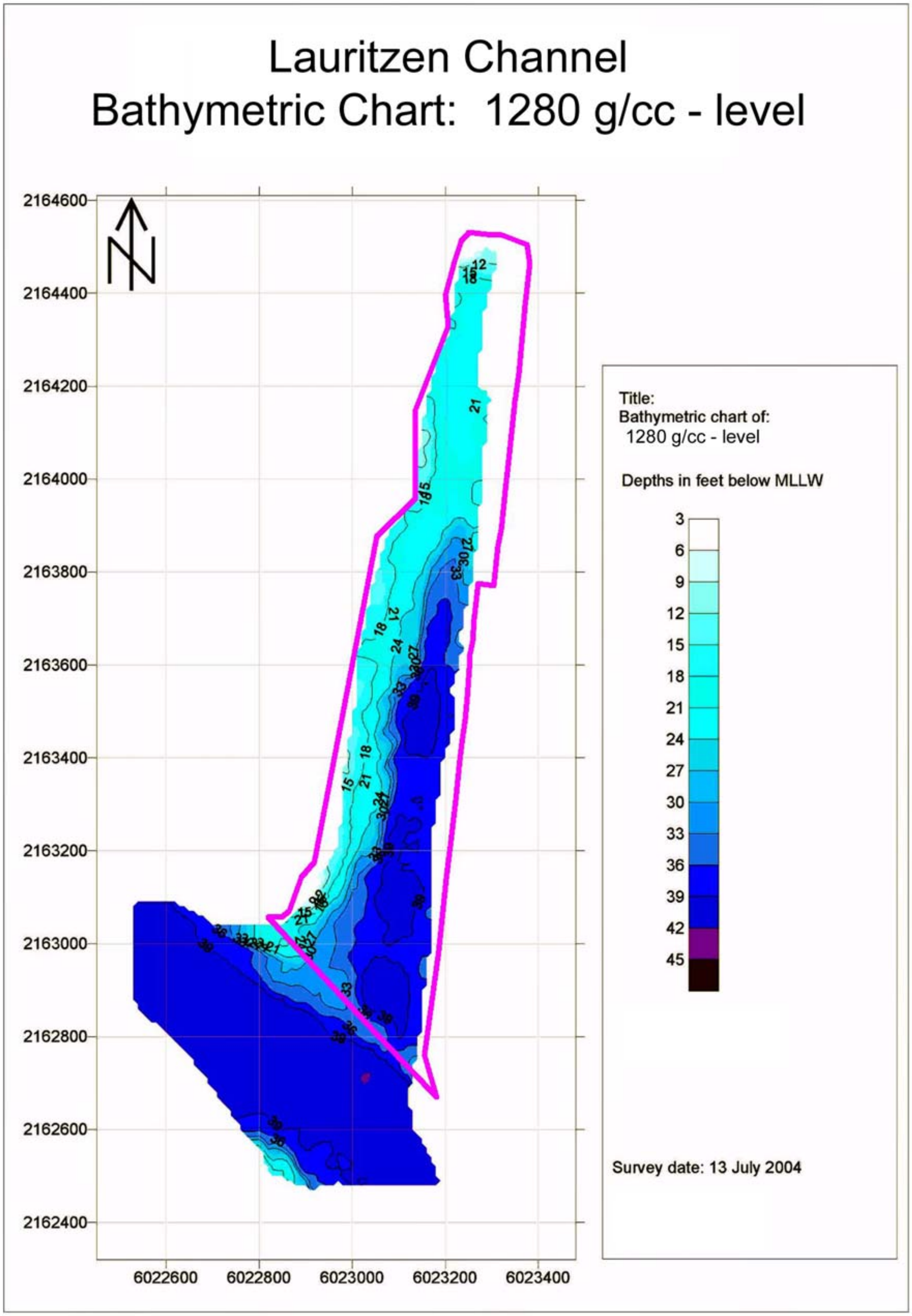

Figure 25. Bathymetric chart of Lauritzen Channel at 1280 g/l level

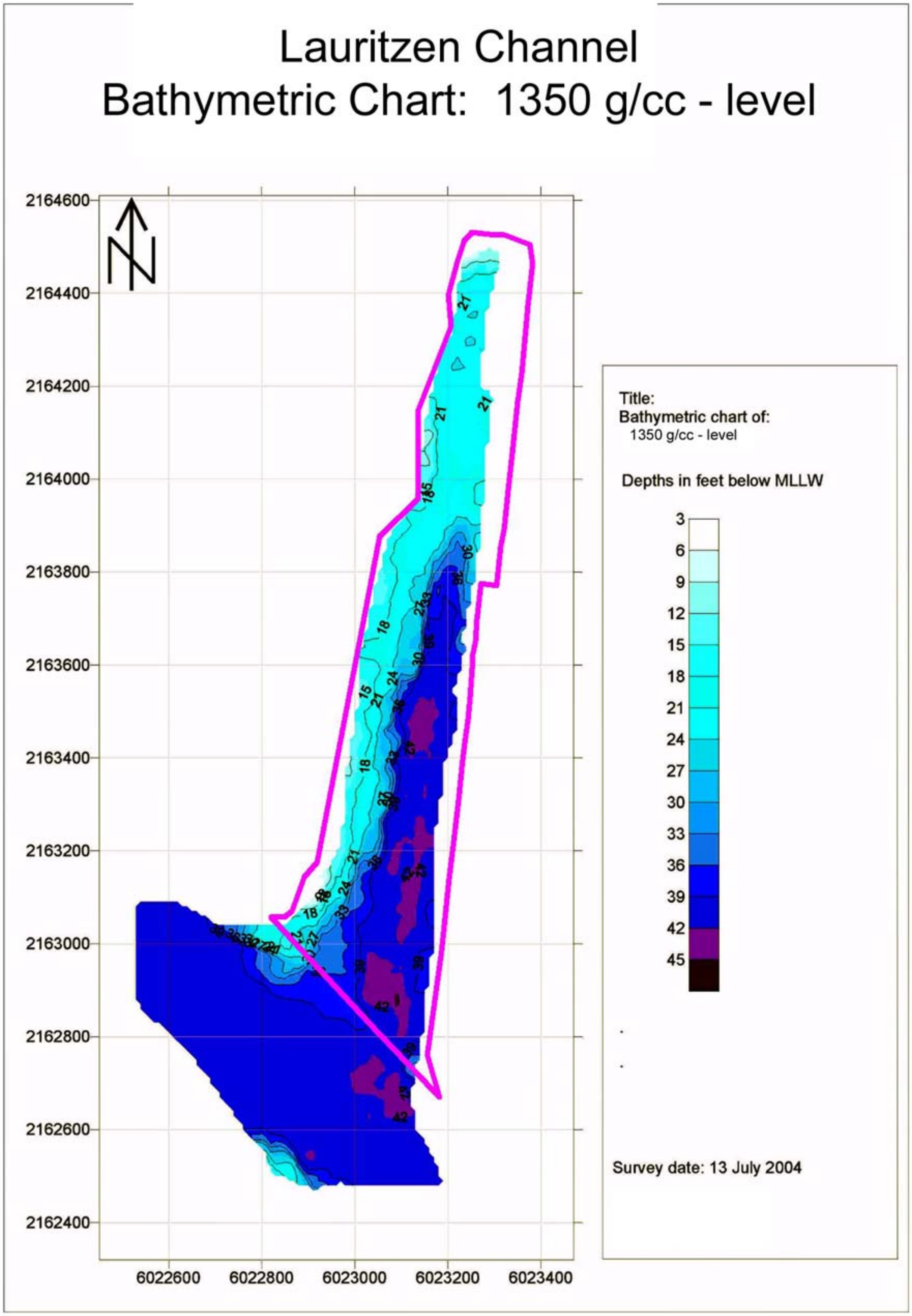

Figure 26. Bathymetric chart of Lauritzen Channel at 1350 g/l level

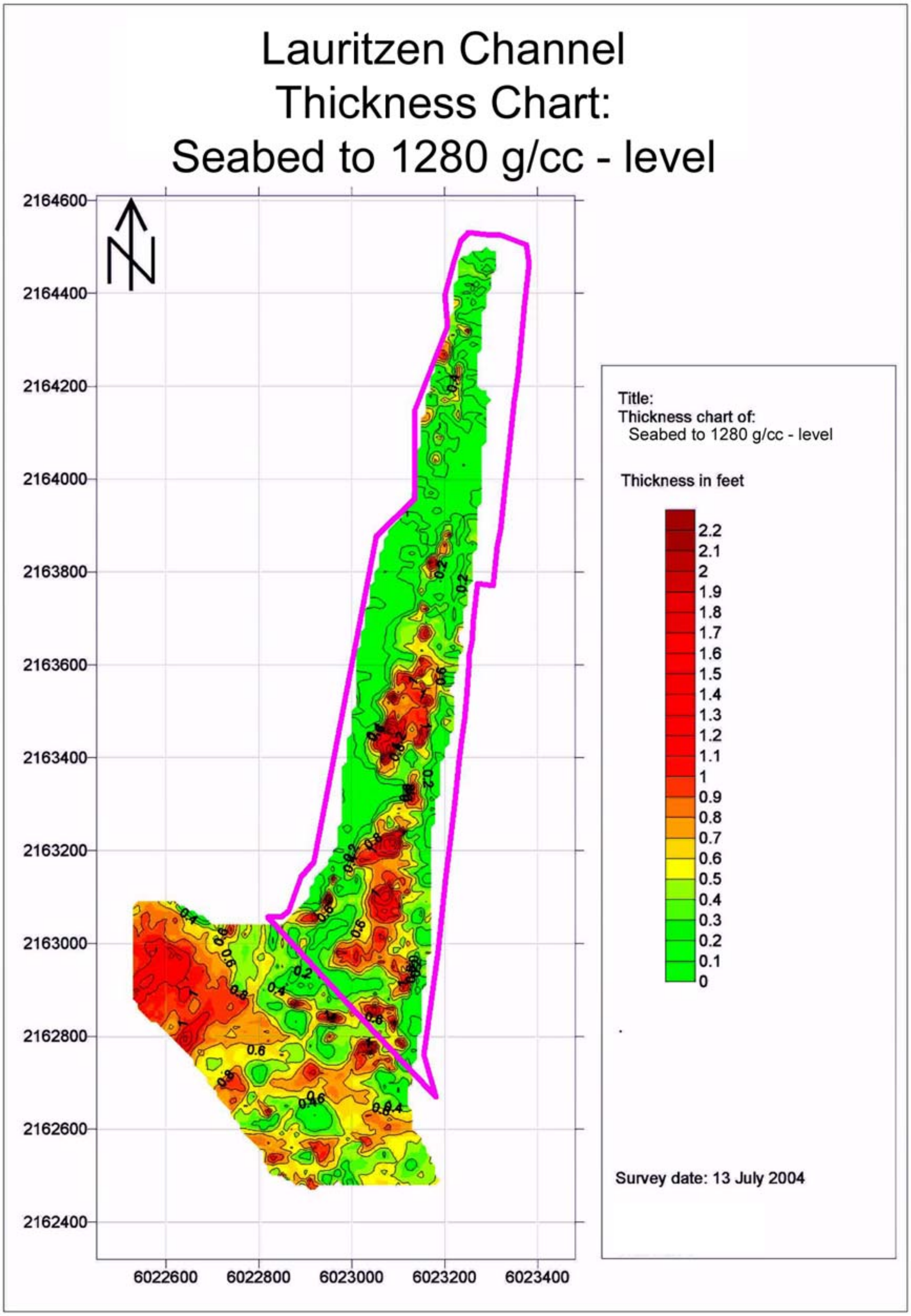

Figure 27. Sediment layer thickness chart of Lauritzen Channel
between seabed and 1280 g/l level

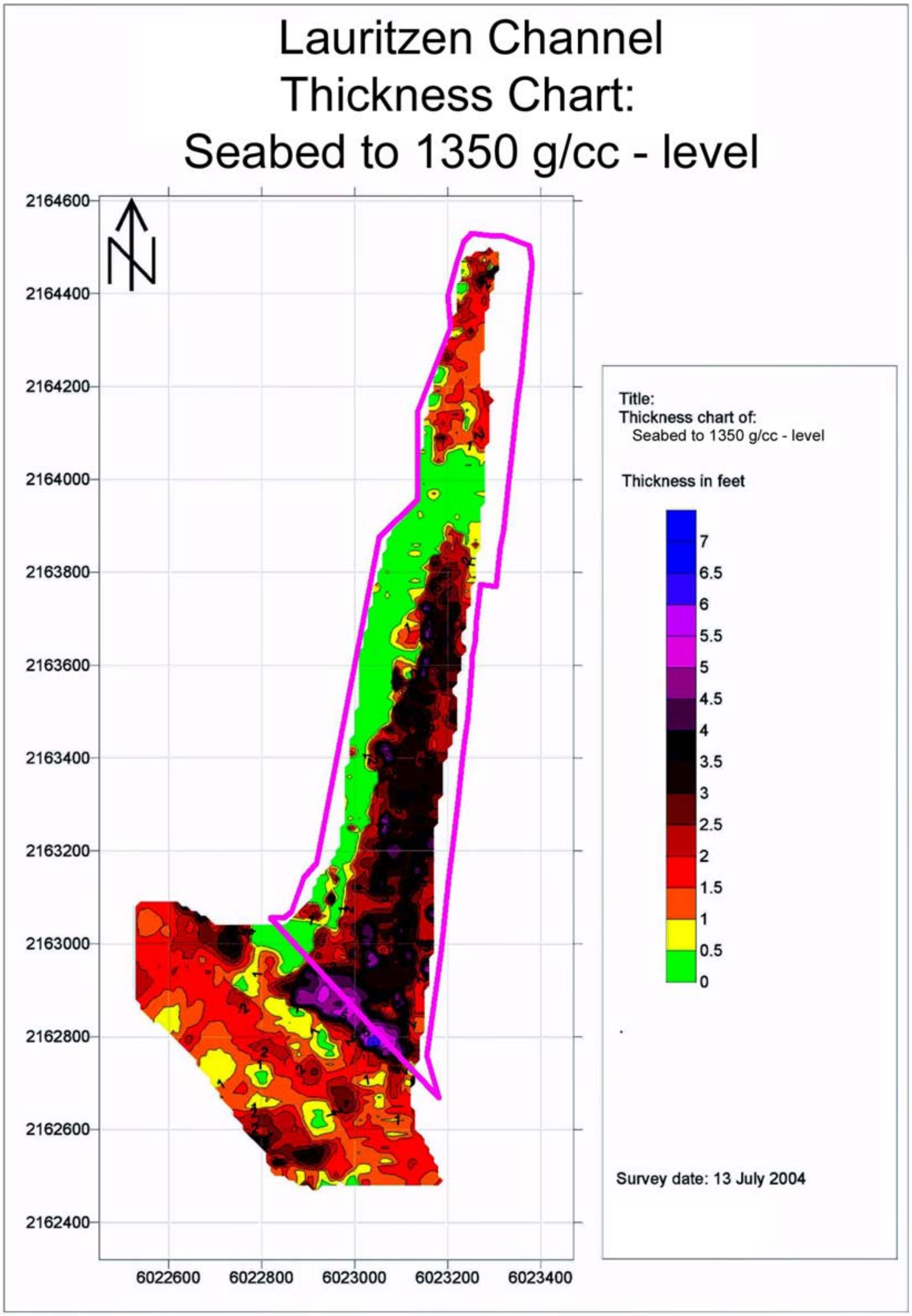

Figure 28. Sediment layer thickness chart of Lauritzen Channel between seabed and 1350 g/l level

Coring positions and station designations from the 1999 study are superimposed on the SILAS seabed bathymetric chart in Figure 29. Taking into account the uncertainty of depth changes over the four-year plus span (sediment deposition, dredging activities, prop scour, etc.) and depth measurement error of lead lining in a soft bottom, when one compares the (SILAS) depth contours to the core mud line depths, the water depths appear to be generally similar, plus or minus several feet.

When comparing 1999 geotechnical data with SILAS survey data, only the roughest generalizations can be attempted. As previously stated, comparison of SILAS acoustic reflection amplitudes of the water/sediment interface transition point and next major transition point (described as "base of mud layer") indicated that the density below this base of mud layer (with a density value of 1350 g/l) is expected to abruptly increase to levels over 1600 to 1800 g/l. From the total solids (percent dry weight) values in Table 2, approximate bulk densities for OBM and YBM were calculated. These values were calculated by the following method. The average YBM and OBM total solids (percent dry weight) values for the coring stations contained within the SILAS survey area were were calculated to be 54.9% and 75.6% respectively. These values were converted to total solids (percent by volume) by the following equation

$$\frac{\text{Solids concentration (i.e. weight of dry solids)}}{\text{Dry density of solids}} = \text{Volume of solids}$$

Where a dry density of solids value of 2700 g/l was assumed to account for the varying solids constituents of sand, gravel, silt, and clay.

Using the total solids (by percent volume) fractions of 20.7% for YBM and 28.5% for OBM, and assuming that a water density of 1025 g/l saturated the remaining voids, sediment/water bulk density values were calculated to be 1370 g/l for YBM and 1500 g/l for OBM. The calculated YBM value of 1370 g/l is relatively close to the 1350 g/l value used to define the base of mud layer. Coring positions and station designations from the 1999 study are superimposed on the SILAS seabed-to-1350 g/l sediment layer thickness chart in Figure 30. When one compares the recovered YBM vertical segment lengths in Table 2 with coincident positions on this sediment layer thickness chart, the longer YBM core lengths generally were recovered from the thicker (seabed-to-1350 g/l) sediment layers identified by the SILAS. While this observation shows some potential promise of the SILAS to acoustically measure sediment density horizons, no definite conclusions about the SILAS's accuracy can be drawn from this study.

Station ID	Mudline (-ft MLLW)	Vertical Segment (ft below mudline)	Sediment Type	Total Solids (% dry weight)	Grain Size and TOC (% dry weight)				
					Gravel	Sand	Silt	Clay	TOC
Between Pilings, northeastern Lauritzen Channel									
PL- 01	7.9	0-2.0	YBM	47.3	23.8	31.6	23.1	21.5	7.4
PL- 01A	9.9	0-2.3	YBM	54.5	19.8	29.4	23.0	27.9	6.5
PL- 01A	9.9	2.3-2.5	OBM-dist	75.6	9.7	39.4	20.3	30.6	0.5
PL- 02	12.9	0-0.5	YBM	46.3	20.5	16.1	20.9	42.5	7.1
PL- 03	12.7	0-1.3	YBM	48.1	3.2	10.2	35.0	51.6	3.0
PL- 03	12.7	1.3-1.7	YBM	41.7	4.1	5.5	40.3	50.2	6.8
PL- 03	12.7	1.7-2.2	OBM-dist	67.8	21.9	26.6	19.6	32.0	1.0
PL- 05	11.9	0-0.6	YBM	54.7	1.4	9.1	38.7	50.9	1.1
PL- 06	15.9	0-0.2	YBM	77.7	17.4	33.9	21.3	27.4	0.3
PL- 07	12.0	0.3-1.0	YBM	70.2	3.9	16.7	31.9	47.5	1.7
PL- 7, 6, 5, 4	various	various	OBM comp	74.4	12.3	19.1	31.1	37.4	0.2
PL- 08	21.8	0-0.2	YBM	NA[a]	NA	NA	NA	NA	NA
PL- 08	21.8	0.2-0.6	OBM-dist	86.4	55.1	16.8	17.6	10.5	0.2
Upper Lauritzen Channel									
UL- 09	21.1	0-0.9	YBM	51.7	1.2	49.2	19.5	30.2	1.5
UL- 09	21.1	0.9-1.4	Sand	75.9	0.5	85.4	4.5	9.6	0.3
UL- 10	19.3	0-1.0	YBM	57.1	1.5	14.8	38.9	44.8	1.2
UL- 9, 10	various	various	OBM comp	74.0	2.1	28.5	33.2	36.2	0.4
UL- 13	22.9	0-1.1	YBM rocks	86.6	73.3	17.2	3.1	6.4	0.2
UL- 14	22.8	0-0.3	YBM	57.1	2.1	26.5	30.3	41.1	1.1
UL- 14	22.8	0.3-0.8	OBM-Dist	74.8	1.9	34.2	36.1	27.9	0.1
UL- 14,11,12	various	various	OBM comp	77.6	4.8	33.9	43.9	17.4	ND

Table 2. Sediment grain size and total organic carbon results, Heckathorn 1999 sediment investigation (after Kohn and Gilmore 2001)

Station ID	Mudline (-ft MLLW)	Vertical Segment (ft below mudline)	Sediment Type	Total Solids (% dry weight)	Grain Size and TOC (% dry weight) Gravel	Sand	Silt	Clay	TOC
Southwest Lauritzen Channel									
SW- 15	17.0	0-0.5	Sand	80.8	3.8	85.2	4.6	6.4	0.2
SW- 15	17.0	0.5-1.2	OBM-Dist	69.5	4.5	33.0	36.5	26.0	0.7
SW- 16	23.8	0-0.5	YBM sandy	69.7	1.0	66.5	13.4	19.2	0.7
SW- 16	23.8	0.5-1.0	OBM	77.0	0.9	68.6	17.3	13.3	0.2
SW- 17	21.8	0-0.8	YBM	59.1	2.6	37.6	27.3	32.5	0.9
SW- 17	21.8	0.8-1.0	OBM	77.1	3.0	53.6	27.9	15.5	0.2
Levin Berths B & C									
BC- 18	38.4	0-0.7	YBM	46.2	1.0	22.5	24.5	52.0	1.5
BC- 18	38.4	0.8-1.3	YBM	53.0	4.6	21.6	31.3	42.5	1.2
BC- 18	38.4	1.3-1.6	OBM	74.1	0.2	22.7	39.7	37.5	0.2
BC- 19	35.4	0-1.2	YBM	50.3	4.7	29.3	18.3	47.8	2.0
BC- 19	35.4	1.4-2.2	YBM	71.0	13.6	31.1	27.4	27.9	1.1
BC- 20	37.4	0-1.6	YBM	52.0	11.3	21.6	22.0	45.0	1.6
BC- 21	39.4	0-1.5	YBM	54.5	5.0	37.5	17.5	40.0	0.8
BC- 21,23,24	various	various	OBM comp	73.6	3.1	15.1	40.7	41.1	0.2
BC- 22	39.4	0-1.4	YBM	56.6	20.9	27.6	16.3	35.2	2.4
BC- 23	40.3	0-1.6	YBM	42.3	0.0	10.2	22.7	67.2	1.4
BC- 24	41.2	0-2.7	YBM	45.9	0.9	18.7	26.0	54.3	1.6

Table 2 continued. Sediment grain size and total organic carbon results, Heckathorn 1999 sediment investigation (after Kohn and Gilmore 2001)

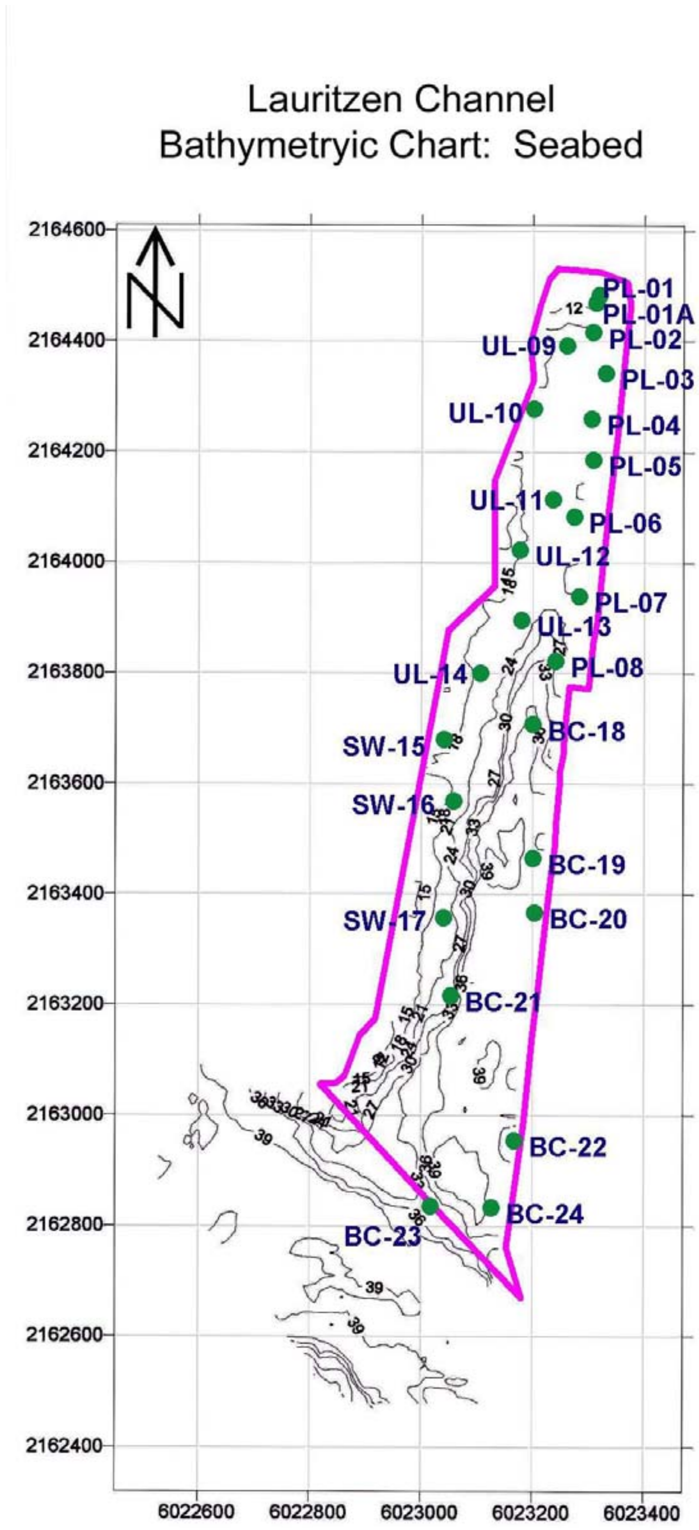

Figure 29. 1999 study coring stations superimposed over SILAS seabed bathymetric chart

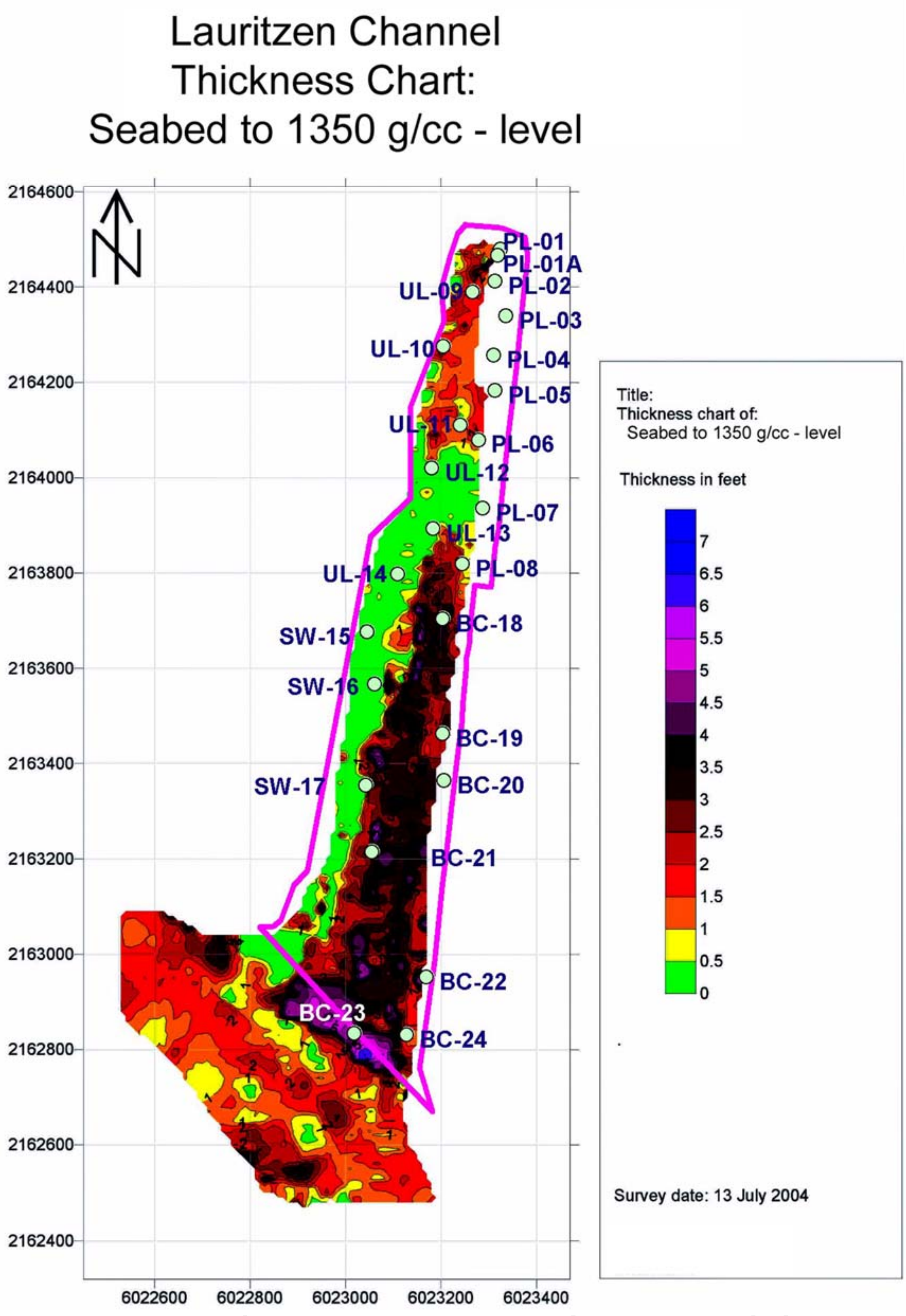

Figure 30. 1999 study coring stations superimposed over SILAS seabed-to-1350 g/l sediment layer

5. Conclusions

The following conclusions are drawn from results of the Lauritzen Channel sediment density survey.

Although several areas indicated “soft” bottom conditions, no typical fluid mud characteristics (duo acoustic reflection traces and relatively flat bathymetry) were collected by the duo frequency echo sounder during the hydrographic survey. The Densitune density versus depth profiles did not indicate the measurable presence of fluid mud (which usually ranges in density from about 1100 g/l to 1200 g/l) and had an average penetration depth of about 0.8 feet below the water/sediment interface. There was no sediment recovered by the ball valve sampler that was specifically designed to collect fluid mud samples. Given these results, it is highly unlikely that fluid mud, in the context of a sediment/water suspension with a fluid consistency definition, existed in measurable quantities in the Lauritzen Channel during the study.

Sediment collected for Densitune calibration exhibited thixotropic tendencies during the calibration process. Although it was retrieved from the channel bottom in a mostly semisolid state (clods), after being stirred, this material was rendered pourable in a semi liquid state. Although not observed, it is assumed that if allowed to settle, the sediment would regain sufficient shear strength to form clods again. After the collected sediment consolidated for 13 hours and formed a thin layer of supernatant overlaying the settled mud, it exhibited a propensity to readily resuspend when entrained by minimal supernatant water movement caused by gently moving the sample bucket. These observations indicate the bottom sediments relative ease for being resuspended after being subjected to external forces.

Before this survey, CEERD had preliminarily evaluated the Densitune’s measurement accuracy and determined that, after correct calibration, it measures sediment density fairly well. Quantification of its in situ measurement accuracy in this study was not possible due to the inability to retrieve discrete in situ sediment samples for comparative purposes. The STEMA subcontractor stated that because the Densitune calibration curves (Figure 16) were typical, the accuracy of in situ density versus depth data plots in Appendix A should be good.

Accuracy of the SILAS’s acoustically-determined density measurements was also to be investigated during this study. This was to be accomplished by collecting fluid mud samples from various positions and depths with the BVS, measuring their respective densities with a field densitometer, and then comparing these densities to SILAS-calculated densities from the same locations. This evaluation did not occur due to lack of fluid mud at the site. Because of this dearth of fluid mud while the field study was conducted, alternative density levels were identified (seabed (water/sediment interface at 1030 g/l), 1280 g/l and 1350 g/cc) to characterize channel sediment conditions. The seabed level was measured by the first acoustic reflection, or water/sediment interface, from the SILAS system. The 1280 g/l level marked the base of a major transition point where it is suspected that the sediment transitions from semi fluid to more solid behavior.

The 1350 g/cc level corresponds with the next major transition point identified by the SILAS and described as the mud layer base that should be regarded as the best estimate based in the acoustic information. Comparison of acoustic reflection amplitudes indicated that the density below this base of mud layer is expected to abruptly increase to levels over 1600 to 1800 g/l. Although not conclusive, comparison of SILAS data with coring logs from a previous study did indicate a general correlation between the seabed-to-1350 g/l sediment layer thicknesses and YBM vertical segment lengths.

Thickness of the seabed-to-1280 g/l layer ranged from approximately 0.2 to 1.2 ft. The calculated volume of material between these boundaries over an area of 533,300 square ft is approximately 10,000 yd^3. Thickness of the seabed-to-1350 g/l layer ranged from approximately 0.2 to 6 ft. The calculated volume of material between these boundaries over the same 533,000 square ft is approximately 38,000 yd^3.

6. References

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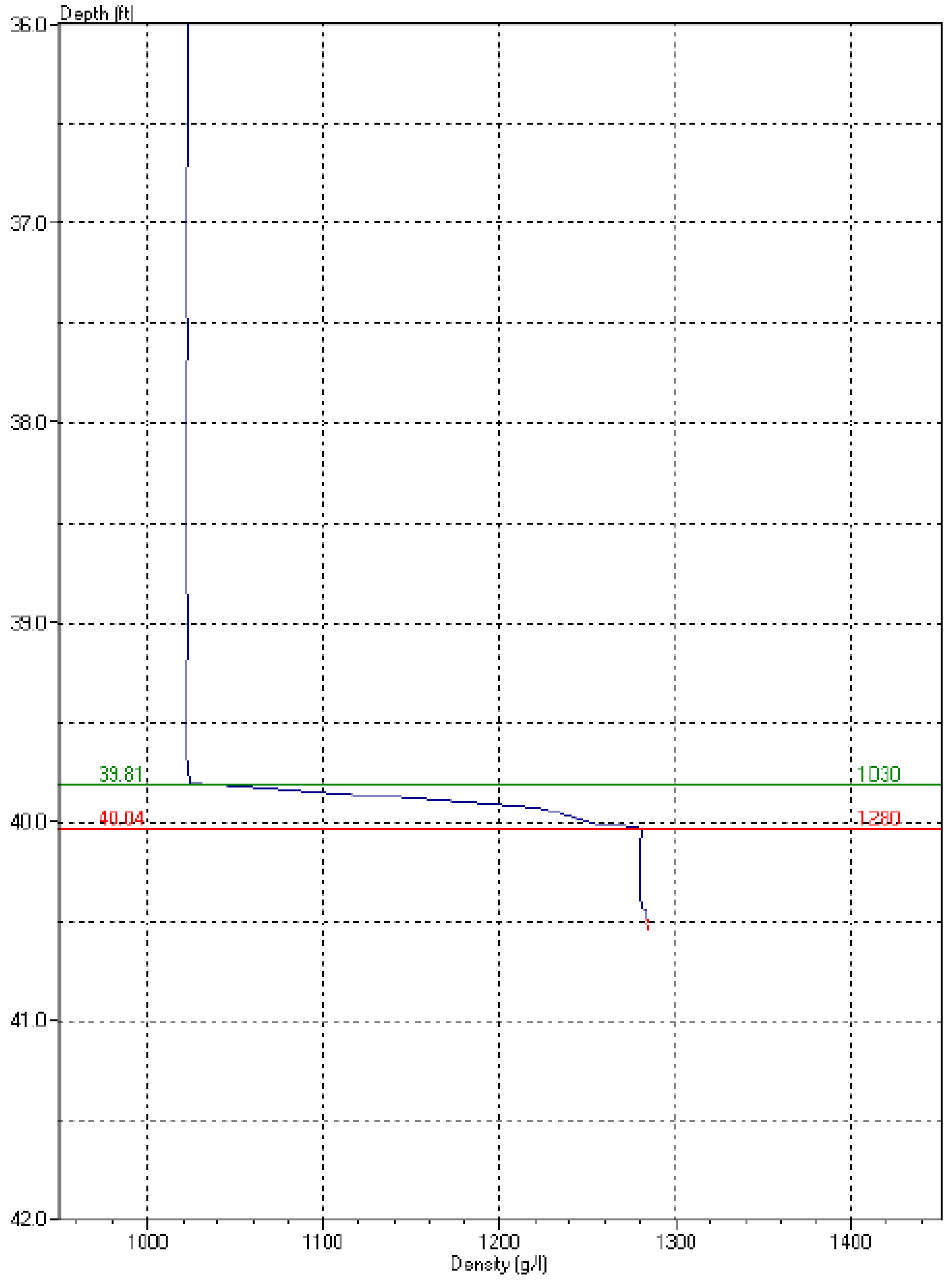
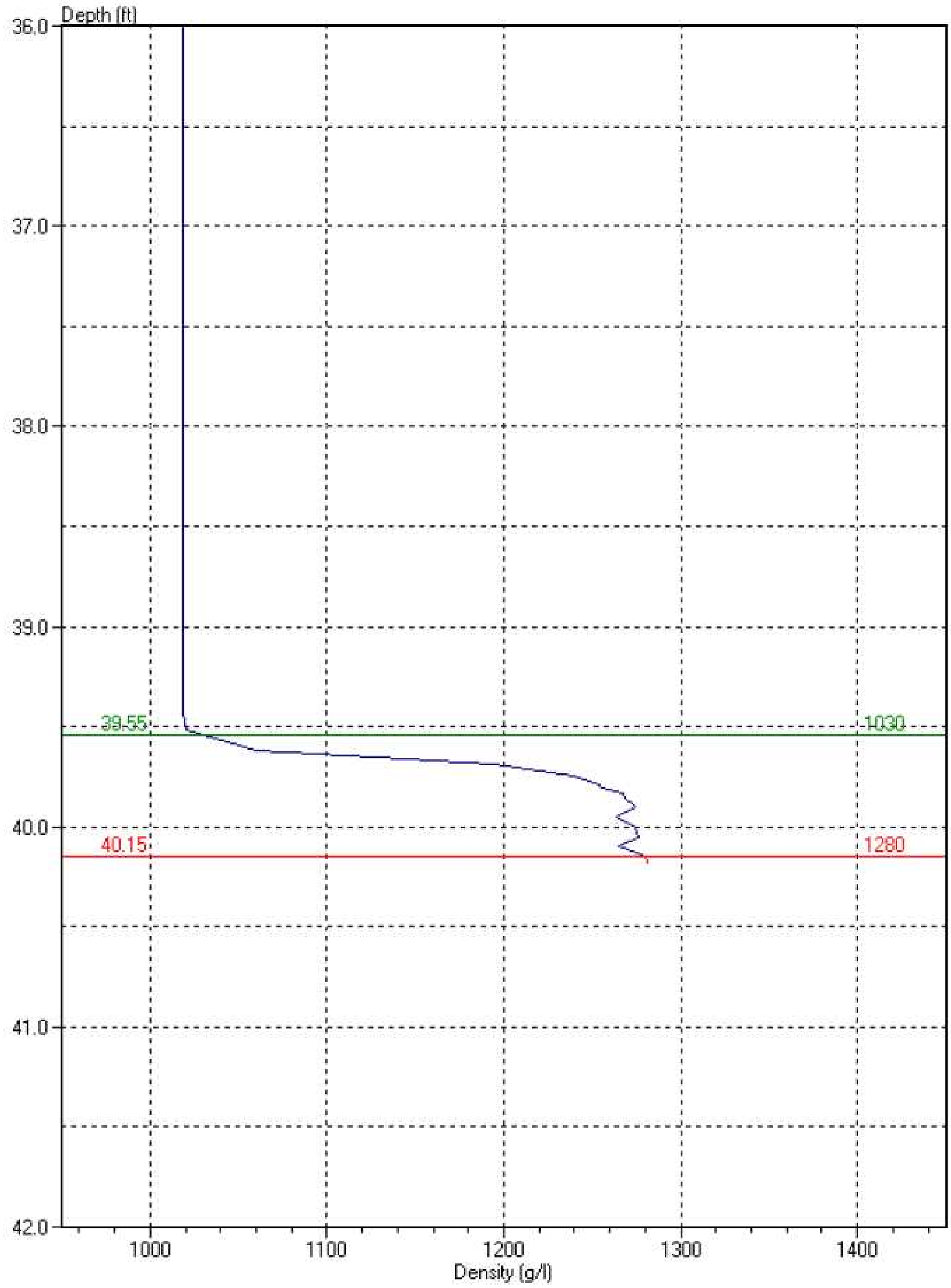
Appendix A. Calibrated Densitune Density Versus Depth Profiles

Density File: dp1b.SDP STEMA DensiTune



Max.Depth:40.54	Location:	6023157.03 X, 2163475.43 Y
DensiTune	Kp:	0.00 ft
Silt Density Probe	Date:	13-7-2004
STEMA Survey Services b.v.	Time:	16:38:33
Geldermalsen - The Netherlands	Tide:	3.00 ft

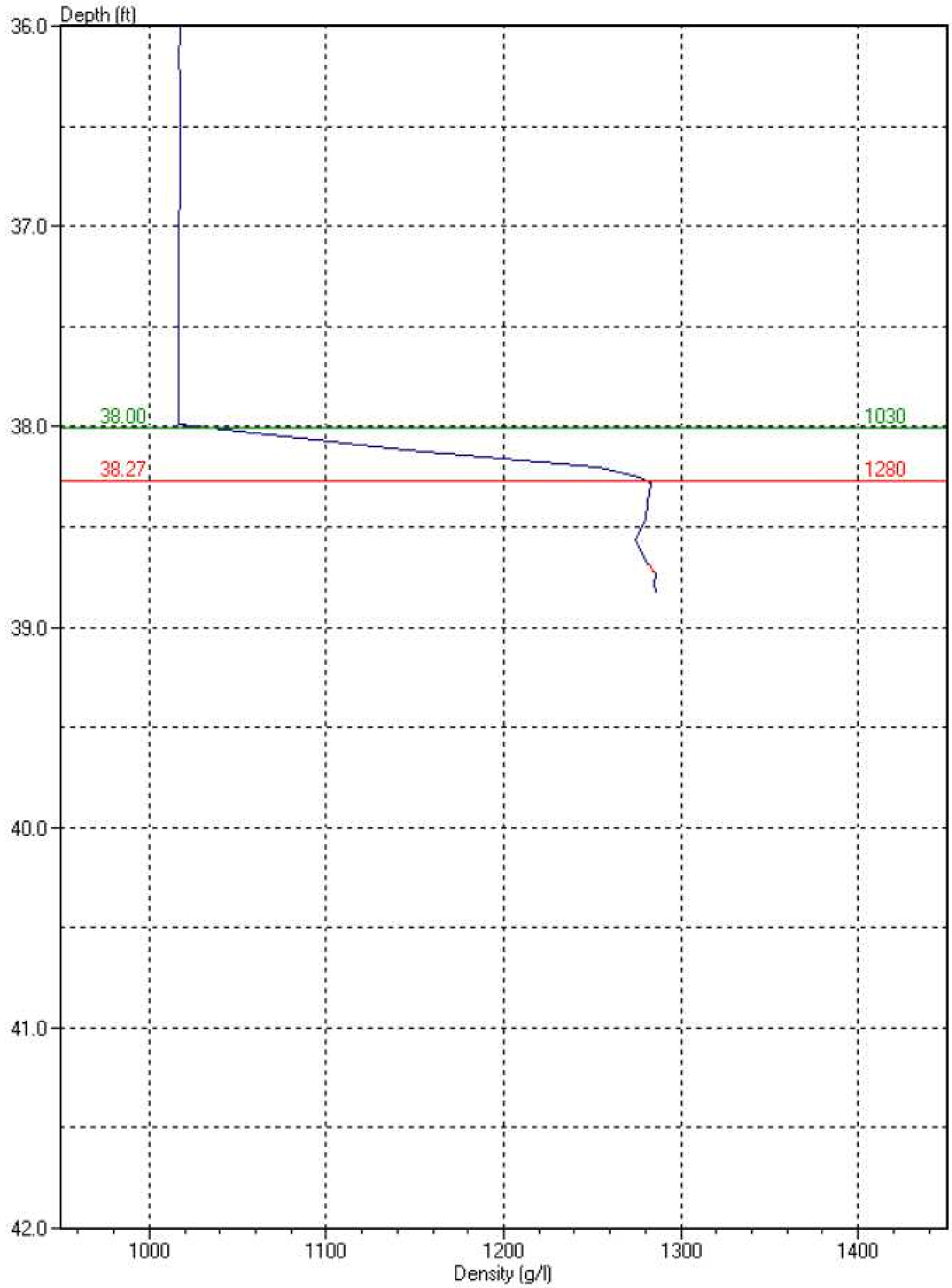
Density File: dp2b.SDP STEMA DensiTune



Max.Depth:40.19
DensiTune
Silt Density Probe
STEMA Survey Services b.v.
Geldermalsen - The Netherlands

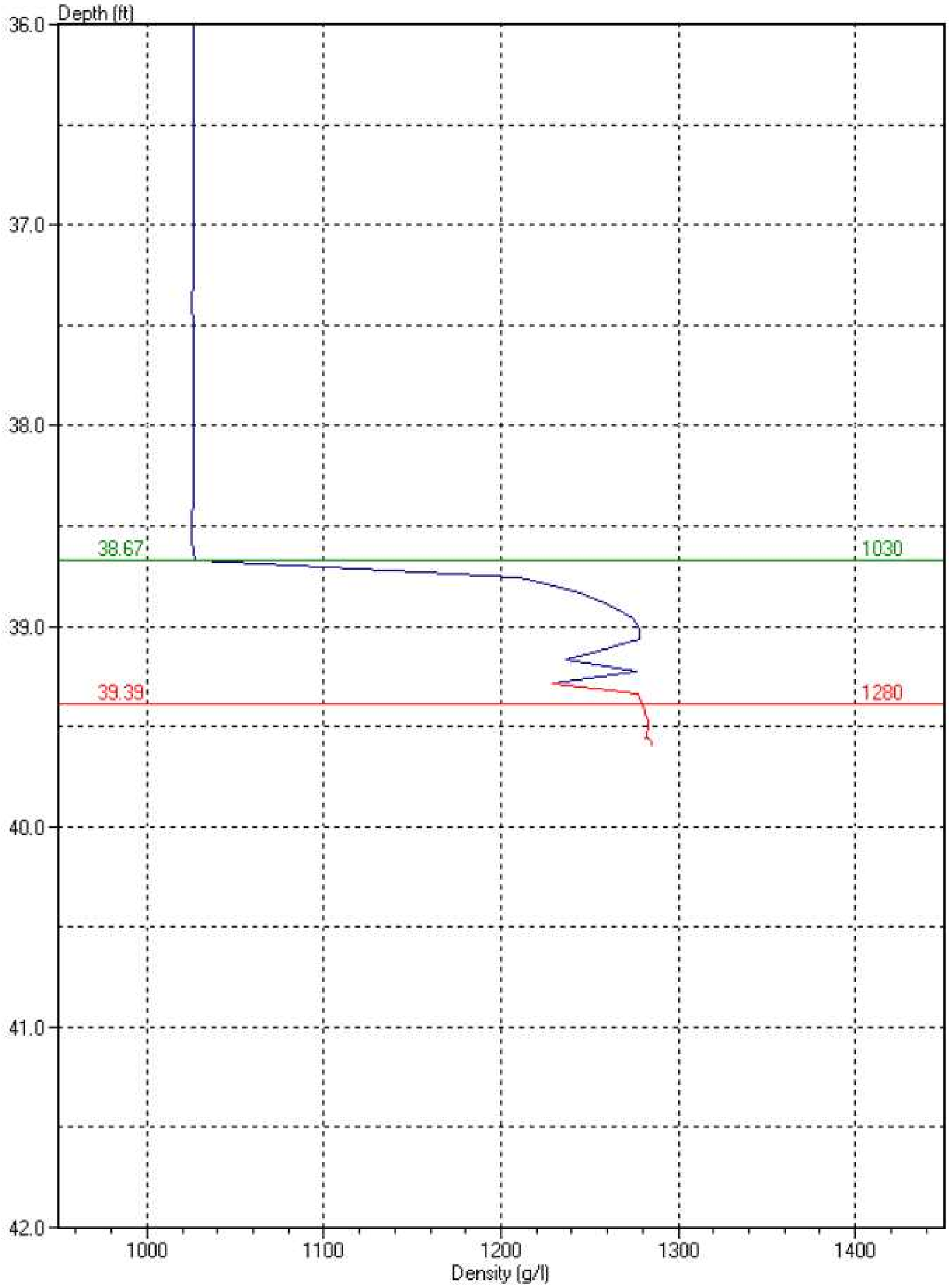
Location: 6023163.64 X, 2163506.40 Y
Kp: 0.00 ft
Date: 13-7-2004
Time: 16:46:50
Tide: 3.00 ft

Density File: dp4.SDP STEMA DensiTune



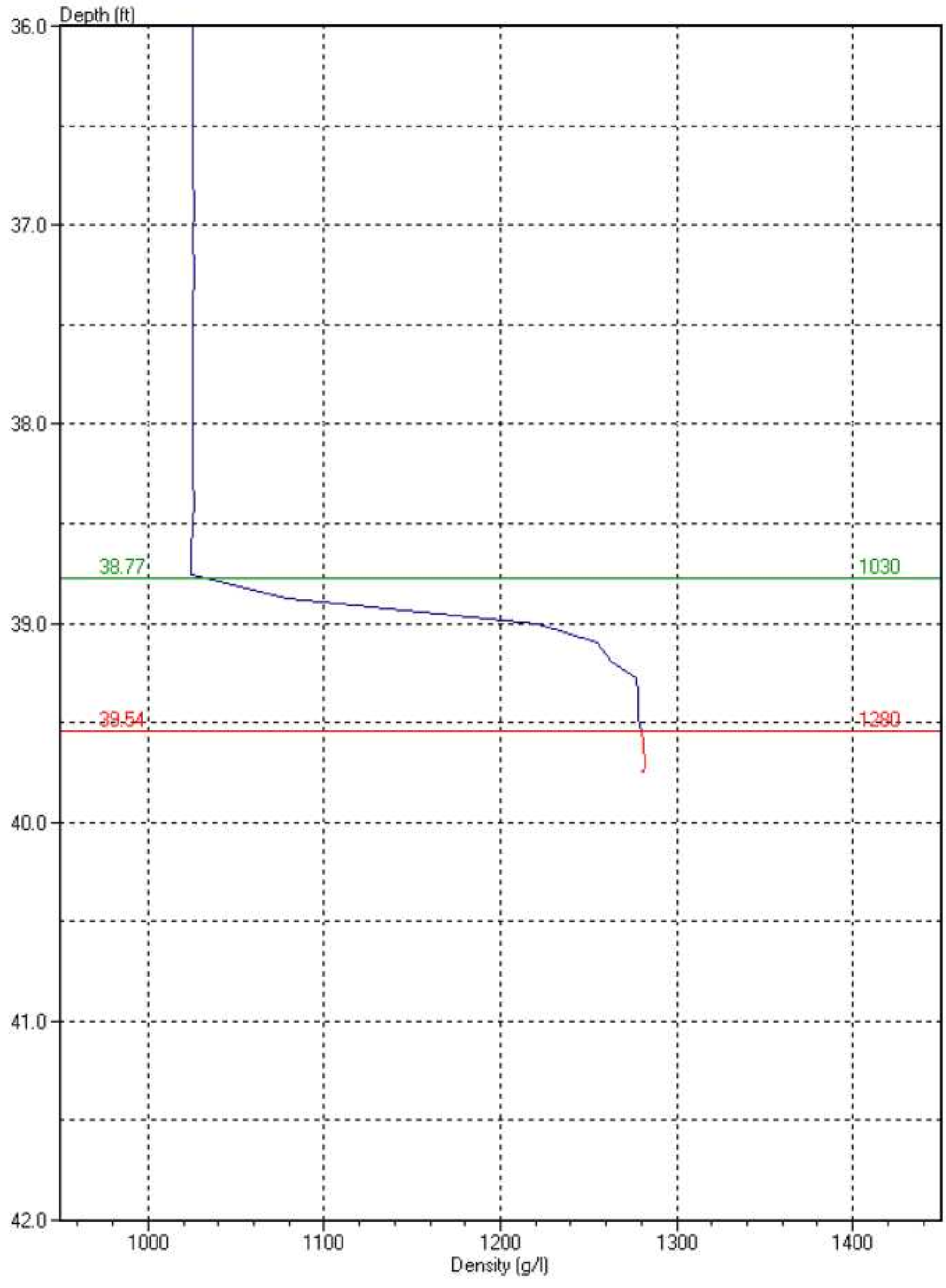
Max.Depth:38.83	Location:	6023105.19 X, 2163409.30 Y
DensiTune	Kp:	0.00 ft
Silt Density Probe	Date:	13-7-2004
STEMA Survey Services b.v.	Time:	16:53:53
Geldermalsen - The Netherlands	Tide:	3.10 ft

Density File: dp5.SDP STEMA DensiTune



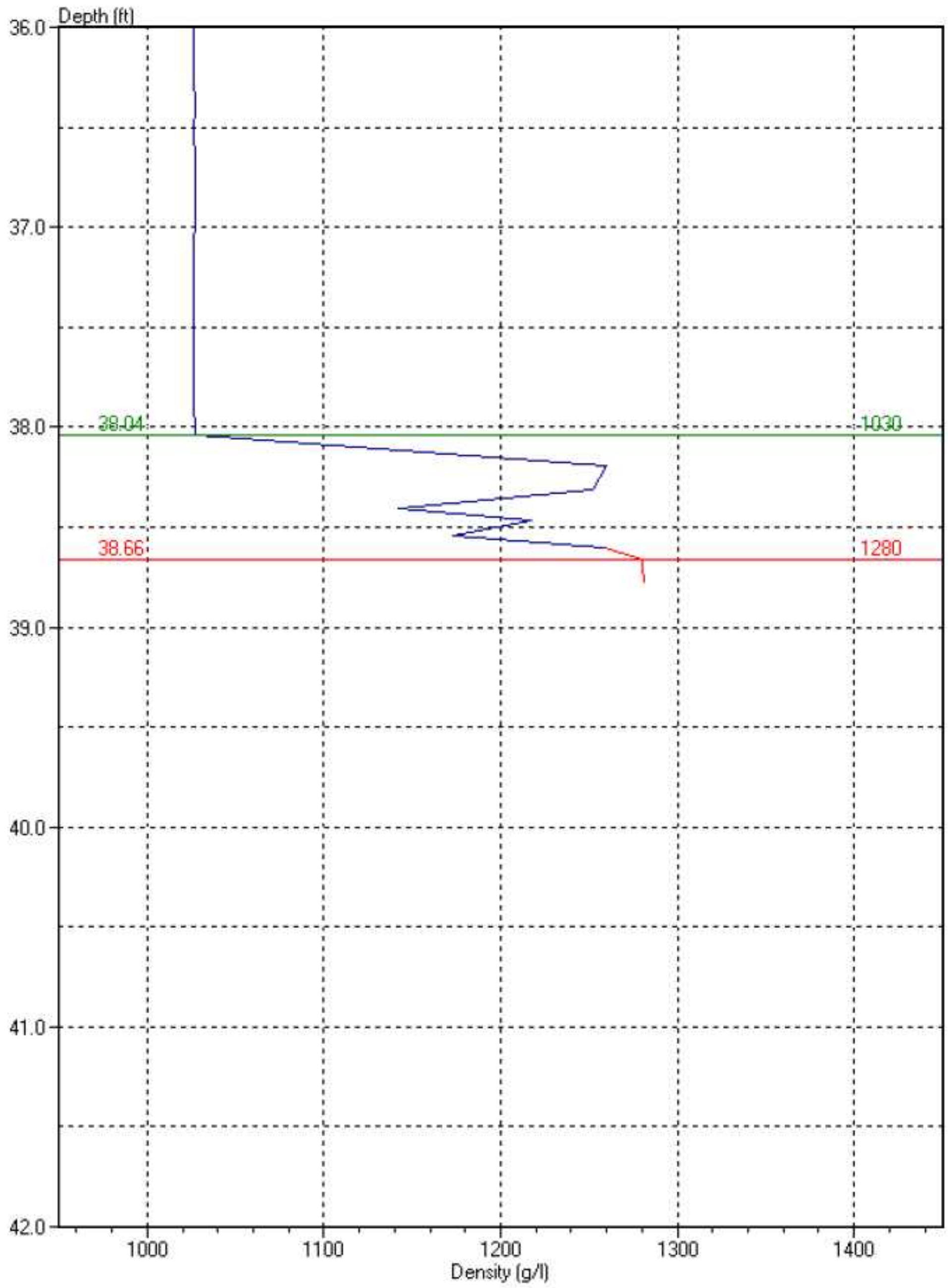
Max.Depth:39.59		Location:	6023105.75 X, 2163139.45 Y
DensiTune		Kp:	0.00 ft
Silt Density Probe		Date:	13-7-2004
STEMA Survey Services b.v.		Time:	17:01:50
Geldermalsen - The Netherlands		Tide:	3.10 ft

Density File: dp6.SDP STEMA DensiTune



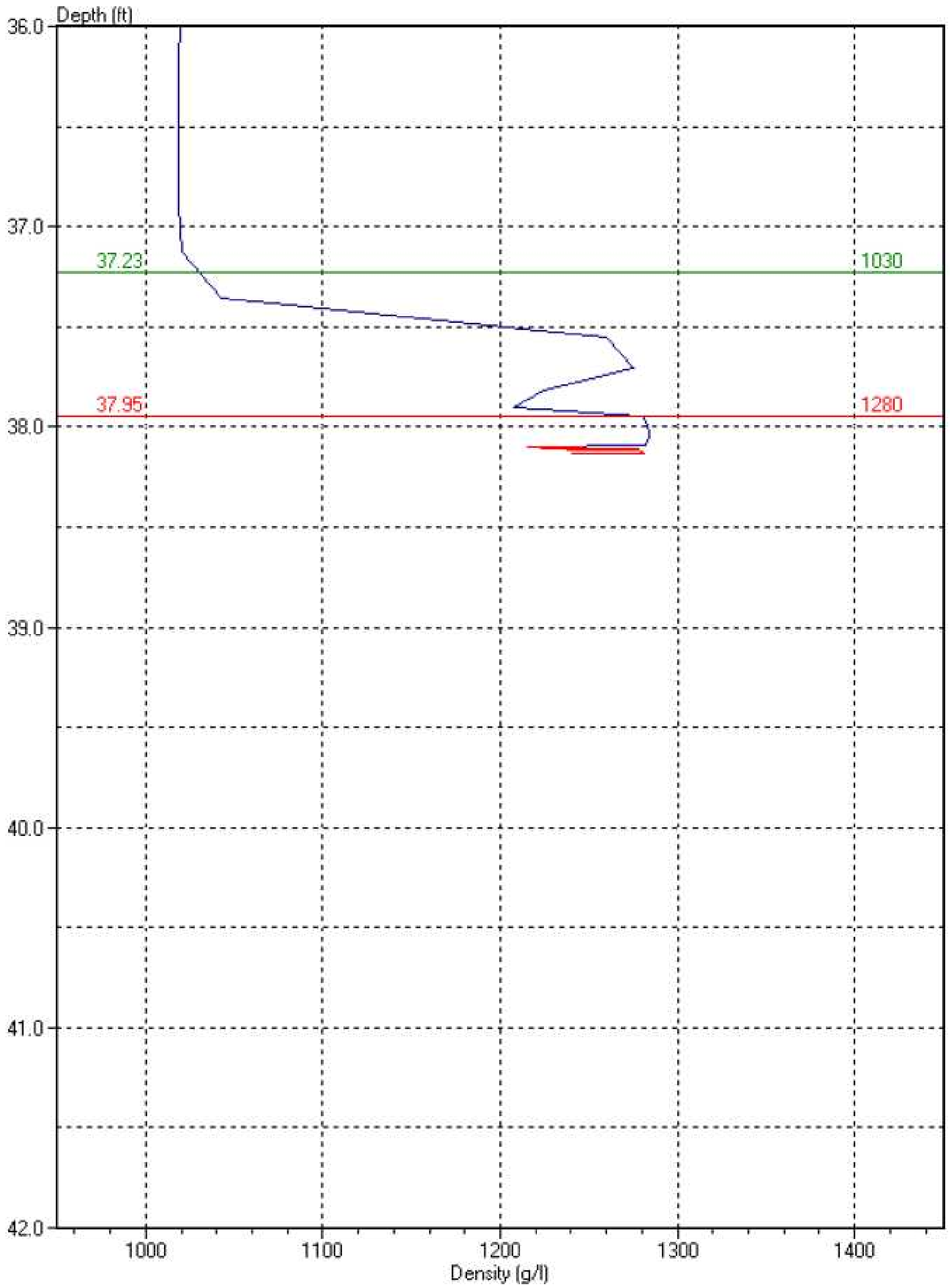
Max.Depth:39.75	Location:	6023098.96 X, 2163071.73 Y
DensiTune	Kp:	0.00 ft
Silt Density Probe	Date:	13-7-2004
STEMA Survey Services b.v.	Time:	17:06:45
Geldermalsen - The Netherlands	Tide:	3.30 ft

Density File: dp7d.SDP STEMA DensiTune



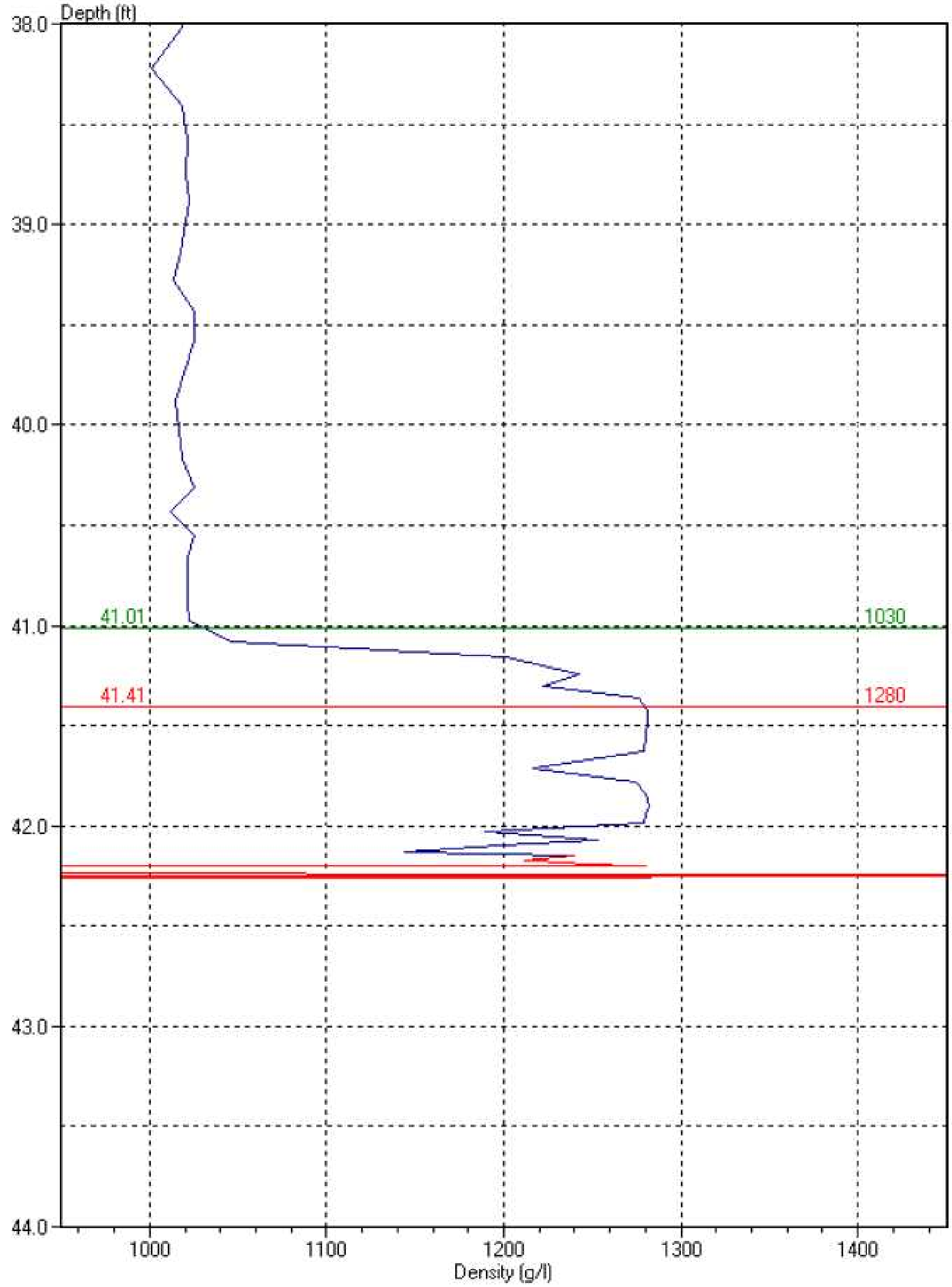
Max.Depth:38.78		Location:	6023093.73 X, 2163018.77 Y
DensiTune		Kp:	0.00 ft
Silt Density Probe		Date:	13-7-2004
STEMA Survey Services b.v.		Time:	17:23:34
Geldermalsen - The Netherlands		Tide:	3.40 ft

Density File: dp8.SDP STEMA DensiTune



Max.Depth:38.13		Location:	6023088.70 X, 2162966.40 Y
DensiTune		Kp:	0.00 ft
Silt Density Probe		Date:	13-7-2004
STEMA Survey Services b.v.		Time:	17:25:52
Geldermalsen - The Netherlands		Tide:	3.50 ft

Density File: dp9b.SDP STEMA DensiTune



Max.Depth:42.26	Location:	6023091.55 X, 2162876.83 Y
DensiTune	Kp:	0.00 ft
Silt Density Probe	Date:	13-7-2004
STEMA Survey Services b.v.	Time:	17:30:14
Geldermalsen - The Netherlands	Tide:	3.50 ft