SEAFLOOR MAPPING LAB
Institute for Earth Systems Science & Policy
California State University, Monterey Bay

100 Campus Center, Seaside CA 93955-8001 (831) 582-3529; FAX:(831) 582-3073

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Edwin Wendell Dean III
Student Research Assistant
Institute of Earth Systems Science & Policy
California State University, Monterey Bay

To Our Readers and the ESSP Faculty:

Elkhorn Slough is one of the largest remaining coastal marshes in California. In the middle of the last century, the Army Core of Engineers breached the mouth of the Slough to create Moss Landing Harbor. Since then, Elkhorn Slough has been directly subjected to tidal flow. This twice-daily rush of water through a relatively narrow channel has created tremendous erosion, or "tidal scour". The erosion endangers the habitat of several rare and endangered species, disrupts the wetland ecosystem as a whole, and endangers human constructions, as well. It also threatens to have repercussions that extend far beyond the twenty-five hundred acres of the slough itself, endangering the Monterey Bay National Marine Sanctuary and the delicate, unique deep-water ecosystem of Monterey Canyon.

In 2001, the Seafloor Mapping Lab at CSUMB performed a sonar bathymetry survey of the Slough, using a wide-angle, multi-beam system that could "paint" wide swaths of the bottom and gather accurate depth information. After cleaning and processing this data, I compared it to a bathymetry survey conducted in 1993, to determine the extent of erosion—or in some areas, deposition—over that eight-year span.

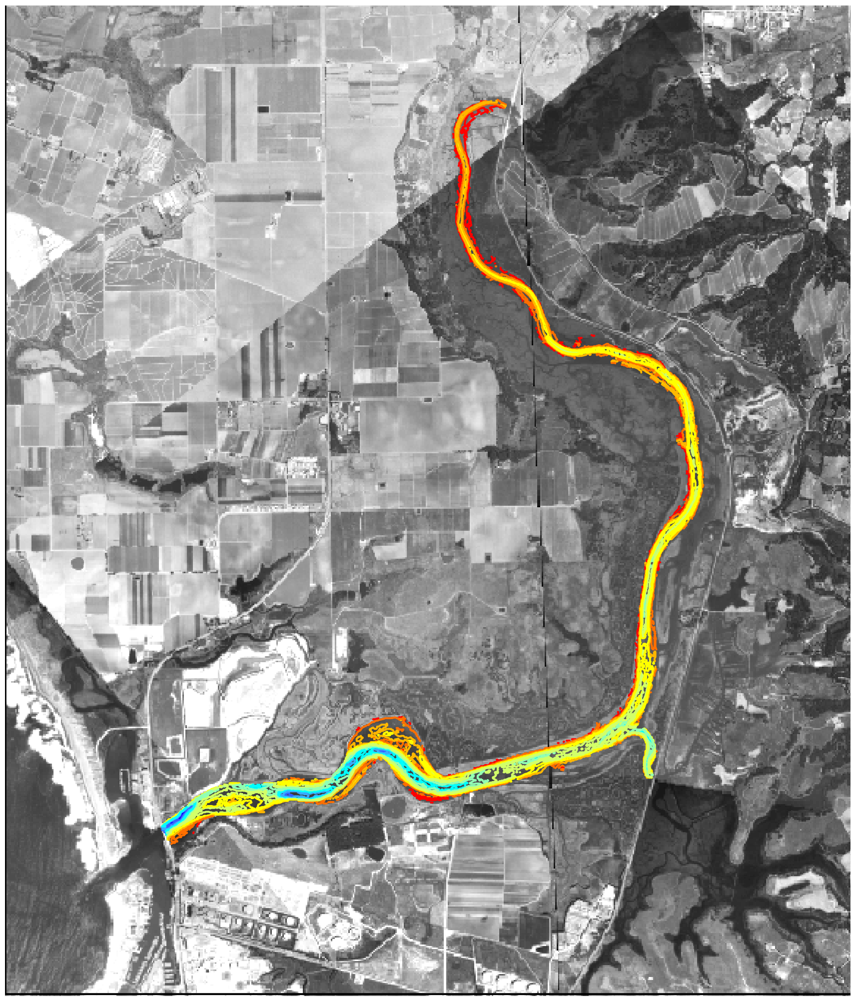
I am preparing this capstone assessment in the areas of *Application of Knowledge in the Physical and/or Life Sciences* (MLO #3) and *Acquisition, Display and Analysis of Quantitative Data* (MLO #5). The discussion of the mechanics of tidal scour and its impact on mudflat ecosystems will satisfy MLO #3, while the creation of the bathymetry model and the comparison of the data set to data gathered in previous years will fulfill MLO #5.

Thank you for your time and attention. I hope you find this exploration of Elkhorn Slough as engrossing as I have.

Sincerely,

Edwin Wendell Dean III

Tidal Scour in Elkhorn Slough, California: A Bathymetric Analysis



A Capstone Project
Presented to the Faculty of Earth Systems Science & Policy
in the
Center for Science, Technology and Information Resources
at
California State University, Monterey Bay
in Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science

By
Edwin Wendell Dean III
07 May 2003

Abstract

In 1946, the Army Corps of Engineers cut through the sand dunes at Moss Landing to create Moss Landing Harbor. Since that time, Elkhorn Slough, one of the largest remaining coastal wetlands in California, has been directly subjected to tidal flow. This twice-daily rush of water through a relatively narrow channel has created tremendous erosion, or "tidal scour". The erosion endangers the habitat of several rare and endangered species, disrupts the wetland ecosystem as a whole, and endangers human constructions.

To manage the region effectively, resource management agencies need to know how far the slough is from equilibrium. The purpose of this project was to determine whether or not the patterns of erosion and deposition have changed since the survey conducted in 1993 by Christopher Malzone. To answer this question, I tested the following hypotheses:

- Erosion in the slough slowed between 1993 and 2001.
- Erosion in the slough remained unchanged between 1993 and 2001.
- Erosion in the slough accelerated between 1993 and 2001.
- The spatial pattern of erosion and deposition changed between 1993 and 2001.
- The spatial pattern of erosion and deposition remained unchanged between 1993 and 2001.

In 2001, the Seafloor Mapping Lab of California State University, Monterey Bay created a detailed bathymetry model of the Slough using multi-beam sonar. Using advanced Geographic Information Systems (GIS) applications, I compared this model to data gathered in previous surveys.

Despite a probable depositional event in 1995, Elkhorn Slough continues to show high rates of overall erosion. Between 1993 and 2001, mean cross-sectional area increased by 24% and maximum depth increased from 6.5 m to 8.0 m. Approximately 0.45 x 10^6 m^3 of material eroded from the survey area, an average erosion rate of 3% of the slough's volume per annum. Most of this erosion occurred in the regions downstream of Parson's Slough. Moderate erosion occurred in the middle slough. Only at the head of the slough, near Hudson's Landing, showed significant deposition.

The most severe erosion occurred at the mouth of Parson's Slough. This narrow channel experienced a depth increase of almost three meters. Mean cross-sectional area more than doubled, increasing by 119%, and the average erosion rate for this region of the slough system was 15% per annum.

Acknowledgements

I would like to thank my capstone advisor, Dr. Rikk Kvitek, for his enduring patience, encouragement and good advice, for offering me the opportunity to explore Elkhorn Slough in the first place, and for letting me play with some really cool toys. I would also like to thank Pat Iampietro, for keeping those toys working, and Kate Thomas, for stepping in as crew when I had the poor timing to injure myself two days before a survey run.

Most of all, my heartfelt thanks go to my wife, Terry Lee Dean, without whose support, confidence and love I could not have seen this project through.

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Introduction

In the closing years of the twentieth century, the importance of wetland habitats became a matter of public awareness. A growing body of work made it clear that these areas once dismissed as "useless swamps" were active, productive biomes that supported large populations of migratory birds, cleaned and filtered water, and performed a host of other key services within the global ecosystem. Decades of development, however, had drained, diked and filled wetlands across the United States and the rest of the world. California alone has lost between 75% and 90% of its coastal wetlands to such "reclamation"(Silberstein 1989, Crampton 1993).

Elkhorn Slough, one of the last and largest remaining coastal marshes in California, sits almost exactly in the middle of the Monterey Bay coastline, a hundred miles south of San Francisco. It contains a wide range of wetland microhabitats that support many unusual and endangered species. It supports more than 250 species of birds, some migratory, others year-round residents. It also supports a great deal of human activity: its watershed includes thousands of acres of farmland, its outer harbor supports an active fishing industry, and for several decades, one of the largest fossil-fueled power plants in California has loomed over its southern shore. Despite this significant human presence, it remains a vital ecological keystone, protected by the California Coastal Commission and,

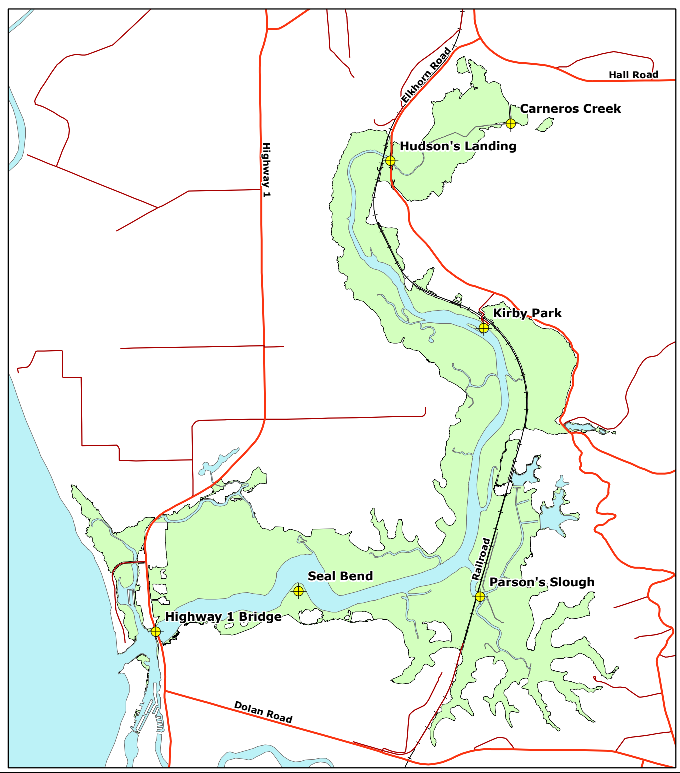

Figure 1. Elkhorn Slough main channel, wetlands, and prominent landmarks.

as the Elkhorn Slough National Estuarine Research Reserve (ESNERR), by federal authorities. The waters of the slough also fall within the boundaries of the Monterey Bay National Marine Sanctuary, providing further federal protection (Silberstein 1989; Christensen 2001; CCC 2002).

Since the opening of Moss Landing Harbor in 1946, Elkhorn Slough has been directly subjected to tidal flow. This twice-daily rush of water through a relatively narrow channel has created tremendous erosion, or "tidal scour". The erosion endangers the habitat of several species, disrupts the wetland ecosystem as a whole, and threatens human constructions.

Site History

Elkhorn Slough sits at the head of the Monterey Submarine Canyon. It was formed when the end of the last glacial epoch caused a rise in sea levels that submerged a former river valley. Sediment filled the valley, forming mudflats and a salt marsh (Silberstein 1989; Crampton 1994; Malzone 1999). For 8,000 years, sediment accumulated steadily.

For more than four thousand of those years, *H. sapiens* has lived in vicinity of the slough. Each successive wave of human habitation left a deep mark on the land. The Ohlone Indians used fire to keep the coastal scrub from overrunning the grasslands where the animals they hunted grazed. The Spanish brought cattle and non-native plants. American farmers and ranchers drained parts of the surrounding marshlands for agriculture and grazing. In 1872, the Southern Pacific Railroad ran a major rail line through the slough region, with a bridge crossing over the narrow mouth connecting Parson's Slough to Elkhorn's main channel and another at Hudson's Landing, at the slough head (Silberstein 1989; PWA 1992). In the last century, however, we have engaged in large-scale engineering projects that have changed the slough's character even more dramatically.

Before 1910, the Salinas River was an integral part of the Elkhorn Slough system. Its channel took a sharp turn to the north just before reaching the coast and skirted the coastline, the high beach dunes forming its western bank. It flowed north to join with Elkhorn Slough, the combined waters exiting half a mile to the north of the slough's main channel. In 1910, however, the dunes were cut through, diverting the river directly into the bay and depriving the slough of its major source of both fresh water and sediment (Silberstein 1989; PWA 1992; Roberson 2000). The connection with the open ocean was restricted, and tidal influence was small. Between 1910 and 1946, the system of dikes and levies became more extensive, turning more marshland into pasture, and salt ponds were constructed near the slough mouth, on the northern shore (PWA 1992).

In the years before and during the Second World War, the Monterey Bay fishing industry increased dramatically. The limited harborage along California's central coast hampered this burgeoning enterprise. Economic pressures led to political pressures, and, in 1947, the Army Corps of Engineers (COE) dredged part of the Salinas River channel and cut across the sandbar that blocked the mouth of the slough, creating Moss Landing Harbor. While the original proposal called for tide gates at the Highway 1 bridge, these were not installed. This exposed the main channel of the slough directly to the ocean and tidal flushing (Smith 1973; PWA 1992; Crampton 1994; Malzone and Kvitek 1994ab; *et al.*).

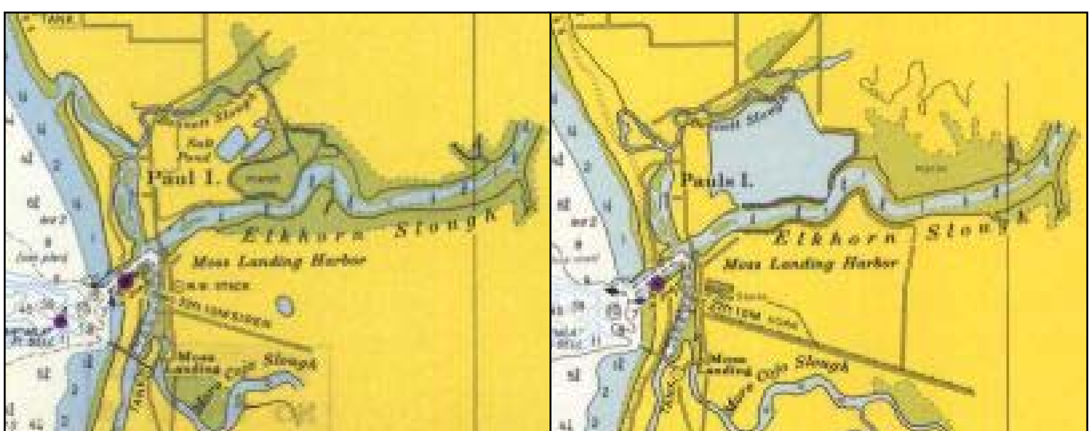

Figure 2. Elkhorn Slough in 1956 (left) and 1966 (right). Note the disappearance of the old river mouth.

Historical charts courtesy NOAA

Tides and Tidal Scour

The opening of the harbor dramatically altered the character of Elkhorn Slough. In his 1973 hydrology study, Richard E. Smith characterized the post-harbor Slough as a "seasonal estuary", noting that in the summer months, little fresh water entered the system. Records show that, during the summer, salinity levels in some parts of the slough frequently exceeds 40 parts per thousand, and can approach or exceed 100 ppt—more than three times the salt content of Bay water (Dean 2000).

This also dramatically increased the *tidal volume* of the slough: the volume of water moving back and forth through the system with every tide cycle. In less than half a century, the slough changed from a largely fresh-water regime dominated by deposition from the Salinas River and the surrounding watershed to a highly saline system characterized by tidally mediated erosion, an effect known as *tidal scour* (Crampton 1994).

Tidal scour increases as the tidal volume of a body of water increases: more water in motion carries away more sediment, creating a feedback loop between tidal volume and erosion. In Elkhorn Slough, other factors have exacerbated the increase in tidal volume caused by the erosion of the main channel and adjacent mudflats. In 1983, the low-lying fields of the Elkhorn Dairy adjacent to the slough were deliberately re-flooded as part of an ongoing wetlands restoration effort. This restoration, however, inadvertently resulted in the failure of the Parson's Slough levee, more than doubling the intended flooding and dramatically increasing the tidal volume of the slough by 30% (Malzone 1999). The Loma Prieta earthquake of 1989 appears to have caused the upper reaches of the slough to subside by about half a meter, increasing tidal volume (Malzone and Kvitek 1994ab). In 1995, however, the Pajaro River flooded, flowing back through Carneros Creek and into Elkhorn Slough. The population crash of the Caspian Tern colony that had established itself in the Reserve revealed that the flood had carried a load of DDT-laden sediments into the back slough (ESNERR 2001). This deposition could offset some of the detectable erosion effects.

Tidal scour has progressively degraded slough habitats. Meter by meter, it eats away at the edges of the pickleweed (*Salicornia virginica*) marshes that outline most of the main channel. Eel grass (*Zostera marina*) currently covers only a fraction of its pre-harbor extents. Mudflats and shallows that harbored a host of burrowing species (Silberstein 1989) have become deep channels (Oliver 1989; Crampton 1994; Malzone 1999; Brantner 2001).

The human presence on Elkhorn Slough has felt the effects, as well. In the summer of 2002, the Union Pacific Railroad replaced the vintage 1946 railroad bridge at the mouth of Parson's Slough, where some of the fastest tidal currents flow. Tidal scour had severely undermined the old bridge, threatening a derailment that could have cost many lives and devastated the delicate ecosystems of both Elkhorn Slough and Monterey Bay (CCC 2002). Much of the sediment load from the slough settles in the Moss Landing Harbor, increasing the expense of harbor operation. The dredging operations to maintain the harbor dump the sediment, laden with DDT and other agricultural chemicals from decades of runoff, into the mouth of Monterey Canyon, which may endanger the sensitive and scientifically invaluable deep-sea ecosystem therein (ESNERR 2001; Mejia 2002).

Eventually, the slough will reach equilibrium in its new regime of erosion and deposition; however, we do not currently know how long it will take to reach that new equilibrium, or how much habitat will be lost in the process.

Prior Studies

The last 15 years have seen several quantified studies of Elkhorn Slough tidal scour. As an ongoing, dynamic process, the scour phenomenon requires regular surveys. Because of the rapid progression of technology during this period, each successive study has used increasingly sophisticated equipment, providing more precise and accurate data at increasingly high data densities. While later surveys yielded data sets several orders of magnitude larger than the earlier projects, the commensurate increase in computing power available allowed this data to be processed and analyzed quickly and efficiently.

In 1988, John S. Oliver *et al.* produced the first bathymetric study of erosion in Elkhorn Slough, using calibrated lines stretched across the slough to determine position along six widely spaced cross-sections. Depth was determined at 5 m intervals along these cross-sections using an unstated method—possibly a lead line. Historical maps, aerial photographs, and scuba divers provided further observational data. Oliver found that extensive erosion had occurred since the opening of Moss Landing Harbor, showing a six-meter increase in channel depth at the slough mouth and estimating a 250% increase in water volume between 1909 and 1988 in the forward slough.

In 1993, Todd Crampton revisited Oliver's study, following the original six cross-sections and adding three more. He used a hand-held Global Positioning System (GPS) to determine the location of the transect endpoints to an estimated accuracy of 30 meters. Electronic surveying gear was used to locate the survey boat with respect to these endpoints. A hand-held fathometer determined depth, again at 5 m intervals. Crampton estimated the total subtidal volume of the main Slough channel at approximately 2.35×10^6 m^3, and that 420,000 m^3 of material had eroded from the slough since 1988—a volume increase of about 22%. He further estimated that 1.61×10^6 m^3 of material eroded between 1946 and 1993, for a mean annual erosion rate of 3.4×10^4 m^3/yr.

Also in 1993, Chris Malzone and Rikk Kvitek used a boat equipped with a differential GPS (dGPS) unit and a single-beam sonar fathometer to conduct an even more detailed survey. The dGPS provided positional accuracy of 2 m. Their boat ran sixty-seven cross-sections along the main channel of the slough and another six across the mouth of Parson's Slough, taking depth readings every meter. In his 1999 thesis based in part on this survey, Malzone found an estimated erosion rate of 8.0×10^4 m^3/yr for the total slough system.

In early 2001, Jeremiah Brantner of the Seafloor Mapping Laboratory (SFML) at California State University, Monterey Bay (CSUMB) surveyed the main channel of the Slough in a boat equipped with a multi-beam sonar system capable of providing continuous bathymetry coverage, rather than just point data along cross-sections. The survey vessel also used Real Time Kinematic (RTK) GPS data, allowing a positional accuracy of 10 cm. The survey covered the main channel only from the Highway 1 Bridge to Kirby Park, but excluded the intertidal mud flats and the portion of the slough from Kirby Park to Hudson's Landing. Brantner calculated a loss of 4.66×10^6 m^3 of material from that region between 1993 and 2001, and an increase in channel volume of 15%.

Purpose and general approach

Resource management agencies face a dilemma regarding the decision to engineer a solution to the tidal scour and habitat loss in the slough. Several plans to mitigate tidal scour have been proposed (PWA 1992; Malzone and Kvitek 1994ab), but have fallen prey to questions of funding, jurisdiction, and conflicting conservation goals (Christensen 2001). Knowing the rate and extent of existing tidal scour, how close the process has come to equilibrium, and what the slough will look like once it has reached equilibrium will profoundly affect the range of options to consider. This project will provide these agencies with information they need to devise effective management strategies, and provide the basis for the construction of a hydrological model that will help planners to predict change.

The purpose of this project was to determine whether or not the patterns of erosion and deposition have changed since the survey conducted in 1993 by Christopher Malzone. To answer this question, I tested the following hypotheses:

- Erosion in the slough slowed between 1993 and 2001.
- Erosion in the slough remained unchanged between 1993 and 2001.
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- The spatial pattern of erosion and deposition changed between 1993 and 2001.
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Taking the Brantner 2001 data as a starting point, this project expanded the survey area to include the shallows of the main channel, the mouth of Parson's Slough, and the area extending upslough from Kirby Park to Hudson's Landing—the same area covered in 1993 by Malzone. It used data collected for the Brantner survey, additional multi-beam sonar bathymetry collected with the same vessel, and LIDAR (**Li**ght **D**etection **A**nd **R**anging) data collected by the NASA Airborne Topographic Mapper (ATM) in 1998. Using Geographic Information Systems (GIS) analysis, I compared the new survey data to the data recorded by Malzone and Kvitek in 1993.

The new bathymetric model will provide a baseline for future multi-beam surveys. Copies of the model and its associated data will be provided to the Elkhorn Slough Foundation, ESNERR, and Monterey Bay National Marine Sanctuary's Sanctuary Integrated Monitoring Network (SIMoN) project as a resource in future Elkhorn Slough policy decisions.

Methods

Data Collection

For this study, the SFML conducted bathymetry surveys on 07 July, 15 and 17 October, and 17 November 2001. The weather remained clear for all four of the survey days; however, it had rained for several days before the 17 Nov run. While the data collected on that day appeared unaffected, the influx of rainwater could have left a freshwater lens on the surface of the slough, changing the density of the water and affecting the sonar readings.

The SFML used Research Vessel *MacGinitie* to perform the surveys, a custom-built Sea Ark "Little Giant" with a 27' (~8.2 m) cathedral hull and a draft of only 16" (~40 cm). A RESON 8101 Multi-Beam Bathymetry Unit and Triton Elics International ISIS computer collected sonar data. The HYPACK hydrographic survey package from Coastal Oceanographics, Inc. provided survey planning and navigation. A Trimble 4700 Global Positioning System (GPS) provided primary positioning, using a Real Time Kinematic (RTK) base station set up near the overlook at the Elkhorn Slough visitor's center for greater accuracy. A ProBeacon differential GPS antenna and a pair of GPS Azimuth Measurement Subsystem (GAMS) antennae tracked the vessel's heading. A Position and Orientation System for Marine Vehicles (POS/MV) computer unit from TSS, Ltd. collected heave, pitch, and roll information from an Inertial Motion Unit (IMU). To compensate for changes in the speed of sound caused by differences in water density, a submersible SV+ sound velocity profiler from Applied Microsystems Limited collected sound-velocity profiles.

After each survey, I used CARIS Hydrographic Information Processing System (HIPS) to create a TIFF image file with associated geographic coordinates (GeoTIFF) of the area surveyed. I imported this into ESRI ArcView version 3.2 and created a DXF file that showed the areas of the slough not yet covered. We loaded these DXF files into the HYPACK navigation system to guide the subsequent survey runs. We intended to have the new survey overlap as much of the 1993 survey lines as *MacGinitie's* draft would allow.

Data Processing

After completing the survey, I imported the XTF files into the CARIS HIPS analysis package. HIPS combined the latitude, longitude, raw depth readings, vessel heading and motion data contained within these files with the SVP files recorded by the SV+, tide information taken from the *Tides & Currents* software by Nobeltec Nautical Software, and a vessel configuration file (VCF) that recorded the differences in position between the GPS antennae, the sonar head, and other sensor systems. While *Tides & Currents* provided different tide models for different locations in the slough, I found that using the Highway 1 tide model for the entire data set gave the most consistent results (See "Tide Anomalies and Survey Design" in ***Discussion***, below).

Filters applied to the combined and merged data removed low-quality returns, stripping the most obvious "noise" from the data set. I then used the Swath Editor in HIPS to further clean the individual lines by hand. Once the new data was combined with the survey of the fore-slough compiled in April of 2001 (Brantner 2001), I attempted to reconcile any differences between the lines using the Subset Editor in HIPS. I exported this combined, "clean" XYZ data set as a comma-separated database file in the Universal Transverse Mercator (UTM) coordinate system, Zone 10 North, using the 1984 World Geodetic System ellipsoid (WGS-1984) for the horizontal (XY) coordinates and recording the depth (Z) relative to the local Mean Low Low Water (MLLW) level as determined by the tide model.

Finally, I created images of the ensonified seafloor, exporting them as TIFF image files with associated geographic coordinates (TIFF/TFW) (See frontispiece).

GIS Analysis

After completing the processing, I imported the XYZ data and GeoTIFF into ArcView version 8.1, along with XYZ data and contour lines from the 1993 Malzone-Kvitek survey. The 1993 survey used a simple single-beam depth sounder and ran widely spaced survey lines perpendicular to the long axis of the main channel, creating depth profiles along regular cross-sections of the channel and mudflats. The deeper draft of *MacGinitie's* hull prevented us from venturing into the shallowest regions of the mudflats and shallows covered by the 1993 survey. Despite this, the multi-beam survey yielded a close-packed grid of points at a resolution of one meter or better—a quantity of data several orders of magnitude greater.

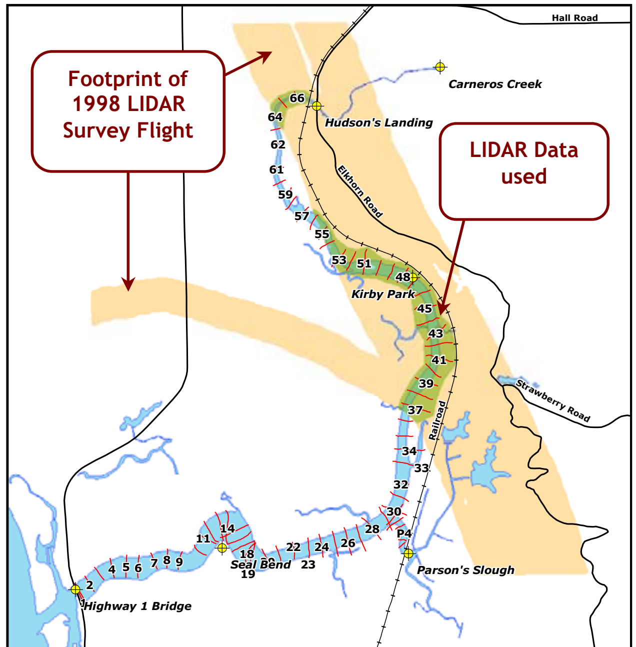


Figure 3. Elkhorn Slough Cross-Sections and LIDAR Extents

To enable a direct comparison between the 1993 and 2001 datasets, I drew a series of lines passing through each of the points of the 1993 survey lines. Using ArcView 8.1's ability to select the features of one data set that lie within a given distance to those of another, I selected those points from the 2001 data that fell within 0.15 meters of those lines (Figure 3).

- ### *Cross-Sections*

In ArcView 8.1, I selected the data points corresponding to each of the seventy-three cross-sections for each of the two surveys and pasted those points directly into Microsoft Excel spreadsheets, one spreadsheet for each section.

Since Elkhorn Slough follows a sinuous, twisting path through its watershed, attempting to describe one bank or the other as "north" or "south" leads to confusion. The "north" shore of the foreslough becomes the "west" shore of the midslough and the "south" shore in vicinity of Kirby Park. I therefore opted to designate the banks as "left" and "right", as seen from a boat traveling from the slough mouth toward Hudson's Landing at the head of the slough.

In Excel, I sorted the data points for each cross-section from "left" to "right", then designated the "leftmost" point as the Origin for that line. Using the Pythagorean theorem, I converted the UTM coordinates of each point to Distance From Origin (DFO). For each cross-section, I then co-plotted the 1993 and 2001 data sets with DFO as the X-axis and Depth along the Y-axis. This produced the series of charts showing superimposed 1993 and 2001 depth profiles for each cross-section. I have included the full set of cross-section profiles in the Appendix.

In the same set of spreadsheets, I conducted a Riemann Sum analysis to determine the change in Cross Section Area (CSA). I selected the portions of each bottom profile that overlapped the other. I then multiplied the difference in DFO values between each pair of adjacent points by the average of the depth values for those points, creating a series of rectangular areas. Adding these areas together gave me an approximation of the total area of the cross-section in each of the two survey years. From this, I determined the total change in area for that cross-section (ΔCSA) and the percentage change relative to the 1993 CSA.

- ***Thalweg and Volume***

From the cross-section spreadsheets, I found the deepest points along each cross-section from both the 1993 and 2001 data sets. I then pasted these points into the same spreadsheet template that I used to create the cross-sections to create thalweg lines for each survey year. Because of the sinuosity of the slough channel, I did not measure distance to each point from an arbitrary origin;

rather, I measured the distance from the lowest point in the previous cross-section, creating a chain of line segments. I then plotted the 1993 and 2001 data sets with Distance Along Thalweg as the X-axis and, again, Depth along the Y-axis, showing the thalweg profiles superimposed over each other.

To determine channel volume, I used an end-area method identical to that used by Crampton in his 1994 study. I averaged the cross-sectional areas of consecutive cross-sections and multiplied that value by the distance between cross-sections. I then summed the values for the entire slough and for the individual slough zones for each of the two survey years. Using these values, I determined the percentage of the total survey volume for each slough zone for each survey year, the increase in volume for the survey area and each zone from 1993 to 2001, the percentage increase relative to the 1993 volume, and the percent of total change accounted for by each zone.

- ***LIDAR (Light Detection And Ranging) Integration***

In 1998, the United State Geographical Survey (USGS), the National Aeronautics and Space Administration (NASA), and the National Oceanic and Atmospheric Administration flew the NASA Airborne Topographic Mapper (ATM) sensor over part of Elkhorn Slough as part of their ongoing Airborne LIDAR Assessment of Coastal Erosion (ALACE) project (Reference). The agencies made this data freely available over the Internet. While it did not cover the entirety of the slough, the portions that it did cover included large regions of otherwise-inaccessible mudflats (Figure 3).

The data set used the UTM Zone 10 N coordinate system and the WGS-1984 ellipsoid for the horizontal (XY) coordinates. For the vertical coordinates, however, it used the North American Vertical Datum for 1988 (NAVD-88), requiring a conversion to determine the height with respect to MLLW. In the Elkhorn Slough area, NAVD-88 lies above the MLLW mark—however, the separations vary from place to place.

Accessing the tidal benchmarks available on the USGS web site (Reference), I found that most of them referred only to the National Geodetic Vertical Datum of 1929 (NGVD-29). Seven reference points had values for NAVD-88, however: two associated with the Elkhorn benchmark, near the mouth of Parson's Slough, and five associated with the Railroad Bridge benchmark, at the head of the slough.

Taking the mean of the separation between NAVD-88 and MLLW for these seven points yielded a value of 0.064 meters ± 0.0066 meters. Since the standard deviation was much smaller than the precision of the instruments involved, I simply applied the mean value as a correction factor.

The cross-section profiles in the Appendix include the corrected LIDAR where available. While it cannot penetrate water deeper than a few centimeters, it provides coverage over mudflats that *MacGinitie* could not reach. Because of uncertainties in the conversion from NAVD-88 to MLLW, however, I did not include it in my mathematical analyses.

- ***Raster Analysis: Erosion/Deposition Map***

Using ArcView 8.1's Spatial Analyst extension, I created raster grids of both the 1993 and 2001 bathymetry data. 8.1's processing algorithms created dramatic anomalies when attempting to interpolate the low-density 1993 data across the complex convolutions of the slough channel—including a point at the west end of Seal Bend that spiked 12 meters above the water surface. Because of this, I defined the boundary of the 1993 grid as a series of stripes, 20 m wide, centered along each 1993 survey line.

I then used the Raster Calculator to subtract the 2001 depth values from the 1993 depth values in all overlapping pixels, assigning a negative value to net erosion and a positive value to net deposition. Color-coding these values let me quickly identify "hot spots" of erosion and deposition.

Results

Tidal scour continues to erode Elkhorn Slough. The sediment deposited in the Pajaro River flood of 1995 has had little impact on the overall high rate of erosion. Between 1993 and 2001, the mean CSA of the main channel increased by 16%. Including the Parson's Slough mouth in the calculations raises that mean to 24%. I calculated a 21% increase over the 1993 volume: an increase in slough volume of 4.48×10^5 m^3, or an average value of 5.60×10^4 m^3 over eight years. While this value is lower than Malzone's prediction of 8.0×10^4 m^3/yr, the Malzone value included shoals, mudflats, the tidal channels in the *Salicornia* marshes, the inundated salt ponds, and the portions of Parson's Slough east of the railroad bridge.

Elkhorn Slough, however, does not behave as a simple, uniform system. Different parts of the slough experience different conditions of flow and runoff, making it difficult to make meaningful statements about any but the most general erosion effects on the slough as a whole. My initial examination of the data suggested distinct patterns across different regions between the slough mouth and the slough head.

Malzone divided the slough into four areas, based on distance from the mouth of the slough: the lower slough (0 to 2500 m), middle slough (2501 to 8600 m), upper slough (8600 m to 10 km), and Parson's Slough (Malzone 1999, p. 21). With access to higher resolution data and greater processing power, I found more detailed structural and erosional patterns within those areas. The slough nearest the Highway 1 bridge had characteristics very different from those of Seal Bend, though Malzone included both areas in the "lower slough". The section running from Seal Bend to the mouth of Parson's Slough had little in common with the rest of Malzone's "middle slough".

Those first three areas divided the cross-sections from the 1993 survey into three groups of ten. Since I had a large number of cross-sections to process, I divided the rest of the main channel into groups of ten as well. Although structure and erosion changed more gradually in the upper slough, I found that the changes occurred sufficiently close to the ten-cross section mark to make those groups useful units of analysis.

This approach created eight zones, using prominent landmarks as reference points: the Foreslough (Highway 1 to Seal Bend), Seal Bend, Seal Bend to Parson's Slough, Parson's Slough, two zones in the Midslough (Parson's Slough to Kirby Park), and two in the Back Slough (Kirby Park to Hudson's Landing) (Figure 4).

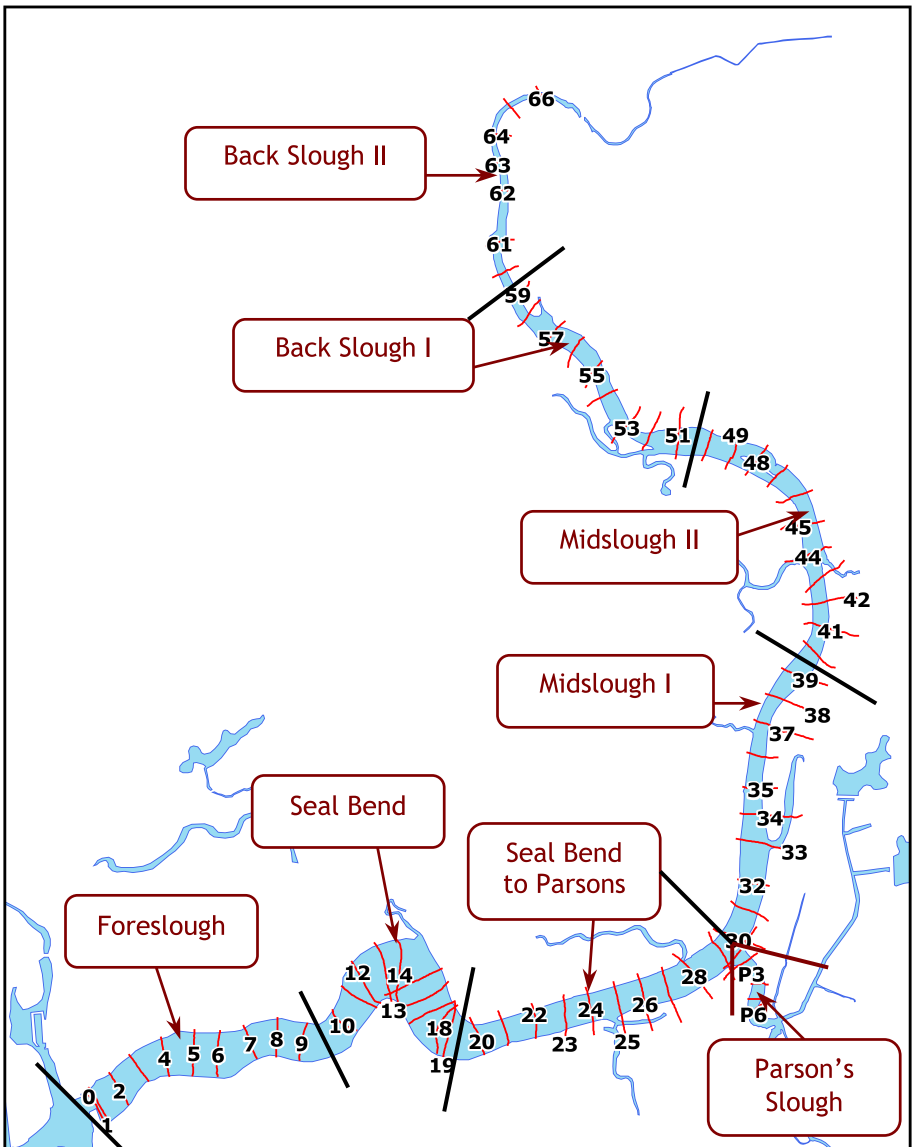


Figure 4. Elkhorn Slough Survey Zones

Slough Overview

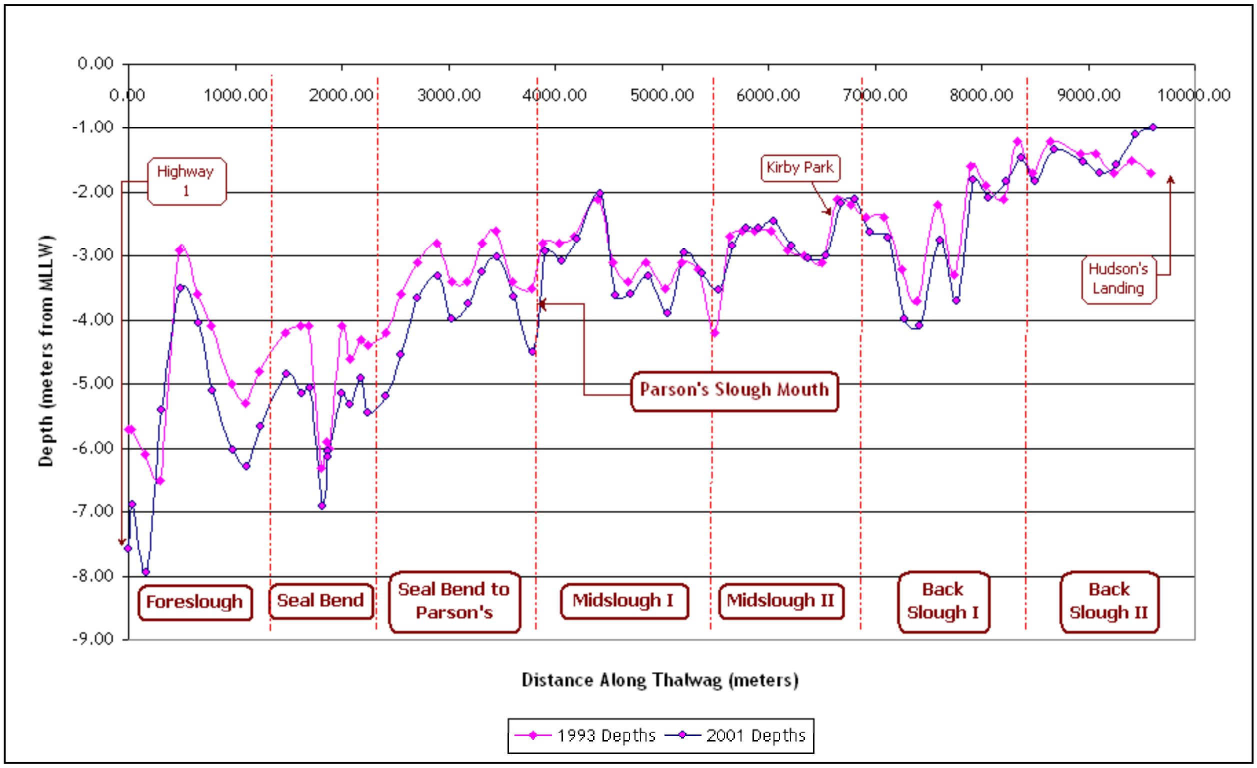


Figure 5. Elkhorn Slough Thalweg: 1993 and 2001

Figure 5 shows changes in depth along the thalweg. Since Parson's Slough is technically a side channel, its depth values are not shown. However, its presence makes itself known. While the portions of the main channel upstream of the Parson's Slough Mouth experienced relatively small changes in maximum depth between 1993 and 2001, the downstream part of the slough grew much deeper, steepening the depth gradient.

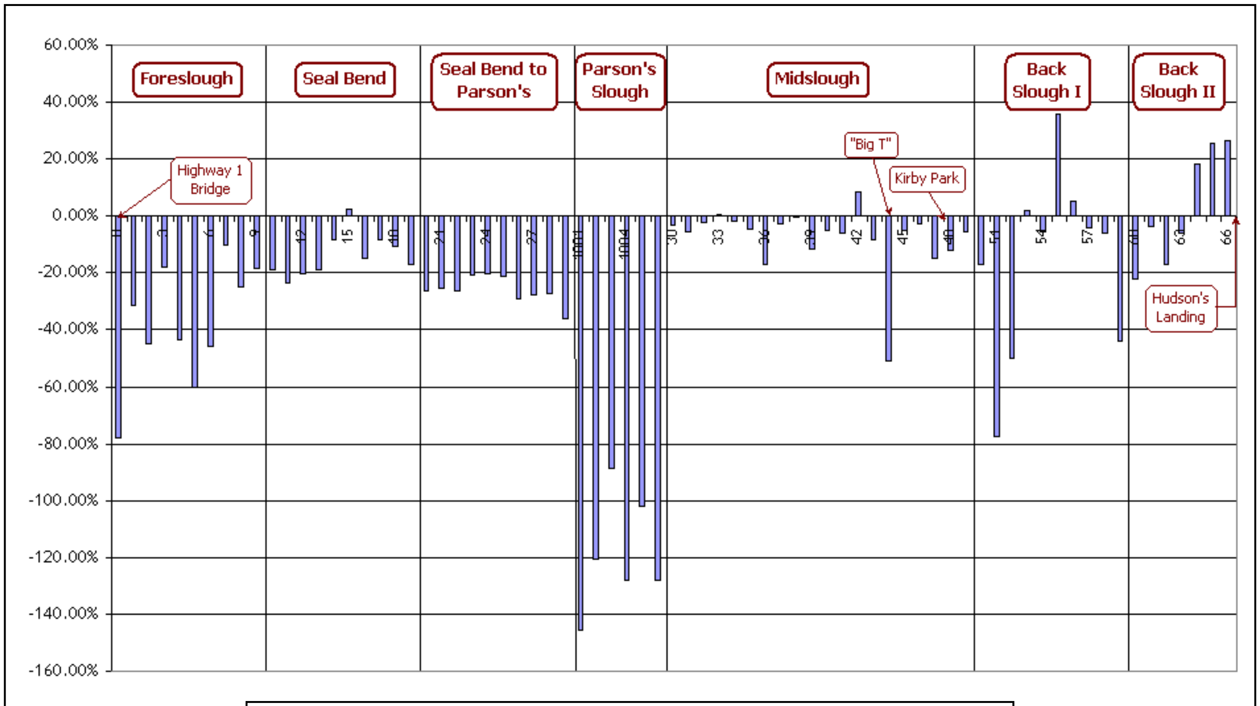


Figure 6: % Change in Cross Section Area
Expressed as a percentage of the 1993 CSA

When the percentage change in cross section area is graphed, similar patterns emerge (Figure 6). The foreslough and the region between Seal Bend and Parson's show large, consistent increases in CSA. Seal Bend is less consistent than its neighbors, but more so than the zones upstream of the slough. The upstream regions tend to small levels of erosion, with occasional spikes of erosion or deposition.

The mouth of Parson's Slough forms a clear dividing line between the high levels of downstream scour and the more erratic patterns upstream—and itself shows the most dramatic erosion of the survey area.

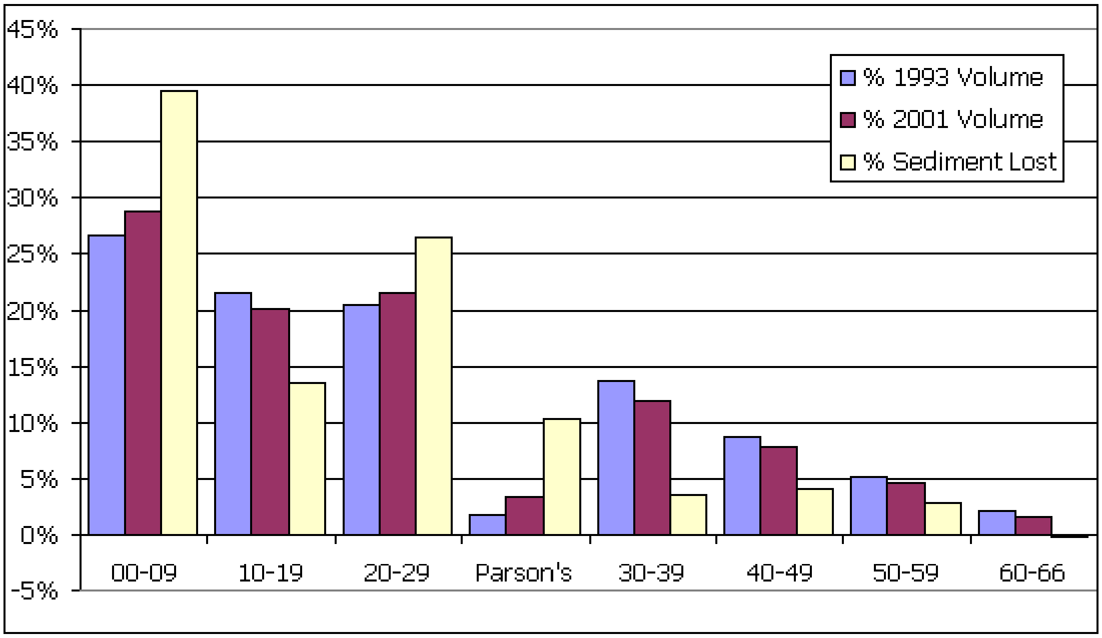


Figure 7. Percentage of total survey volume at MLLW in each zone and percentage of total sediment lost between 1993-2001.

Figure 7 shows the percentage of the total slough volume in each zone for 1993 and 2001, and the percentage of total sediment lost between those years. The distribution of total slough volume changed very little. About 70% of the volume in the survey region lies downstream of Parson's Slough, and those zones account for 80% of the sediment volume lost between 1993 and 2001. In the main channel, the percentage of sediment lost from each zone is roughly proportional to its percentage of total survey volume. The mouth of Parson's Slough, however, accounted for a far greater percentage of sediment loss than its percentage of the overall volume would suggest.

In the following sections, I discuss the different slough zones in detail. Each section begins with an aerial photograph taken in 2000, showing the zone at MLLW. The Erosion/Deposition Raster and color-coded contour lines a superimposed over this, along with outlines of the 1993 and 2001 survey extents. I then present a table showing changes in the area of each cross-section in the zone, and another summarizing volume and volume changes for the entire zone. A brief discussion follows.

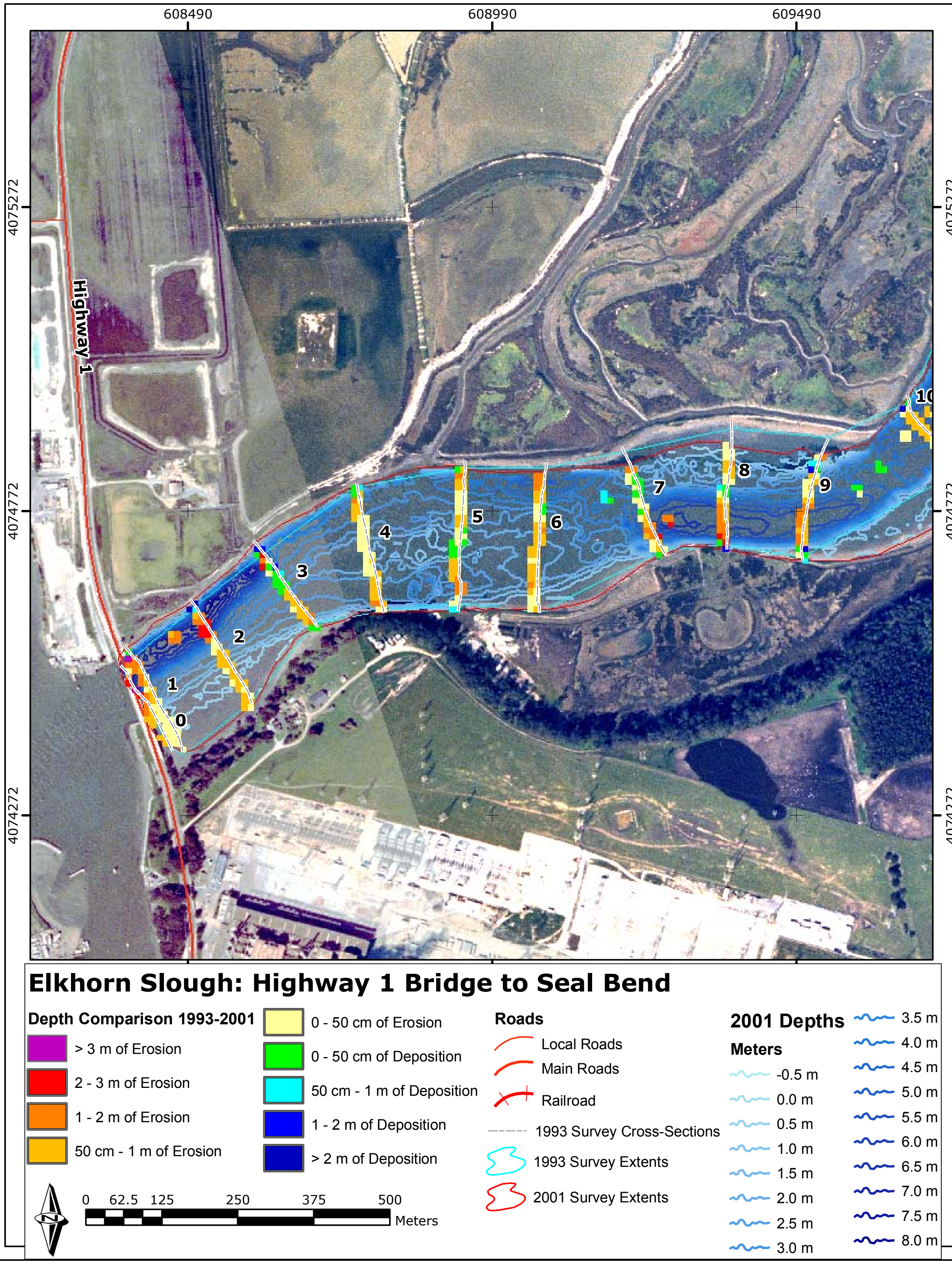


Figure 8. Foreslough: Highway 1 Bridge to Seal Bend (Cross-Sections 00-09).
2000 Aerial Photograph taken at MLLW. Courtesy ESNERR.

Foreslough: Highway 1 to Seal Bend (Cross-Sections 00-09)

Table 1: Change in Cross-Section Area—Highway 1 to Seal Bend

Cross Section	1993 CSA (m^2)	2001 CSA (m^2)	ΔCSA (m^2)	% Change in CSA
00	237	422	-184	-78% Erosion
01	321	422	-101	-31% Erosion
02	365	529	-164	-45% Erosion
03	362	428	-66	-18% Erosion
04	319	458	-139	-44% Erosion
05	339	542	-203	-60% Erosion
06	375	546	-171	-46% Erosion
07	467	514	-47	-10% Erosion
08	452	564	-112	-25% Erosion
09	449	531	-82	-18% Erosion
			Mean	-37% Erosion
			Std Dev	21%

Table 2: Volume—Highway 1 to Seal Bend

1993		2001		Change		
Volume m^3	% Total	Volume m^3	% Total	Volume m^3	% Change	% Total
5.6×10^5	27%	7.4×10^5	29%	-1.8×10^5	-31%	39%

Depths in the foreslough reach or exceed eight meters, making it the deepest part of the slough. The deepest portions fall within 350 meters of the Highway 1 Bridge, and form a channel that runs along the left (northwest) bank. The left shore is steep, almost vertical in places, while depths decrease more gradually to right, creating a broad band of shallows. Further from the bridge, the thalweg shallows somewhat. About a kilometer upstream, it abruptly shifts to the right (south) bank, creating another region of deep water just before the first northward twist of Seal Bend.

The foreslough was the largest and deepest region in the survey area, accounting for 29% of the total 2001 volume, and experienced the greatest quantity of sediment loss: 1.8×10^5 m^3. That volume accounts for 39% of the total calculated sediment loss. The mean CSA of this area increased by 37%, a greater proportional increase than any zone other than the mouth of Parson's Slough.

The most severe erosion occurred along the thalweg—a depth increase of 2 meters or more in the portions close to the Highway 1 Bridge. The channel shifted, deepened and widened, cutting into the banks and the *Salicornia* marshes along them. Where the deep channel approaches the banks most closely, the 2001 survey boundary actually extended further than the 1993 data set, despite *MacGinitie*'s greater draft. The shallows and mudflats also experienced erosion. In some places, wide areas dropped half a meter in depth.

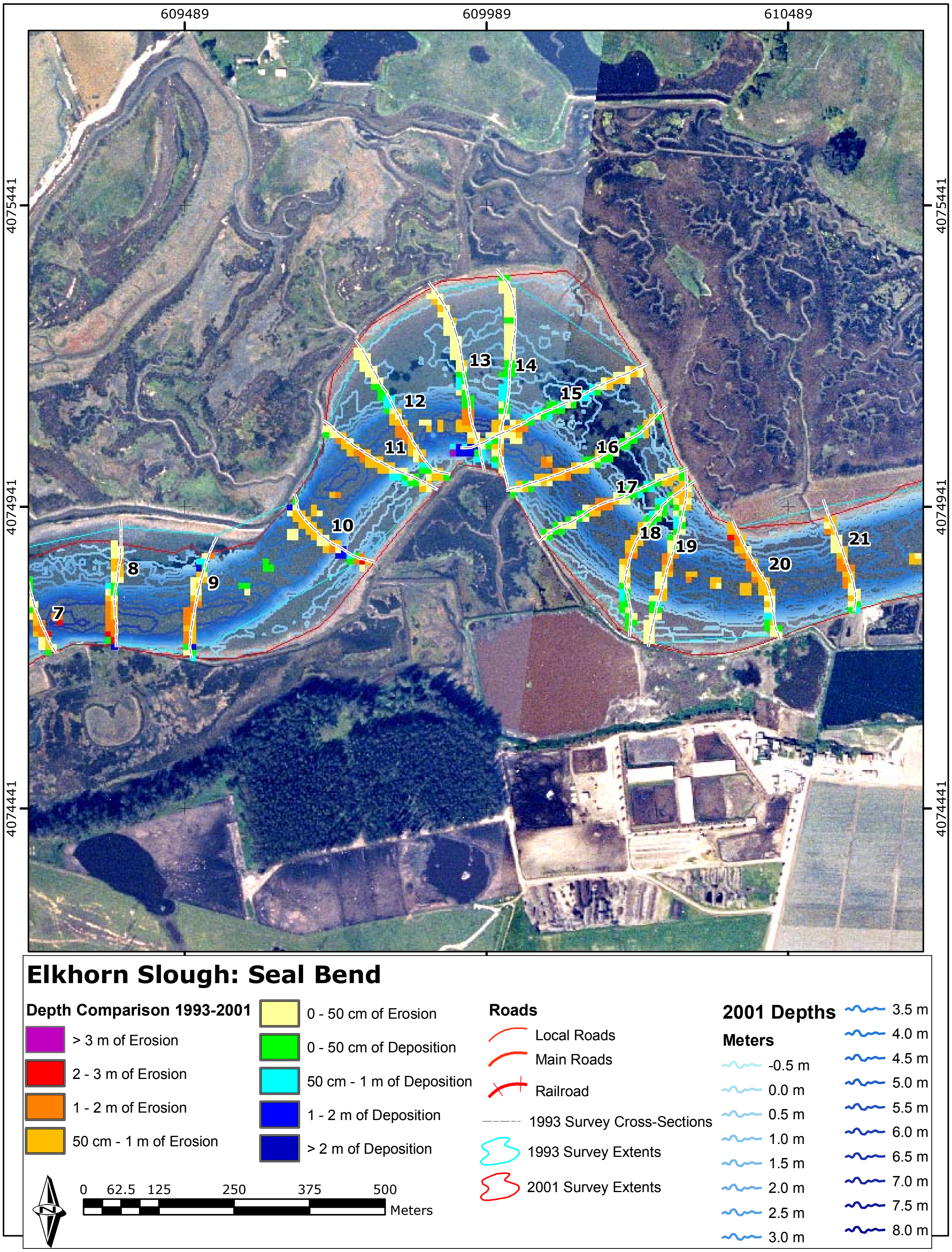


Figure 9. Seal Bend (Cross-Sections 10-19).
2000 Aerial Photograph taken at MLLW. Courtesy ESNERR.

Seal Bend (Cross-Sections 10-19)

Table 3: Change in Cross-Section Area—Seal Bend

Cross Section	1993 CSA (m^2)	2001 CSA (m^2)	ΔCSA (m^2)	% Change in CSA
10	380	451	-71	-19% Erosion
11	447	552	-105	-23% Erosion
12	460	554	-94	-20% Erosion
13	522	621	-99	-19% Erosion
14	586	634	-48	-8% Erosion
15	**686**	**670**	**+16**	**2% Deposition**
16	498	572	-74	-15% Erosion
17	516	558	-42	-8% Erosion
18	476	526	-50	-11% Erosion
19	453	531	-78	-17% Erosion
			Mean	-14% Erosion
			Std Dev	8%

Table 4: Volume—Seal Bend

1993		2001		Change		
Volume m^3	% Total	Volume m^3	% Total	Volume m^3	% Change	% Total
$4.6x10^5$	22%	$5.2x10^5$	20%	$-6.0x10^4$	-13%	13%

Seal Bend is a sharp oxbow in the middle of the west-east leg of the slough, so named for the pinnipeds that once basked on the mudflats along the right-hand shore. When those mudflats eroded away, the harbor seals and sea lions relocated to the left bank. As the slough course shifts from left to right, the thalweg shifts between the left bank and the right, with broad areas of shallows leading to the opposite shore. Seal Bend reaches 7 m at its deepest point, an abrupt drop near the right bank where the oxbow bends most sharply. A prominent crescent of shallows dominates the Bend's northernmost curve and provides a convenient habitat for eel grass. While *Zostera* occurs elsewhere in the slough, the false echoes created by the thick growth in Seal Bend combined with the shallow water conditions to limit *MacGinitie's* multi-beam sonar to a very narrow swath. In the shallowest parts of the Bend, coverage narrowed almost to the point of single-beam sonar (Figure 10).

In 2001, Seal Bend had a calculated volume of 5.2×10^5 m^3—20% of the total surveyed. It lost 6.0×10^4 m^3, accounting for 13% of the total calculated sediment loss.

Once again, the most severe erosion in this zone occurred along the thalweg, with depths increasing up to a meter at the deepest points. The profiles clearly showed erosion of the right bank, and the 2001 survey boundary extended further to the left, indicating erosion along that bank as well. In the shallows, new shoals created from eel grass-trapped sediment punctuated a general trend of low-level erosion. In short, the deeps got deeper, and the shallows, wider.

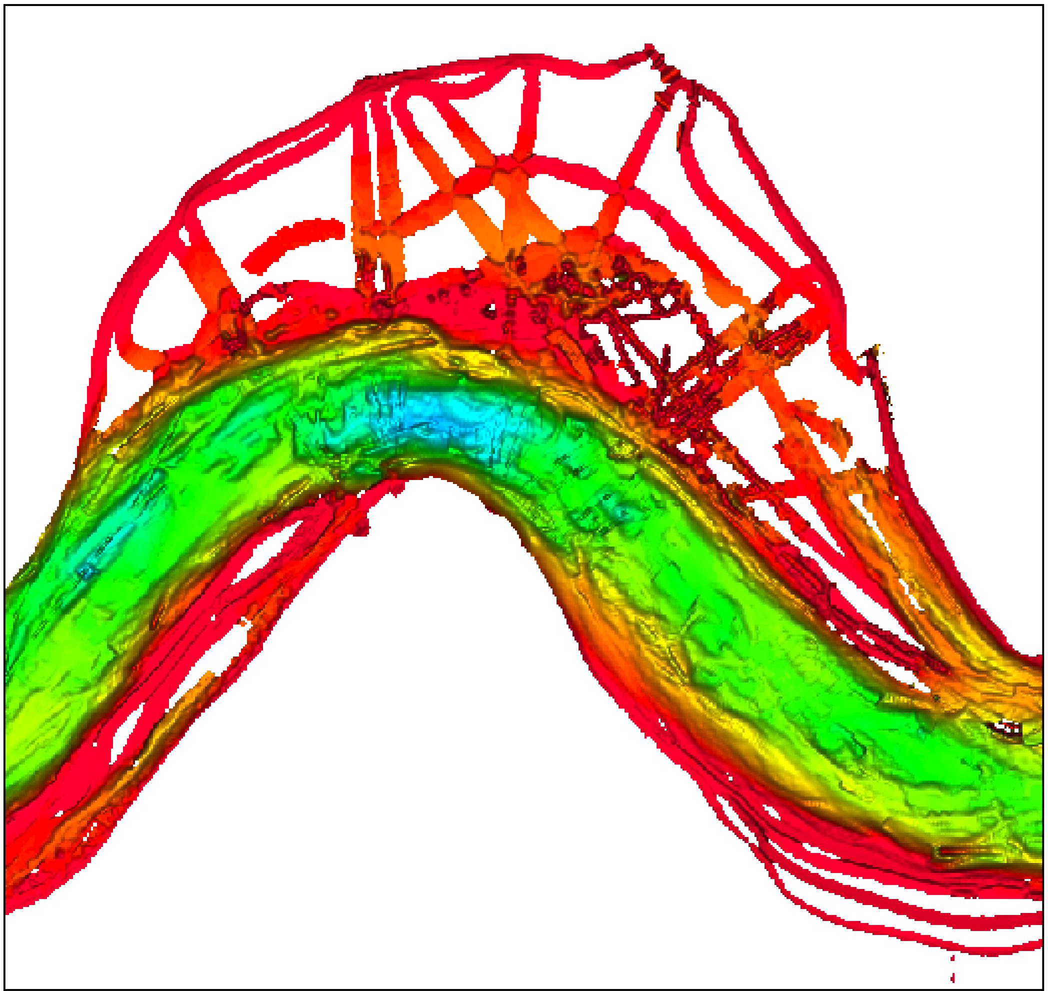


Figure 10. Seal Bend Sonar Bathymetry. Note the gaps in the data set due to shallow water and *Zostera*-induced noise.

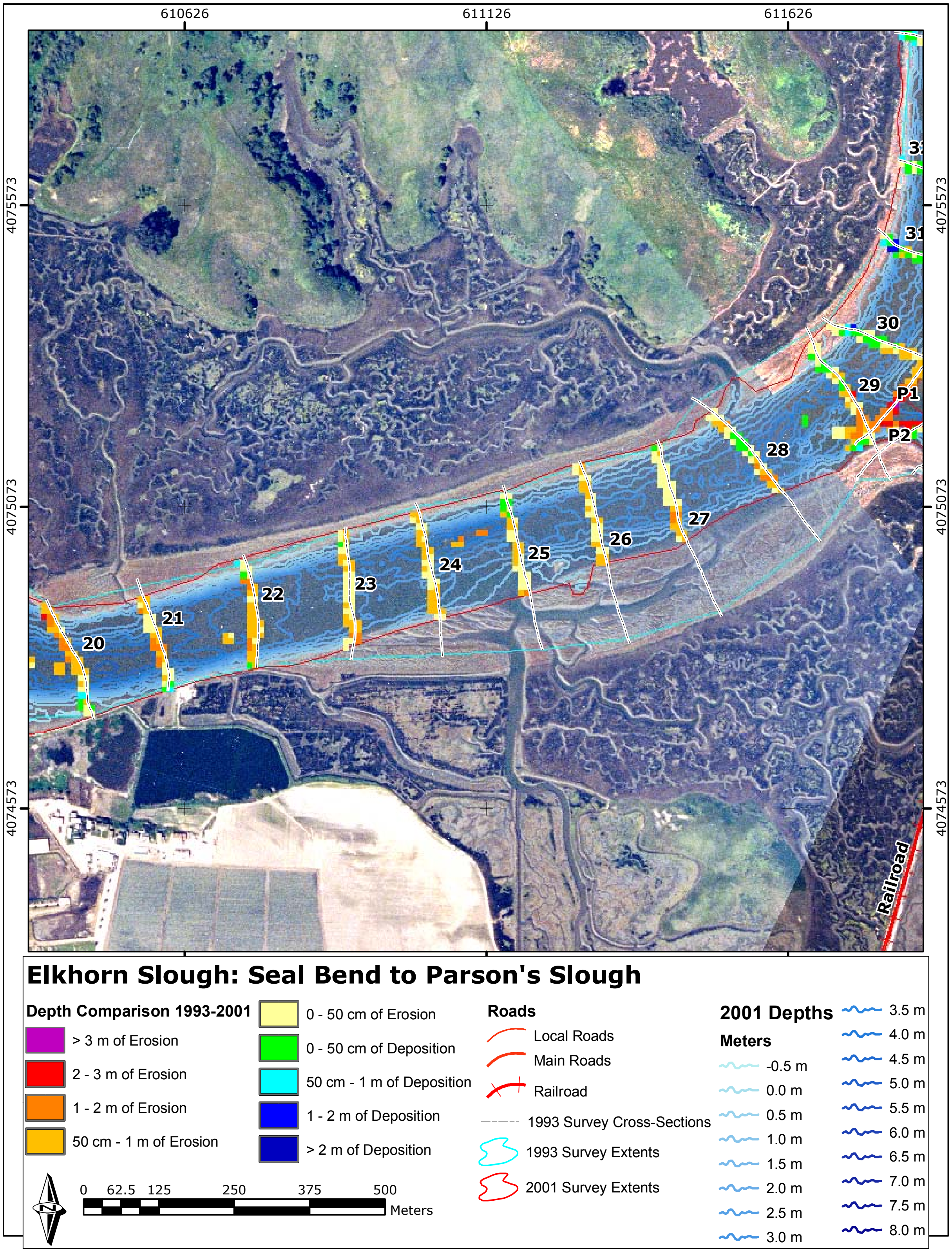


Figure 11. Seal Bend to Parson's Slough (Cross-Sections 20-29).
2000 Aerial Photograph taken at MLLW. Courtesy ESNERR.

Seal Bend to Parson's Slough (Cross-Sections 20-29)

Table 5: Change in Cross-Section Area—Seal Bend to Parson's Slough

Cross Section	1993 CSA (m^2)	2001 CSA (m^2)	ΔCSA (m^2)	% Change in CSA
20	370	467	-97	-26% Erosion
21	349	438	-88	-25% Erosion
22	333	420	-87	-26% Erosion
23	309	373	-64	-21% Erosion
24	308	371	-63	-20% Erosion
25	257	311	-54	-21% Erosion
26	223	288	-65	-29% Erosion
27	237	302	-65	-28% Erosion
28	282	359	-77	-27% Erosion
29	336	457	-121	-36% Erosion
			Mean	-26% Erosion
			Std Dev	4%

Table 6: Volume—Seal Bend to Parson's Slough

1993		2001		Change		
Volume m^3	% Total	Volume m^3	% Total	Volume m^3	% Change	% Total
4.4×10^5	21%	5.5×10^5	22%	-1.2×10^4	-27%	27%

More than a kilometer of long, straight, largely symmetrical channel runs from Seal Bend to the mouth of Parson's Slough. On the right bank of the upstream end, shallow channels braid through a wide arc of even shallower mudflats. *MacGinitie* could not progress into these areas.

This zone increased in volume from 4.35×10^5 m^3 in 1993 to 5.53×10^5 m^3 in 2001, a total of 1.19×10^5 m^3 of sediment lost. Only the foreslough lost a greater absolute quantity of sediment.

This zone had the smallest standard deviation of the change in cross-section area of any in the slough. This suggested even, steady erosion across the breath of this region. The raster and bottom profiles confirmed this. Unlike the foreslough and Seal Bend, the thalweg only showed small depth increases along the bottom. It consistently widened in every cross-section, however. The Erosion/Deposition Raster suggests that the banks of this zone are crumbling, leaving an occasional slump of material that registers as mild, isolated shoaling amidst a more general pattern of even erosion.

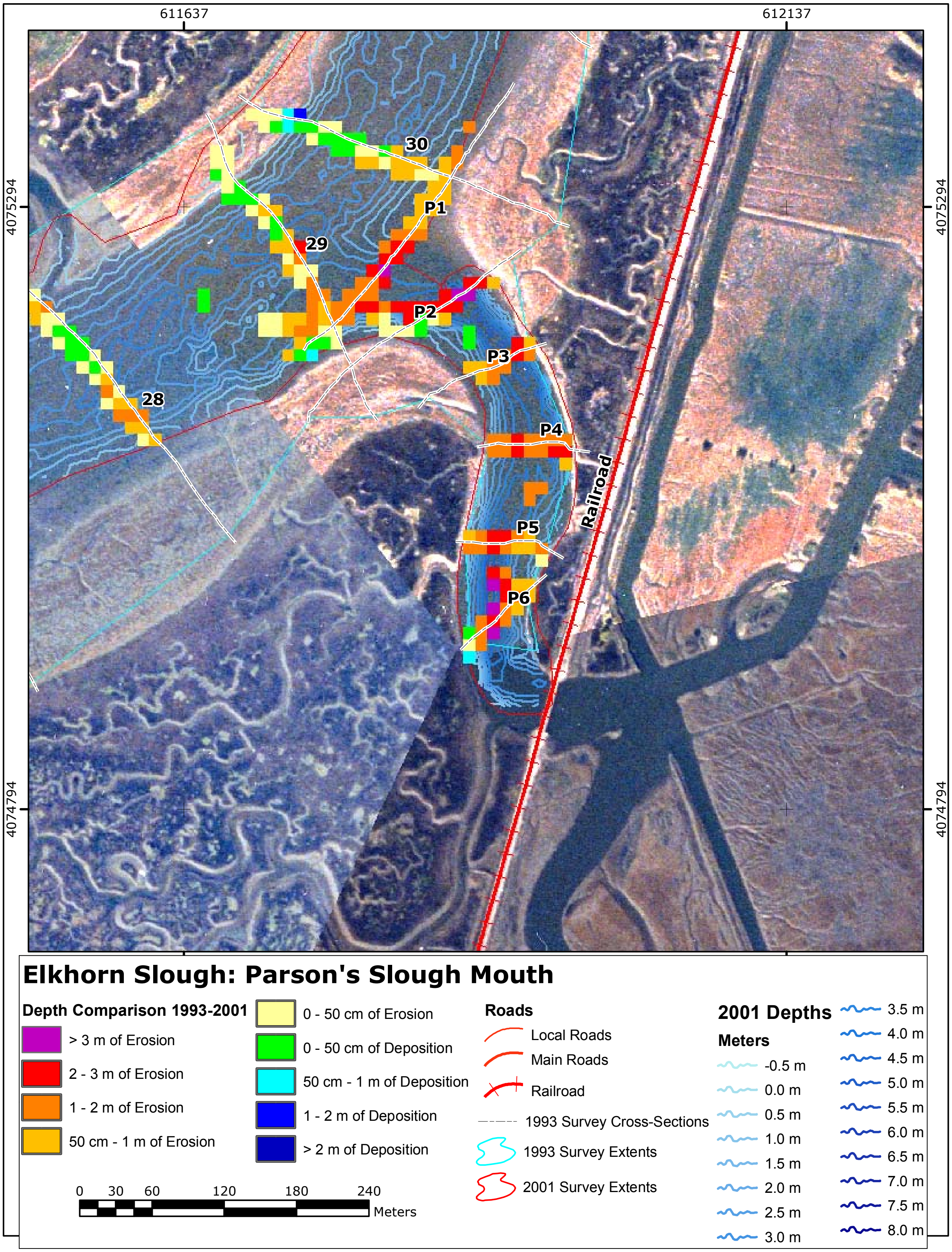


Figure 12. Parson's Slough Mouth (Cross-Sections P1-P6).
2000 Aerial Photograph taken at MLLW. Courtesy ESNERR.

Parson's Slough (Cross-Sections P1-P6)

Table 7: Change in Cross-Section Area—Parson's Slough

Cross Section	1993 CSA (m^2)	2001 CSA (m^2)	ΔCSA (m^2)	% Change in CSA
P1	136	334	-198	-146% Erosion
P2	112	248	-136	-121% Erosion
P3	80	151	-71	-89% Erosion
P4	92	210	-118	-128% Erosion
P5	92	186	-94	-102% Erosion
P6	96	219	-123	-128% Erosion
			Mean	-119% Erosion
			Std Dev	20%

Table 8: Volume—Parson's Slough

1993		2001		Change		
Volume m^3	% Total	Volume m^3	% Total	Volume m^3	% Change	% Total
3.9×10^4	2%	8.5×10^4	3%	-4.6×10^4	-119%	10%

The narrow throat connecting Parson's Slough to Elkhorn Slough juts off sharply to the south as the main channel sweeps north. The depth contours show a fork in the thalweg at the juncture, one side heading up the main channel while the other veers off toward Parson's. During periods of rising or falling tide, powerful currents rush through this constriction. In the 2001 survey, the Parson's Slough mouth was actually deeper than the portion of the main channel just upstream.

The most dramatic erosion in the survey area occurred here. Ten percent of the sediment lost from the survey area came from this tiny appendix, which constituted only three percent of the total survey volume. Maximum depths doubled in eight years, from a 2-3 m range in 1993 to a 4-6 m range in 1992. Volume and mean CSA more than doubled, each showing 119% erosion. The greatest depths occurred nearest the railroad bridge at the south tip of Parson's mouth. This was one of the few places in the survey area where, despite *MacGinitie's* greater draft, the 2001 survey covered more area than the 1993 survey.

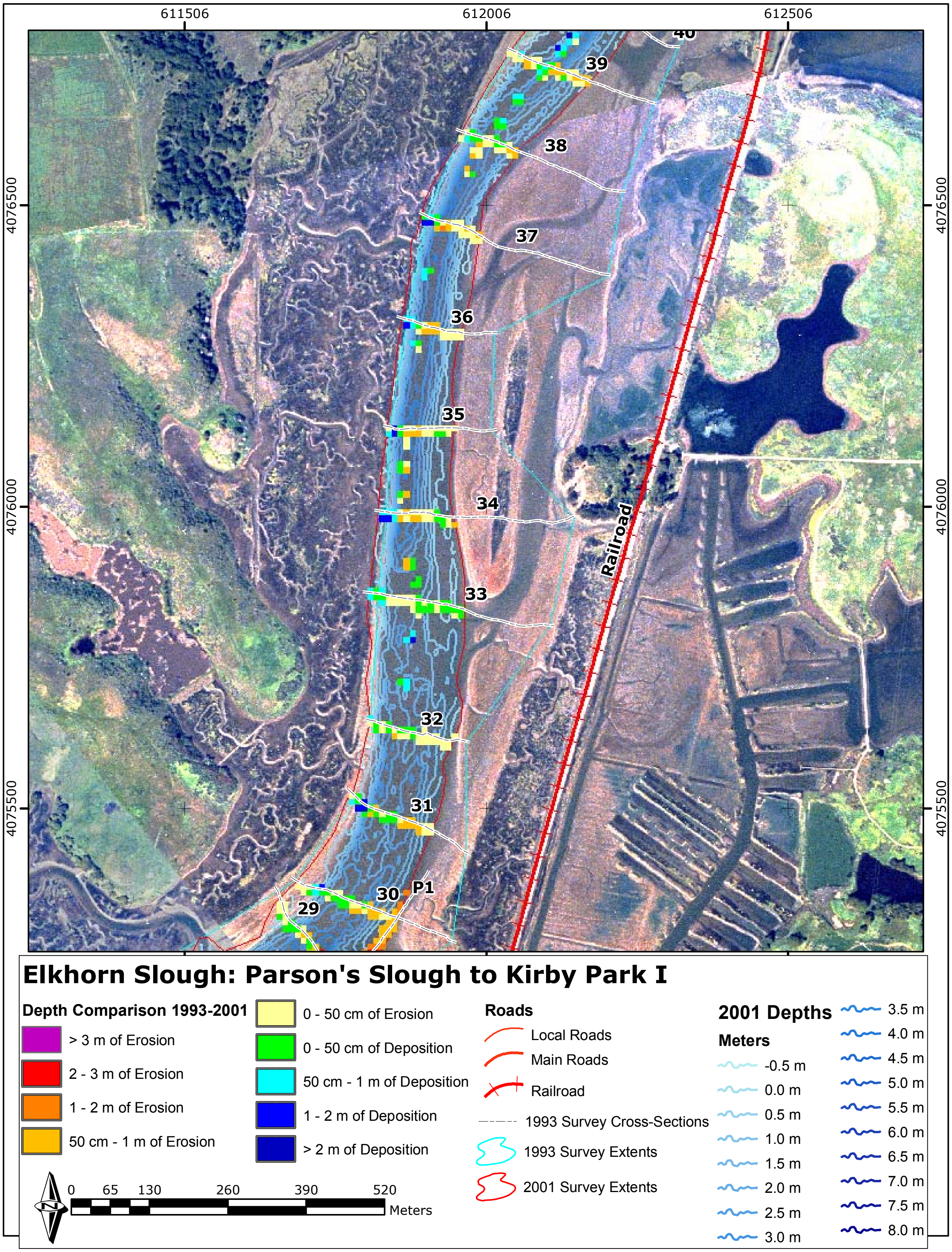


Figure 13. Midslough I: Parson's Slough to Kirby Park (Cross-Sections 30-39).
2000 Aerial Photograph taken at MLLW. Courtesy ESNERR.

Midslough: Parson's Slough to Kirby Park I (Cross-Sections 30-39)

Table 9: Change in Cross-Section Area—Parson's Slough to Kirby Park

Cross Section	1993 CSA (m^2)	2001 CSA (m^2)	ΔCSA (m^2)	% Change in CSA
30	254	263	-8	-3% Erosion
31	244	258	-14	-6% Erosion
32	227	231	-5	-2% Erosion
33	**154**	**154**	**0**	**0% Change**
34	174	177	-3	-2% Erosion
35	171	179	-8	-5% Erosion
36	138	162	-24	-17% Erosion
37	153	157	-4	-3% Erosion
38	157	158	-1	-1% Erosion
39	178	199	-20	-11% Erosion
			Mean 30-39	-5% Erosion
			Std Dev	5%

Table 10: Volume—Parson's Slough to Kirby Park I

1993		2001		Change		
Volume m^3	% Total	Volume m^3	% Total	Volume m^3	% Change	% Total
$2.9x10^5$	14%	$3.1x10^5$	12%	$-1.6x10^4$	-5%	4%

As the main channel runs north from Parson's Slough, the right bank spreads out into a broad mudflat, up to 200 meters wide. The left bank is steep, almost vertical, abutting another *Salicornia* marsh threaded with twisting tidal channels. The thalweg runs closest to the left bank, often cutting a V-shaped channel between three and four meters in depth. The Union Pacific Railroad tracks separate this section of the main channel from ESNERR's South Marsh and the reclaimed wetlands of the former Elkhorn Dairy. While *MacGinitie* could not safely navigate the shoal, the 1998 LIDAR survey flew over the north end of this zone and collected data.

This zone showed only modest changes in CSA and volume, and accounted for only 4% of the total sediment volume lost from the survey region. In the mudflats, the 1998 LIDAR data ran roughly parallel to the 1993 sonar data, rising above it in several places. The proximity to the South Marsh, where contaminants caused the crash of the Caspian Tern population in 1995 (ESNERR 2001), suggested that this could be the remnant of a sediment blanket from the Pajaro River flood.

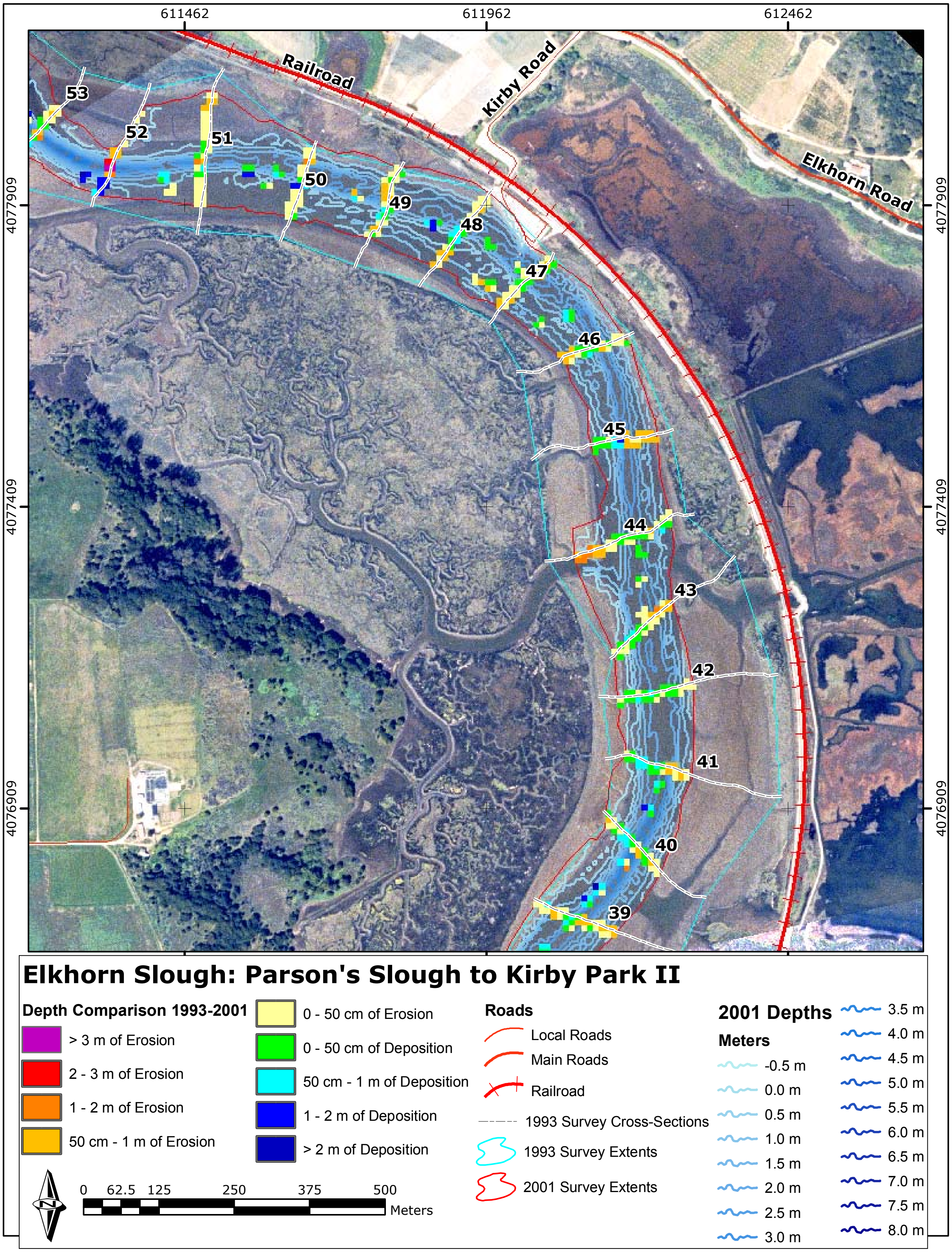


Figure 14. Midslough II: Parson's Slough to Kirby Park (Cross-Sections 40-49).
2000 Aerial Photograph taken at MLLW. Courtesy ESNERR.

Midslough: Parson's Slough to Kirby Park II (Cross-Sections 40-49)

Table 11: Change in Cross-Section Area—Parson's Slough to Kirby Park II

Cross Section	1993 CSA (m^2)	2001 CSA (m^2)	ΔCSA (m^2)	% Change in CSA
40	161	169	-8	-5% Erosion
41	142	151	-9	-6% Erosion
42	**162**	**148**	**+14**	**8% Deposition**
43	165	179	-14	-8% Erosion
44	88	132	-45	-51% Erosion
45	117	123	-6	-5% Erosion
46	128	132	-3	-3% Erosion
47	131	151	-19	-15% Erosion
48	122	136	-15	-12% Erosion
49	111	116	-6	-5% Erosion
			Mean 40-49	-10% Erosion
			Std Dev	16%

Table 12: Volume—Parson's Slough to Kirby Park II

1993		2001		Change		
Volume m^3	% Total	Volume m^3	% Total	Volume m^3	% Change	% Total
1.8×10^5	9%	2.0×10^5	8%	-1.8×10^4	-12%	4%

As the main channel slowly curves to the west, another shallow area develops along the left bank, providing a buffer for the *Salicornia* marsh on that side of the channel. The V shape of the channel persists, though it broadens somewhat. In the middle of the zone, a major tidal channel through the marsh joins with the main channel; this is known locally as "The Big T" (Pers. Comm. Rikk Kivtek). The thalweg downstream of this juncture is noticeably shallower for roughly 400 meters, suggesting ongoing deposition of sediment from the erosion of the network of tidal channels.

Like the previous zone, this section showed only minor erosion. Much of the depth change fell within ±0.5 meters. The patterns of deposition and erosion in the raster corresponded to slight channel shifts seen in the cross-sections. LIDAR data once again suggested a depositional event between 1993 and 1998, most noticeably along the higher banks.

The large negative ΔCSA of CS-44 gave this section a higher standard deviation than the previous zone. It appeared that a prominence at the "Big T" was planed off between 1998 and 2001.

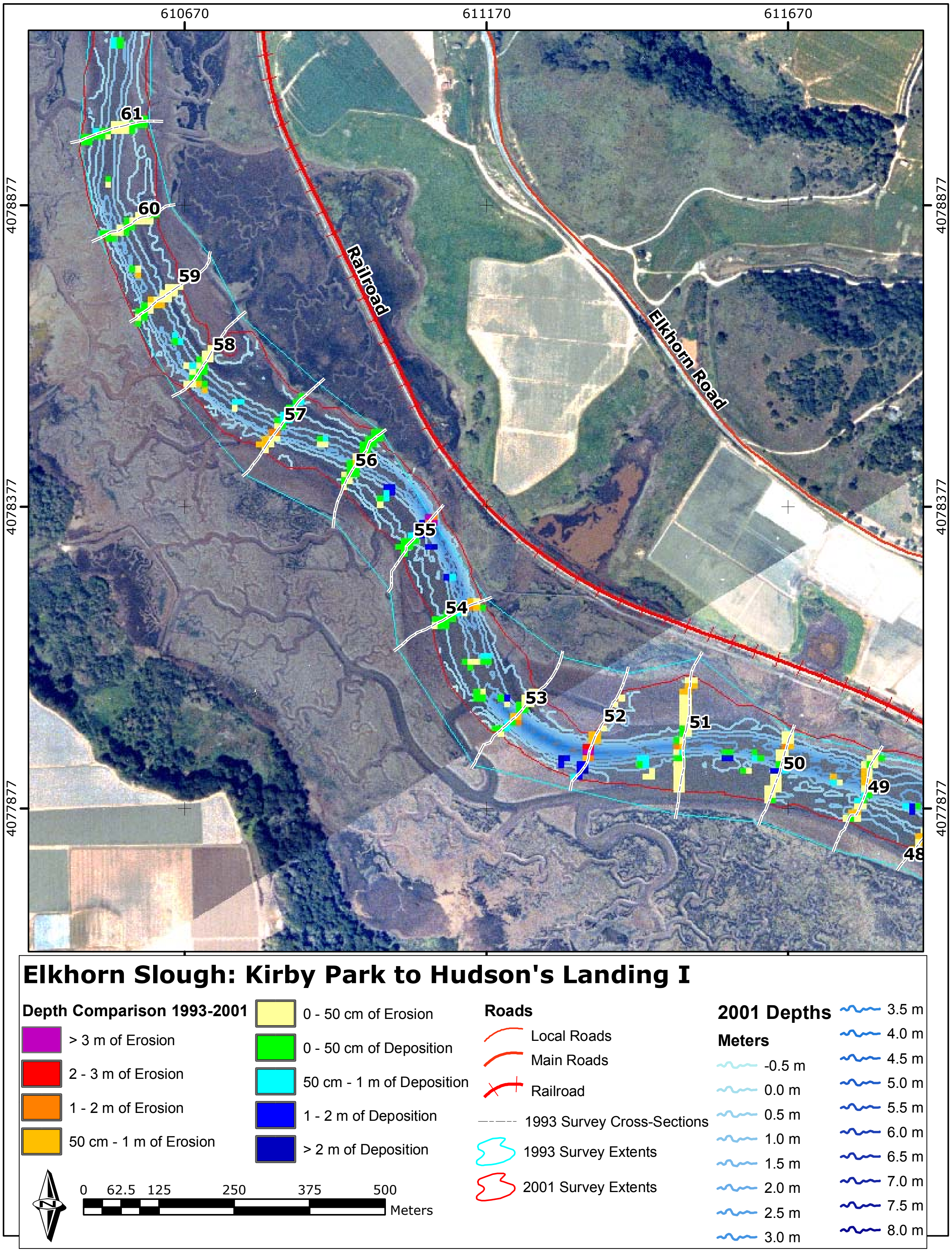


Figure 15. Back Slough I: Kirby Park to Hudson's Landing (Cross-Sections 50-59).
2000 Aerial Photograph taken at MLLW. Courtesy ESNERR.

Back Slough I (Cross-Sections 50-59)

Table 13: Change in Cross-Section Area—Back Slough I

Cross Section	1993 CSA (m^2)	2001 CSA (m^2)	ΔCSA (m^2)	% Change in CSA	
50	111	130	-19	-17%	Erosion
51	65	115	-50	-77%	Erosion
52	71	106	-35	-50%	Erosion
53	**99**	**97**	**+2**	**2%**	**Deposition**
54	64	68	-4	-6%	Erosion
55	**83**	**53**	**+30**	**36%**	**Deposition**
56	**70**	**66**	**+4**	**5%**	**Deposition**
57	63	65	-3	-4%	Erosion
58	50	52	-3	-6%	Erosion
59	38	54	-17	-44%	Erosion
			Mean	**-16%**	**Erosion**
			Std Dev	**33%**	

Table 14: Volume—Back Slough I

1993		2001		Change		
Volume m^3	% Total	Volume m^3	% Total	Volume m^3	% Change	% Total
$1.1x10^5$	5%	$1.2x10^5$	5%	$-1.3x10^4$	-12%	3%

Upstream of Kirby Park, the main channel meanders between mudflats on either side, and has shifted over time, as well.

This zone had the highest standard deviation of ΔCSA in the survey area. Individual ΔCSA values ranged from high erosion to high deposition in this zone, but closer examination of the bottom profiles revealed that lateral shifts in the thalweg skewed the results. The ΔCSA calculation for CS 55 resulted in the largest proportional deposition in the entire survey area; however, the bottom profiles showed that the channel actually shifted 20 m to the right, and deepened by roughly a meter. Most of this substantial erosion fell past the edge of the 1993 survey boundaries, and thus was omitted from the CSA calculations, while the shift in the left edge of the new channel "filled in" the old.

Some degradation of the mudflats occurred, with depths in those areas increasing by as much as half a meter. LIDAR continued to show higher banks and higher prominences in the mudflats.

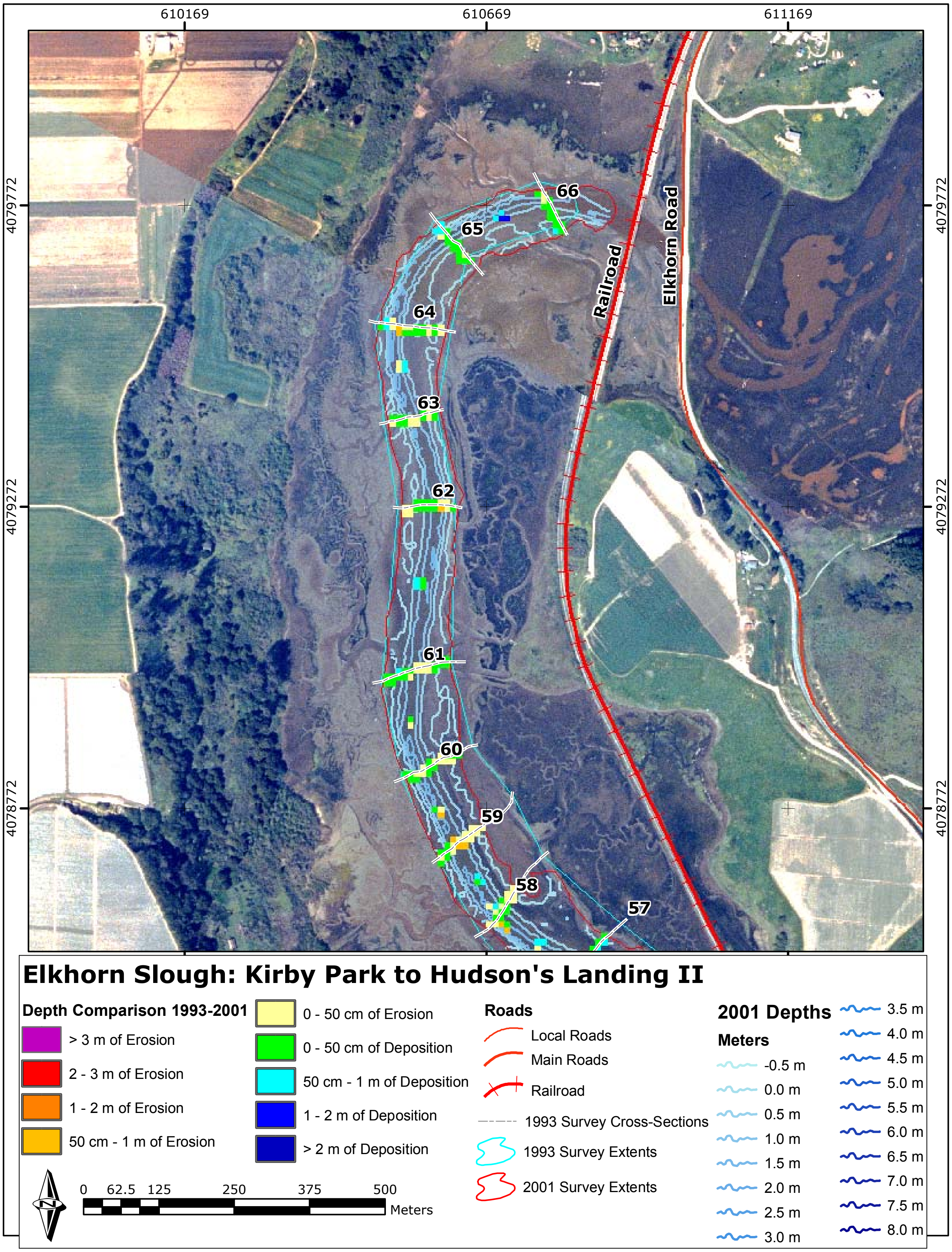


Figure 16. Back Slough II: Kirby Park to Hudson's Landing (Cross-Sections 60-66).
2000 Aerial Photograph taken at MLLW. Courtesy ESNERR.

Back Slough II (Cross-Sections 60-66)

Table 15: Change in Cross-Section Area— Back Slough II

Cross Section	1993 CSA (m^2)	2001 CSA (m^2)	ΔCSA (m^2)	% Change in CSA
60	42	51	-9	-22% Erosion
61	44	46	-2	-3% Erosion
62	37	43	-6	-17% Erosion
63	38	41	-2	-6% Erosion
64	37	30	+7	18% Deposition
65	36	27	+9	26% Deposition
66	39	28	+10	26% Deposition
			Mean	3% Deposition
			Std Dev	20%

Table 16: Volume— Back Slough II

1993		2001		Change		
Volume m^3	% Total	Volume m^3	% Total	Volume m^3	% Change	% Total
$4.3x10^4$	2%	$4.2x10^4$	2%	$+7.1x10^2$	+2%	-0.2%

The head of the slough tapers to a narrow stream of shallow water. Depths in this region did not exceed 2 m.

This was the only zone in which deposition dominated, and then only in the sections closest to Hudson's Landing and the slough head. LIDAR data indicated a rise of half a meter or more in the depths of the mudflats and almost a meter along the steeper banks between 1993 and 1998, followed by erosion between 1998 and 2001. At CS-65, the depths along the mudflats in 2001 were almost at the level as those recorded in 1993, while the LIDAR showed a 40 cm rise over the same area. This suggests that this area had either reached equilibrium or was continuing to erode in 1993. After the deposition of the Pajaro River flood, it rapidly returned to its previous state.

Discussion

Changes in Erosional Trends

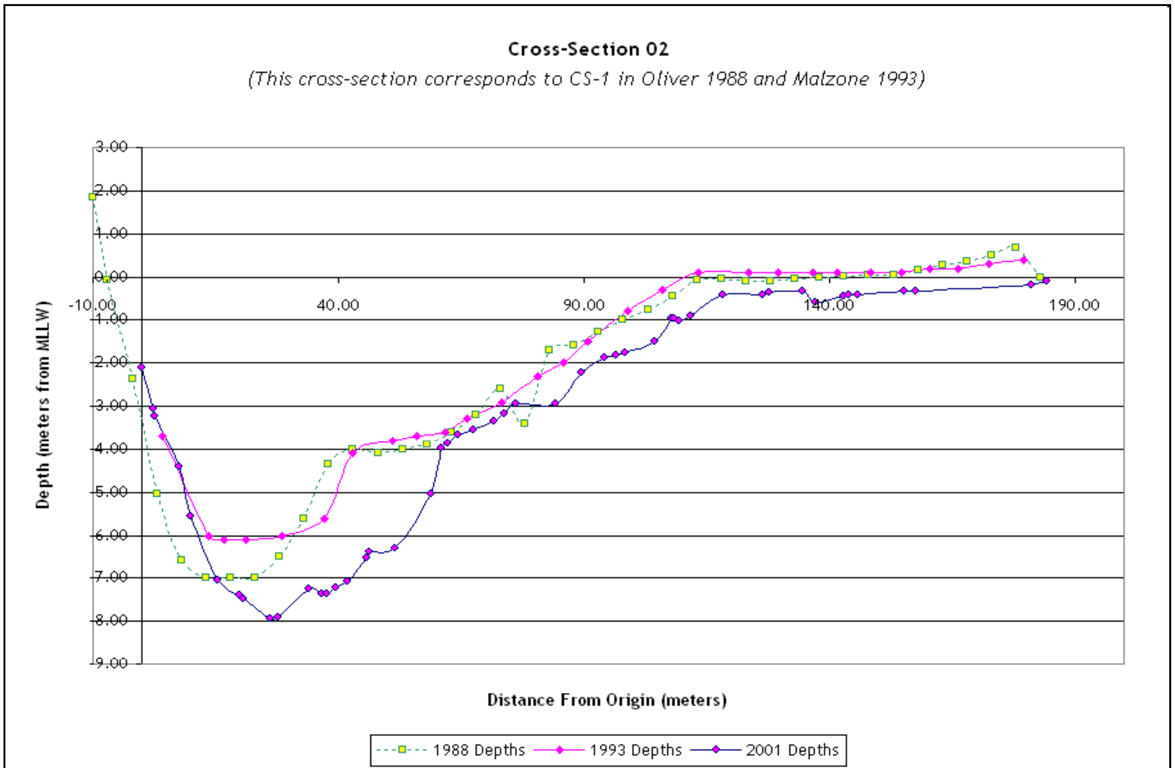
After a half-century of exposure to the tides, Elkhorn Slough continues to erode. There is no sign that this process is approaching equilibrium—the volume of sediment lost *per annum* remains within an order of magnitude of that found in previous studies.

The 1993 survey found that in the lower slough and middle slough, the deepest parts of the main channel had shoaled since 1988, while the mudflats along the banks had eroded. Cross-Section 02 in Figure 17 shows this clearly. The upper slough had experienced high rates of erosion in all areas (Malzone 1999).

The 2001 survey found patterns that contrasted sharply with this. While mudflats continued to deepen, the channel also degraded, eroding the sediment accumulated between 1988 and 1993, and reaching even greater depths. The Foreslough and Seal Bend—Malzone's "lower slough"—showed large increases in depth, CSA, and volume. Malzone included the region from Seal Bend to Parson's Slough in the middle slough—an area that showed some of the strongest, most consistent erosion in the 2001 survey. This accentuated that division's bias toward net erosion. The upper slough had filled in since 1993 (most likely due to sediment from the 1995 Pajaro River flood).

Parson's Slough was a major factor in this process. The mouth of Parson's Slough and the three zones downstream from it accounted for 90% of the volume lost from the survey region. The mouth itself accounted for volume of sediment loss equal to that of the entire survey region from that point to the slough head.

The expansion of the *Zostera* beds seen in 1993 continued in 2001, with a prominent shoal forming in Seal Bend from sediment trapped by the eel grass.



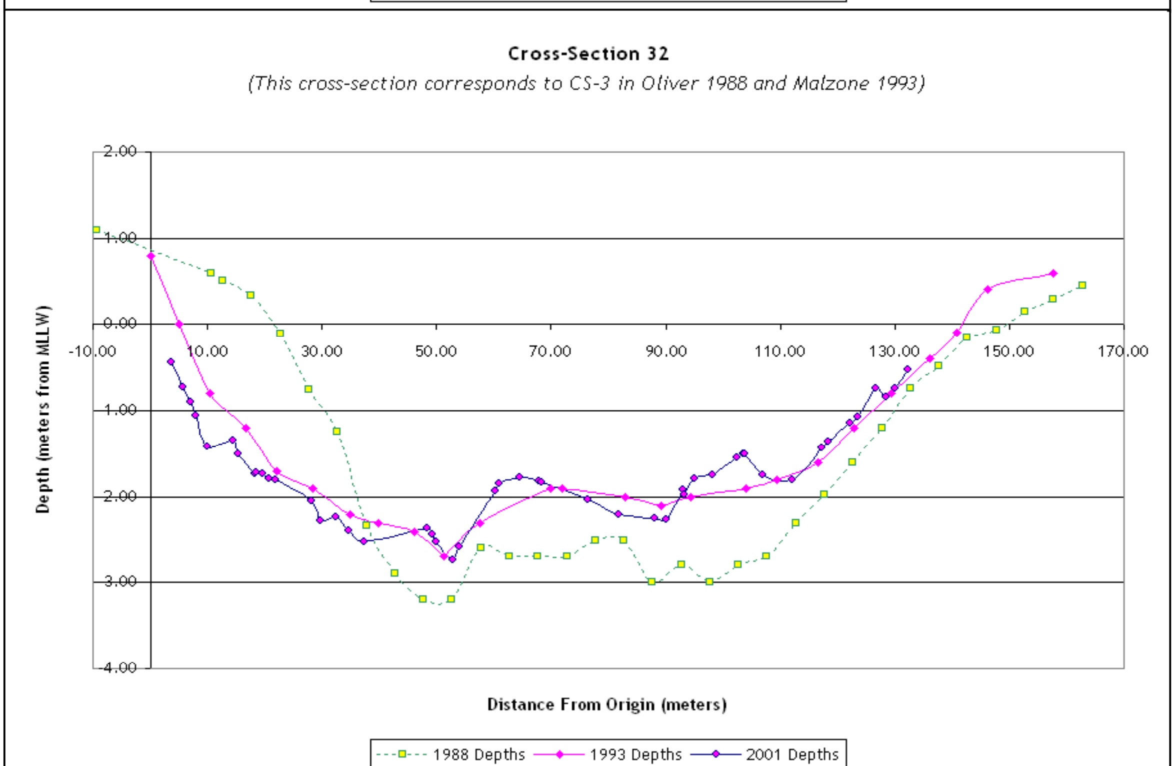


Figure 17. Representative Cross-Sections showing data from 1988, 1993 and 2001 surveys. Note deposition between 1988 and 1993 in the deepest parts of the channel.

Surveying the Slough

When the Seafloor Mapping Lab first acquired *R/V MacGinitie* and its multi-beam capabilities, we thought the close proximity, sheltered conditions, and limited surface area of Elkhorn Slough would make it a simple, straightforward project, an ideal locale for testing equipment and training new students. Instead, it proved among the lab's most challenging survey area. Its twisting channel strained software designed to survey wide, straight swaths of coast and open ocean. The erosion that we came to study had compromised the reliability of navigational charts and tide models. Thick patches of eel grass cluttered sonar returns with noise, tangled propellers, and trapped sediment to create unseen shoals.

Moreover, much of the tidal volume of the slough spread across areas too shallow to survey with our equipment. Our boat had no access whatsoever to the critical areas of Blohm/Porter marsh, above the Elkhorn Road culverts, or to Parson's Slough, which contains 30% of the system's tidal volume (Malzone and Kvitek 1994ab). The airborne LIDAR data collected by the ALACE project only covered a portion of the region. We must use other methods to assess these areas.

The eight-year gap since the last survey introduced certain assumptions. I could only calculate bathymetry changes for the entire eight-year period, and translate that to a per-annum erosion rate. However, we cannot assume that erosion rates are constant. The Pajaro River flood of 1995 left sediment traces still evident six years later (Personal communication with Rikk Kvitek). A strong El Niño condition brought severe weather to the California coast in 1997 and 1998. The heavy seas it brought could have increased tidal scour, while runoff from the heavy rains could have increased sedimentation. We simply lack the data to estimate the net effect.

Processing the sonar data from the combined surveys revealed serious discrepancies in the existing tide models for Elkhorn Slough. The *Tides & Currents* software offered tide models from three different stations in the Slough: the Highway 1 bridge, Kirby Park, and the railroad bridge at

Hudson's Landing. During the initial processing of the sonar data in CARIS HIPS, I discovered several persistent depth anomalies. I found that using a single model for the entire slough gave the most consistent results. Even so, the color-coded bathymetry grids revealed several places where obvious depth differences followed along track lines (Figure 17). HIPS Swath and Subset Editors confirmed these. The most distinct examples occurred when a track line from one day crossed a set of lines from another day; however, in some instances, lines surveyed at widely-separated times in the same day showed noticeable depth discrepancies.

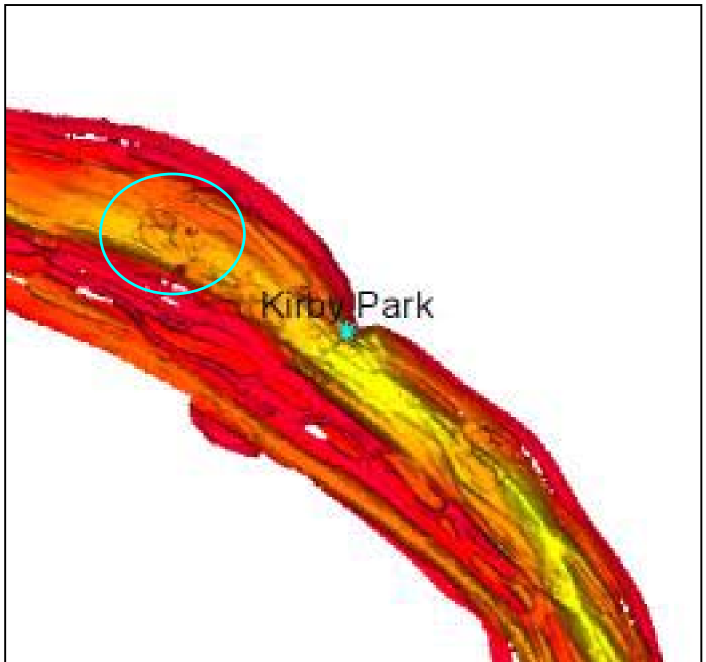


Figure 18. Kirby Park Sonar Bathymetry. Note the distinct loop upstream of the park.

These results are not entirely unexpected. Even the best tide models can only estimate an approximate value for the water depth in a given area at a given time. However, current conditions in Elkhorn Slough exacerbate this situation. The *Tides & Currents* software bases its three Elkhorn Slough tide models on a base station in San Francisco Bay, and uses mathematical algorithms to correct them. The differences between the three Elkhorn Slough stations stem from the effects a long, narrow, sinuous channel has on tidal flow. Since tidal scour has altered the characteristics of that channel, divergence from the model seems inevitable.

Conclusion

The purpose of this project was to ascertain if the patterns of erosion and deposition in Elkhorn Slough had changed between 1993 and 2001, and to determine if the slough had approached erosional equilibrium.

Comparison of sonar and LIDAR data to the 1993 survey showed that erosion in Elkhorn Slough remained within an order of magnitude of that predicted by Malzone. However, the patterns of erosion and deposition shifted in the intervening years. Deep channels in the lower slough that filled in between 1988 and 1993 eroded even further between 1993 and 2001. The strong erosion seen in the upper slough between 1988 and 1993 gave way to deposition and shoaling. The erosion of the banks and mudflats seen in the 1993 survey continued unabated in 2001.

The bulk of the erosion seen between 1993 and 2001 occurred downstream of the mouth of Parson's Slough, suggesting that the tidal volume of Parson's Slough has become a significant factor in the Elkhorn Slough system.

Like the weather, erosion is a complex, dynamic phenomenon. Accurate weather prediction requires a continual input of real-world data to verify and correct the prediction model. The more often one samples the data, the more accurately one can predict future trends, and the further into the future one can extrapolate. With a dense, sophisticated network of satellites and instruments at their disposal, however, meteorologists still express weather forecasts in terms of probabilities.

We know far more about the weather than we do about wetlands erosion.

A single survey is not enough to understand the complex character of tidally mediated erosion in Elkhorn Slough. The region requires regular assessment to record changes over time. This project is part of a continuing effort to determine the effects of tidal scour on the Elkhorn Slough system. The high-resolution bathymetric model generated by this study will provide a base line for future surveys.

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Cartographic Resources

Historical Charts of Elkhorn Slough courtesy of the National Oceanographic and Atmospheric Administration Office of Coast Survey. Available via the internet: http://chartmaker.ncd.noaa.gov/csdl/ctp/abstract.htm

Aerial photo mosaics courtesy of the Elkhorn Slough Foundation and ESNERR.

GIS SHAPE files of the Elkhorn Slough area courtesy of the Elkhorn Slough Foundation and ESNERR. Available via the internet: http://www.elkhornslough.org/GIS/GIS.HTM

LIDAR survey data courtesy of the National Oceanographic and Atmospheric Administration Coastal Services Center. Available via the internet: http://www.csc.noaa.gov/crs/tcm/

Tidal Scour in Elkhorn Slough, CA: A Bathymetric Analysis

Appendix A:
Cross-Sections

Data Sources

- 1993 Single-beam sonar data collected by Chris Malzone and Rikk Kvitek
- 1998 LIDAR data collected by the Airborne LIDAR Assessment of Coastal Erosion (ALACE) project
- 2001 Multi-beam sonar data collected by CSUMB SFML


Cross-Section 00
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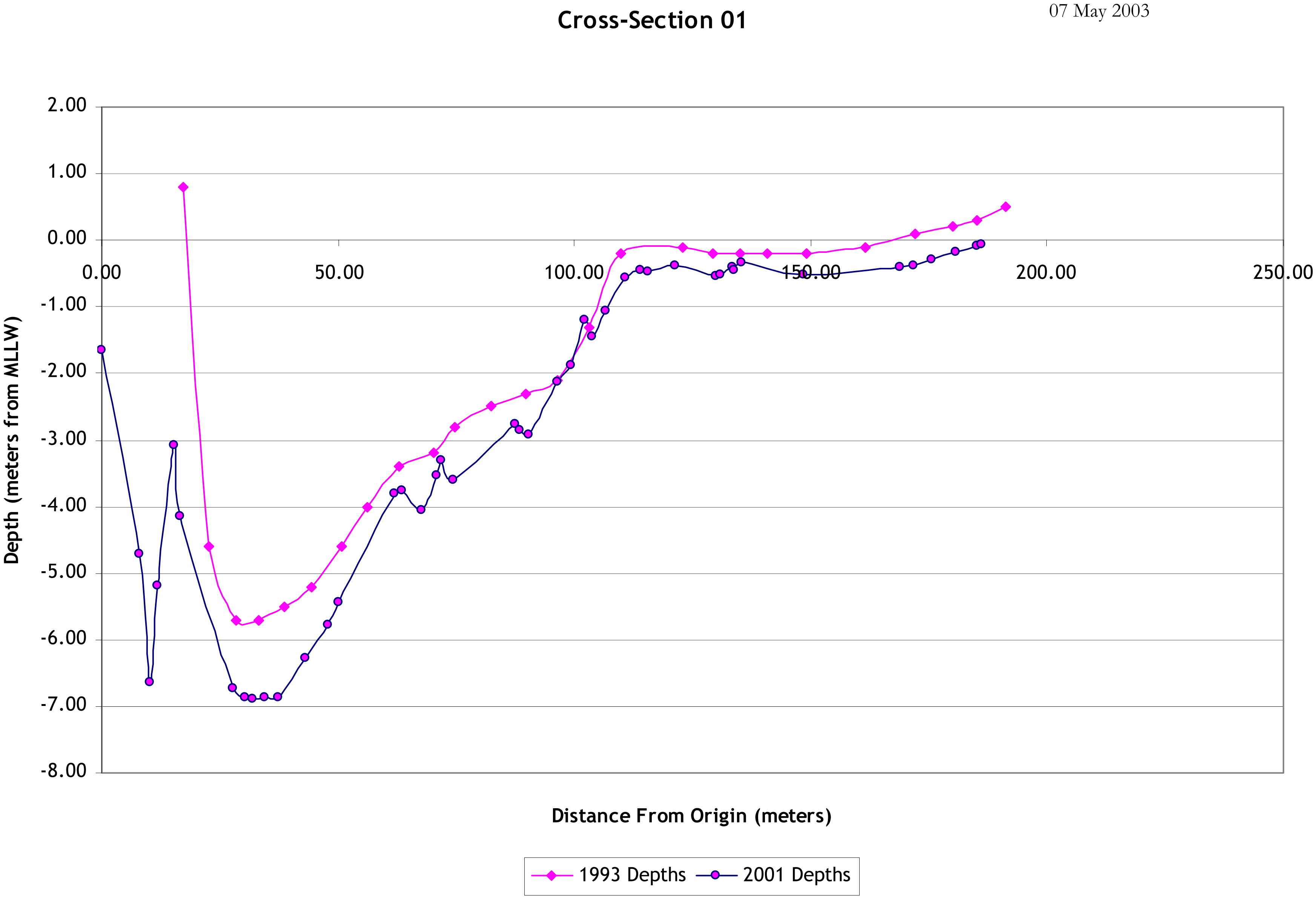
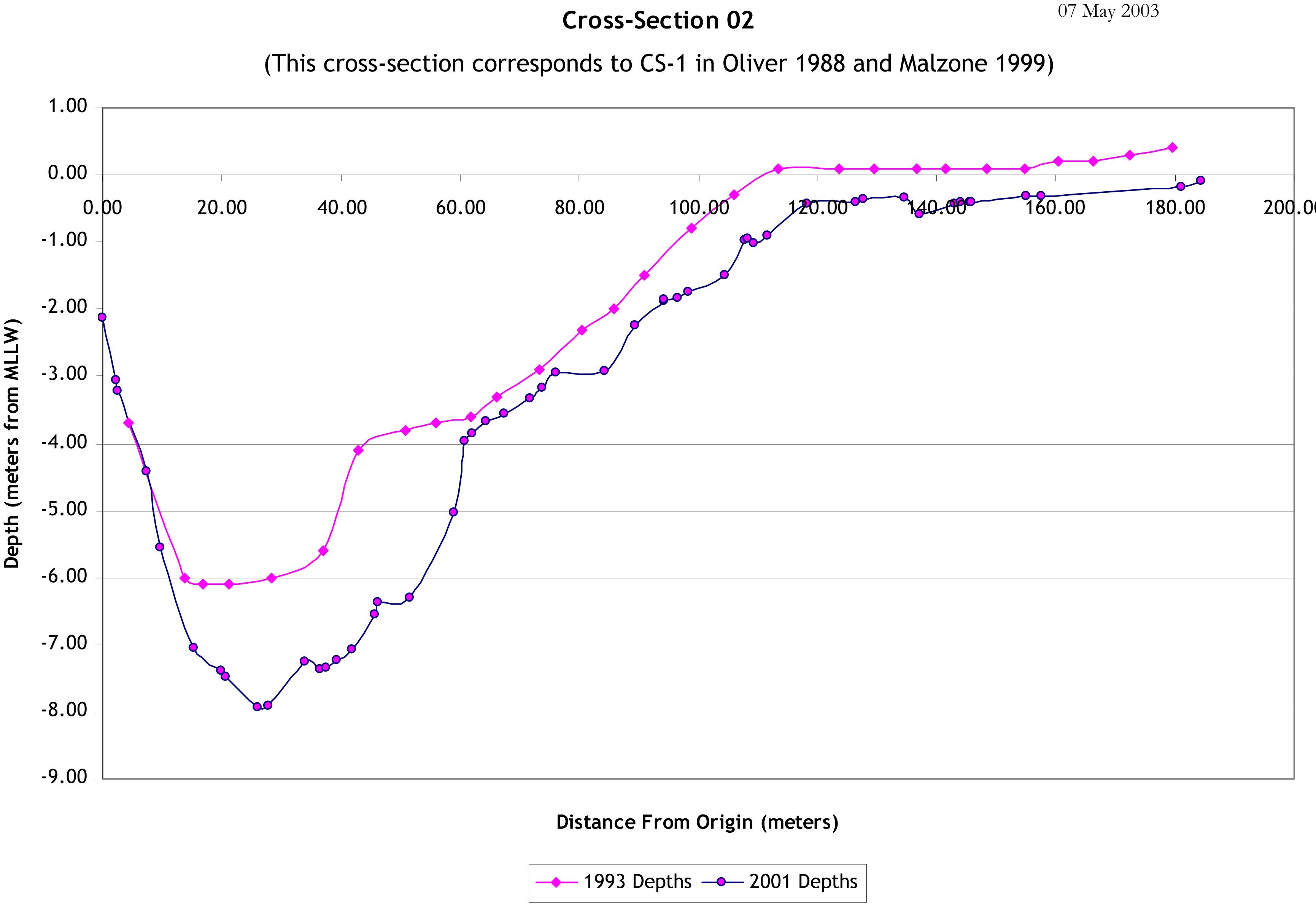
40.00
60.00
80.00
100.00
120.00
140.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths

Edwin Wendell Dean III

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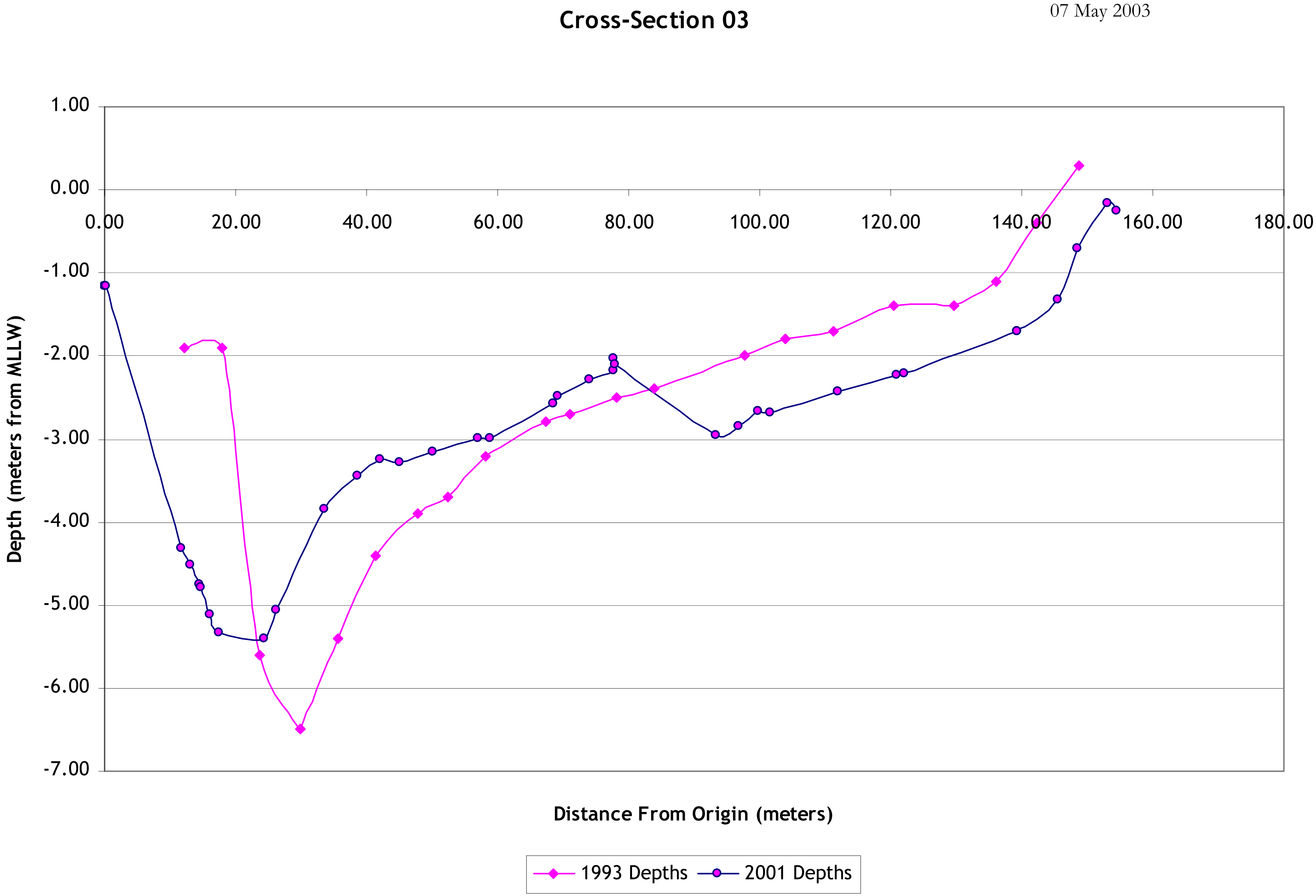
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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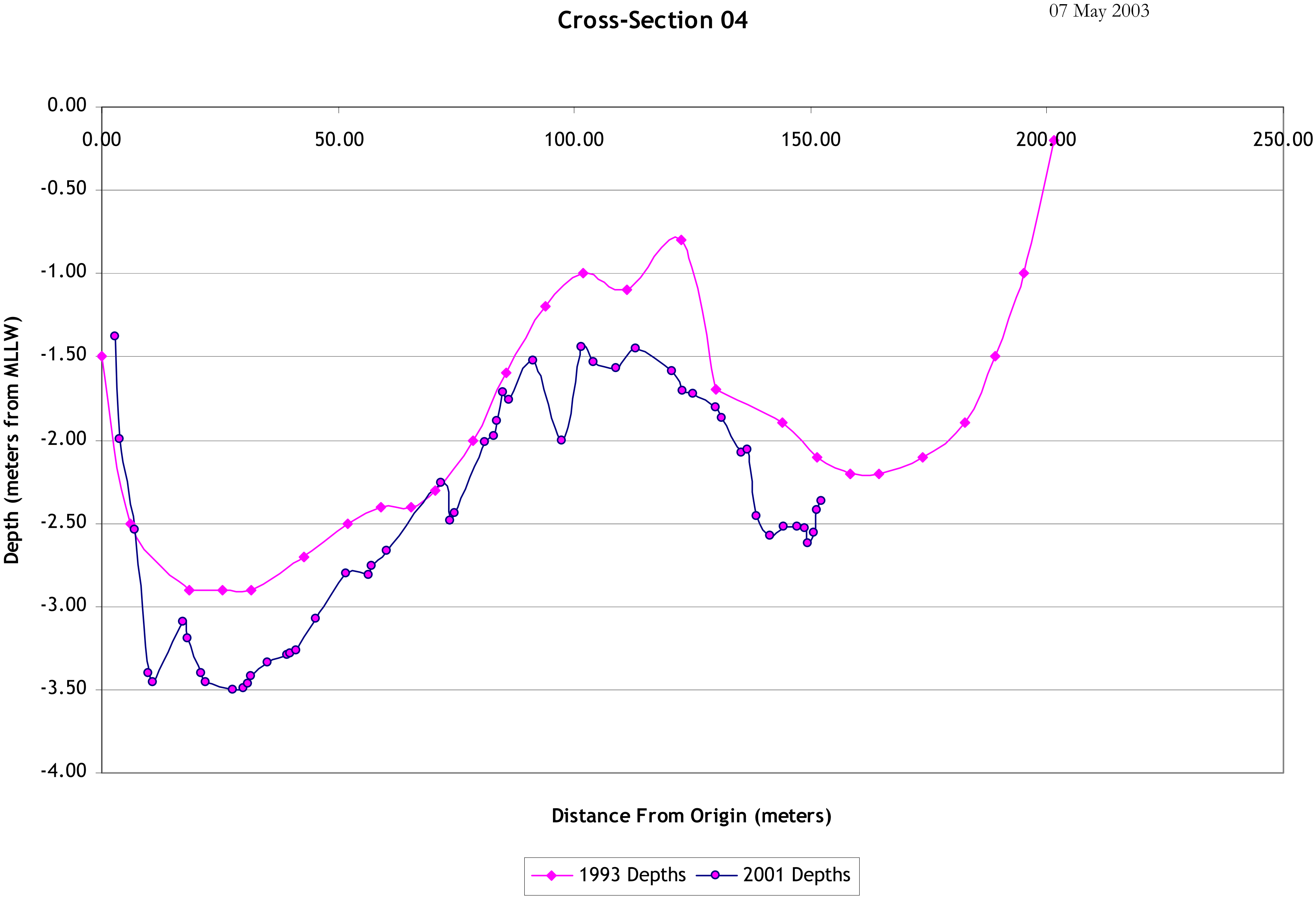
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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150.00
200.00
250.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths


Cross-Section 05
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-0.50
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-1.50
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-2.50
-3.00
-3.50
-4.00
-4.50
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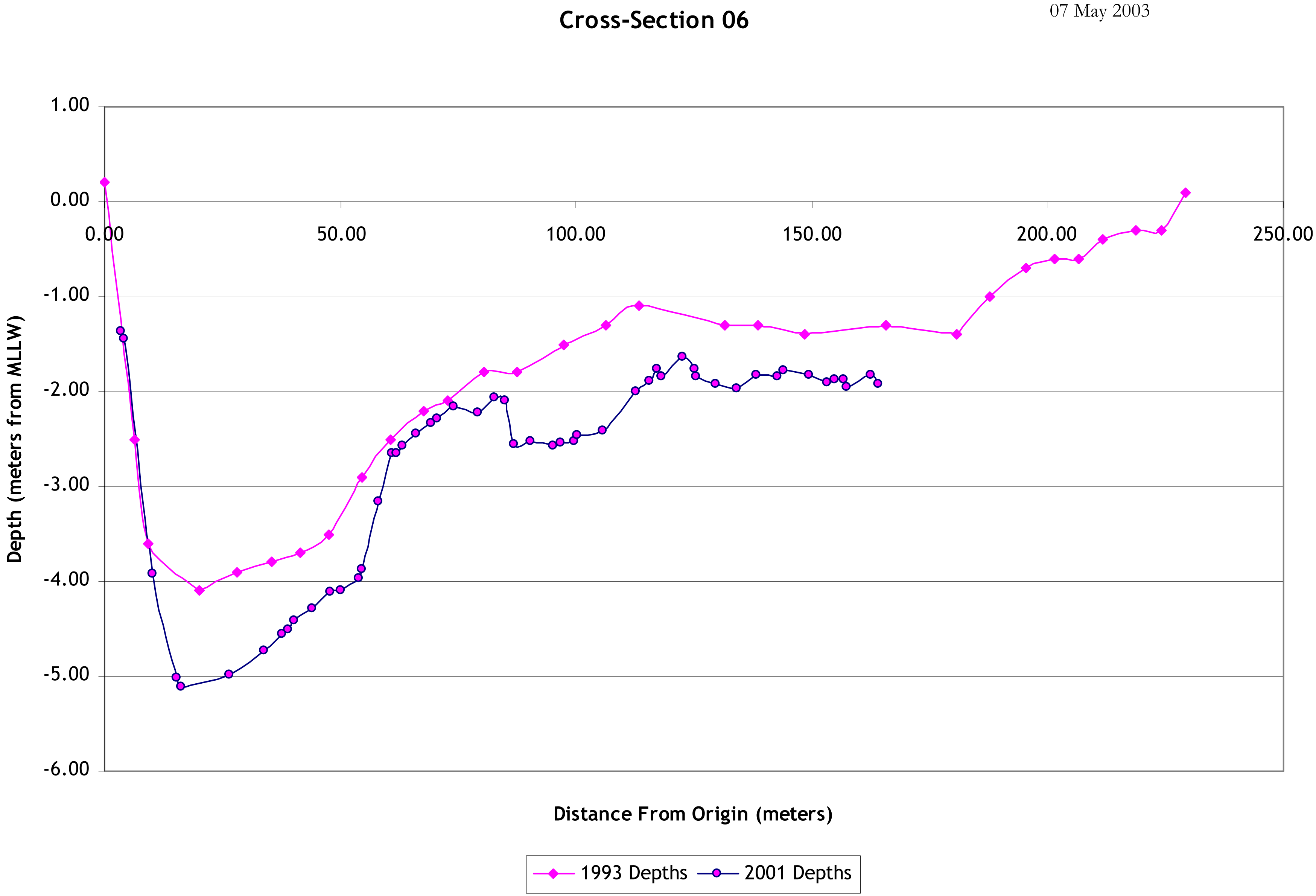
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths


Cross-Section 07
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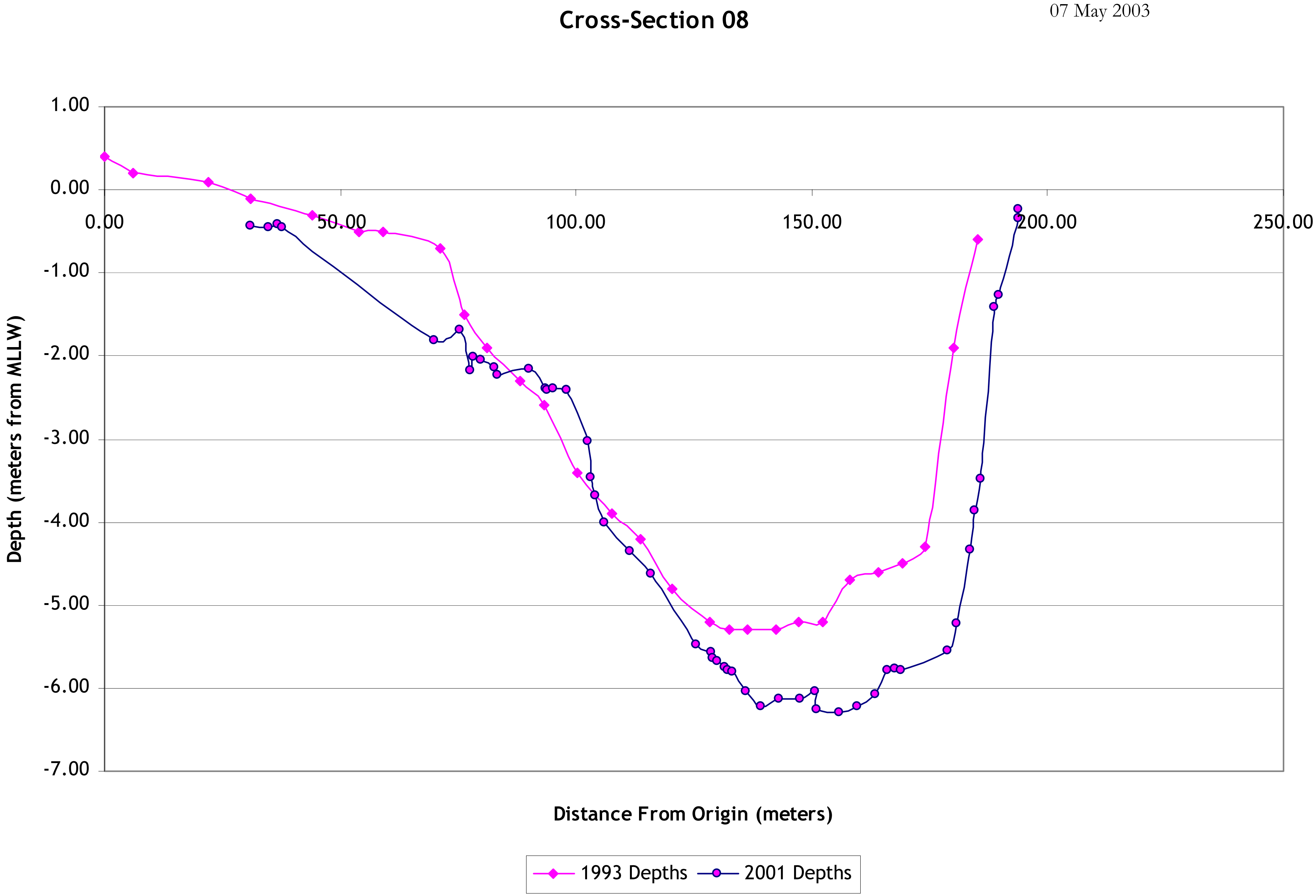
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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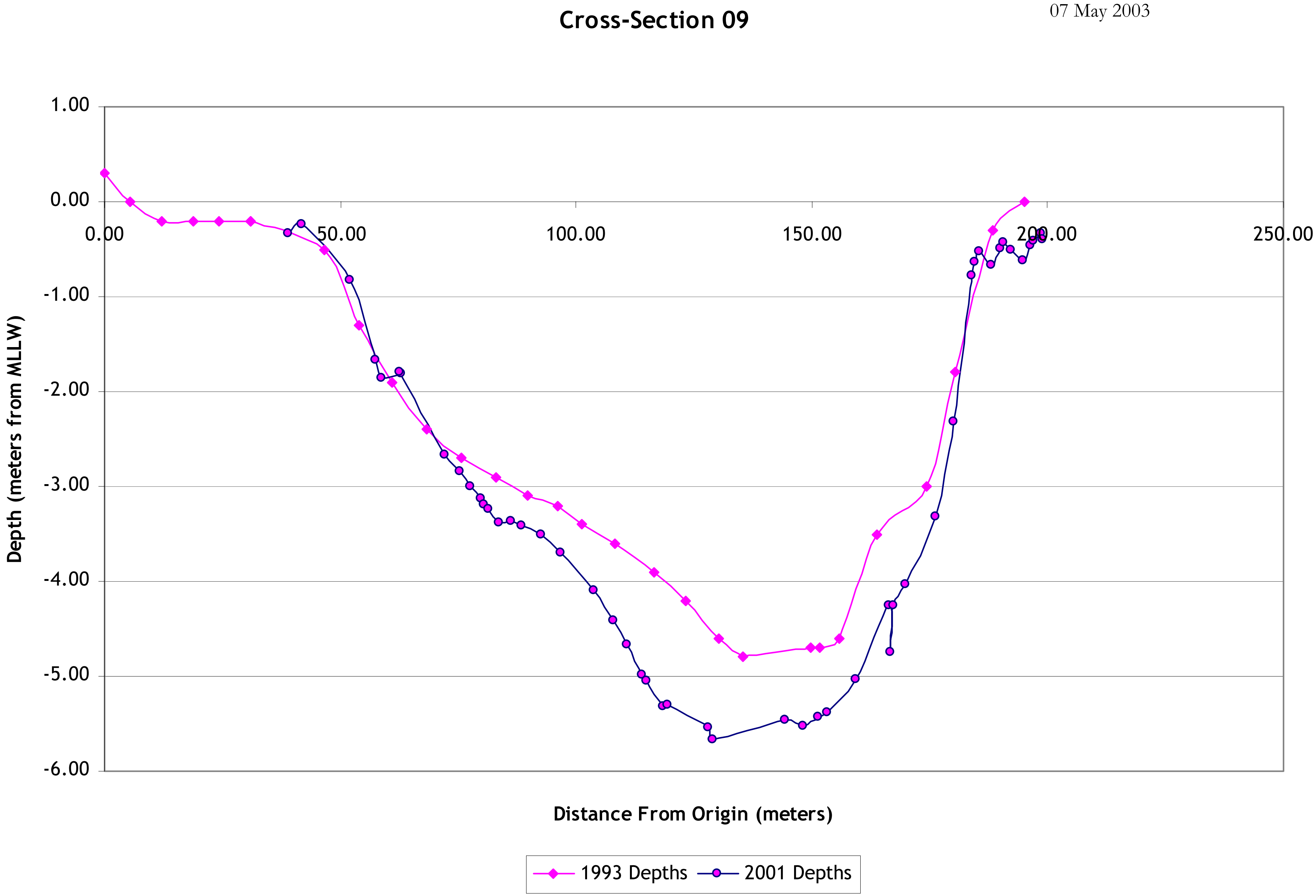
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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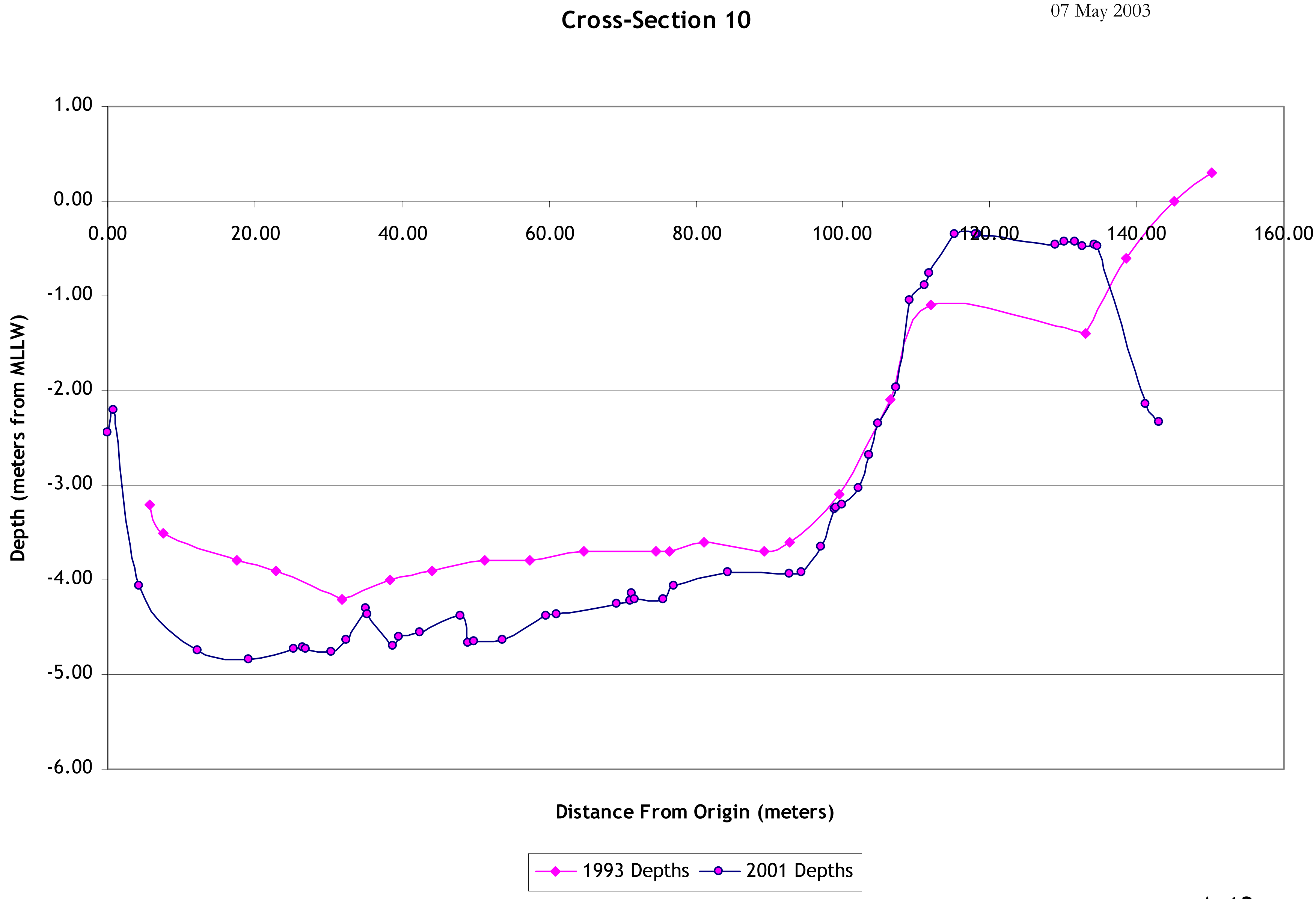
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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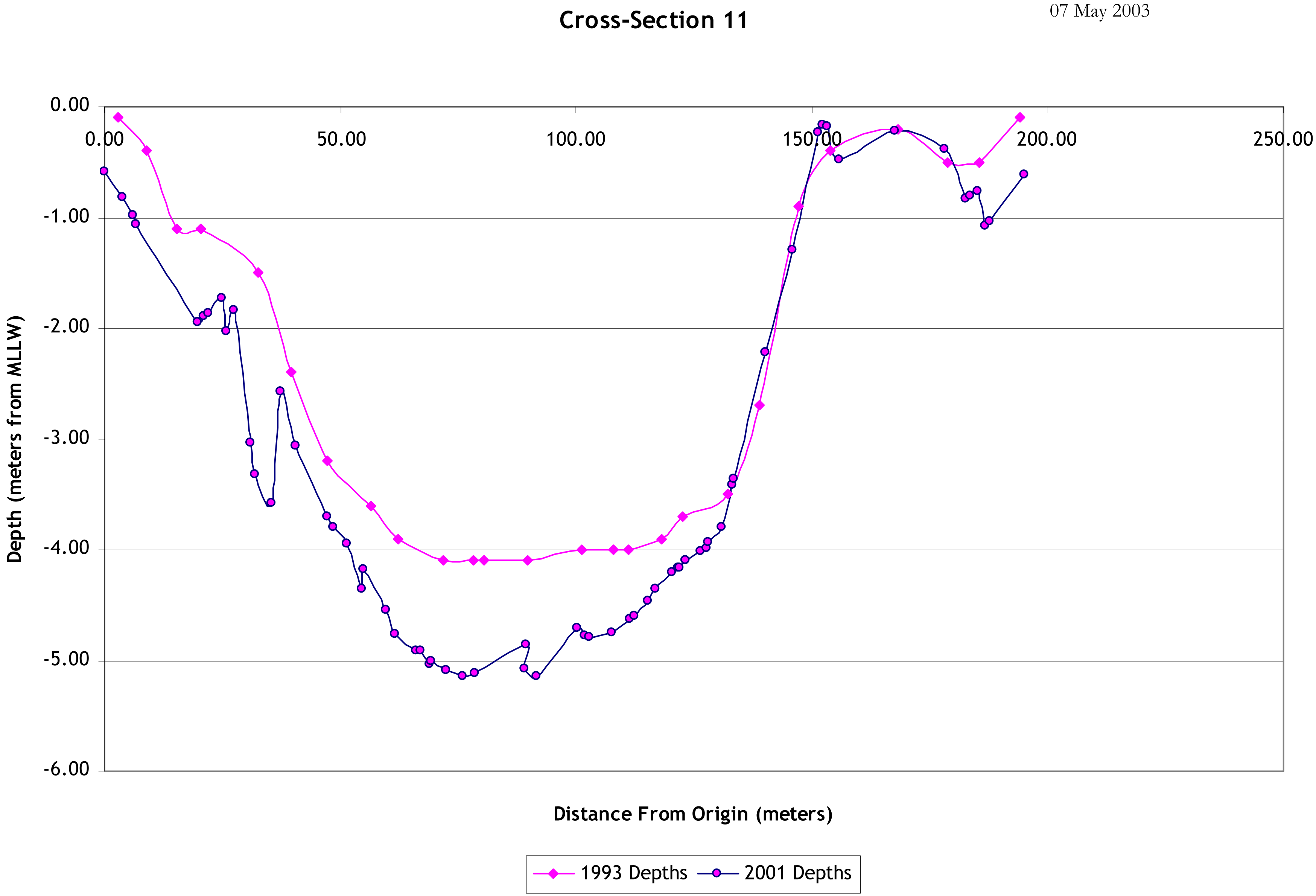
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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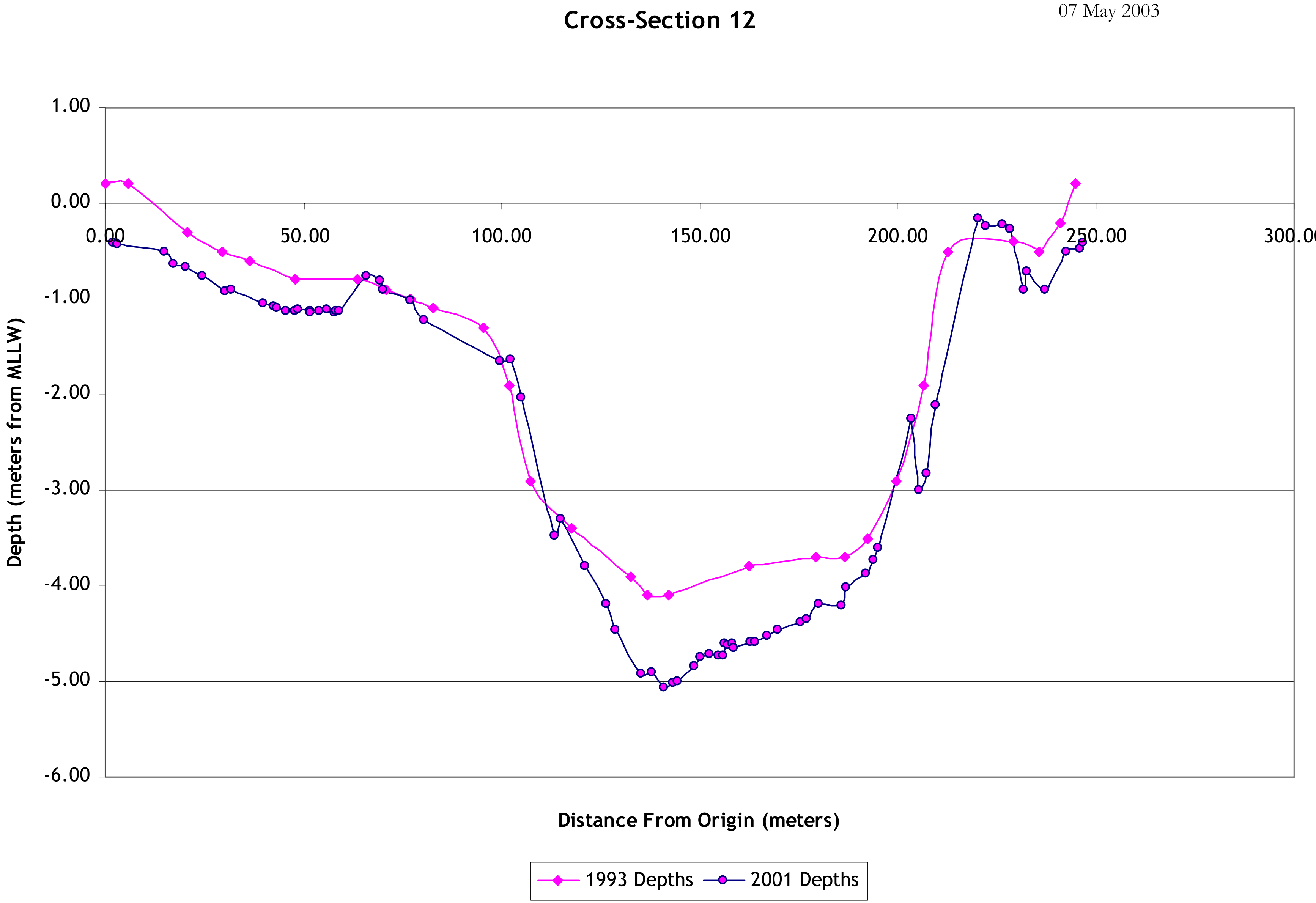
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths


Cross-Section 13
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Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths


Cross-Section 14
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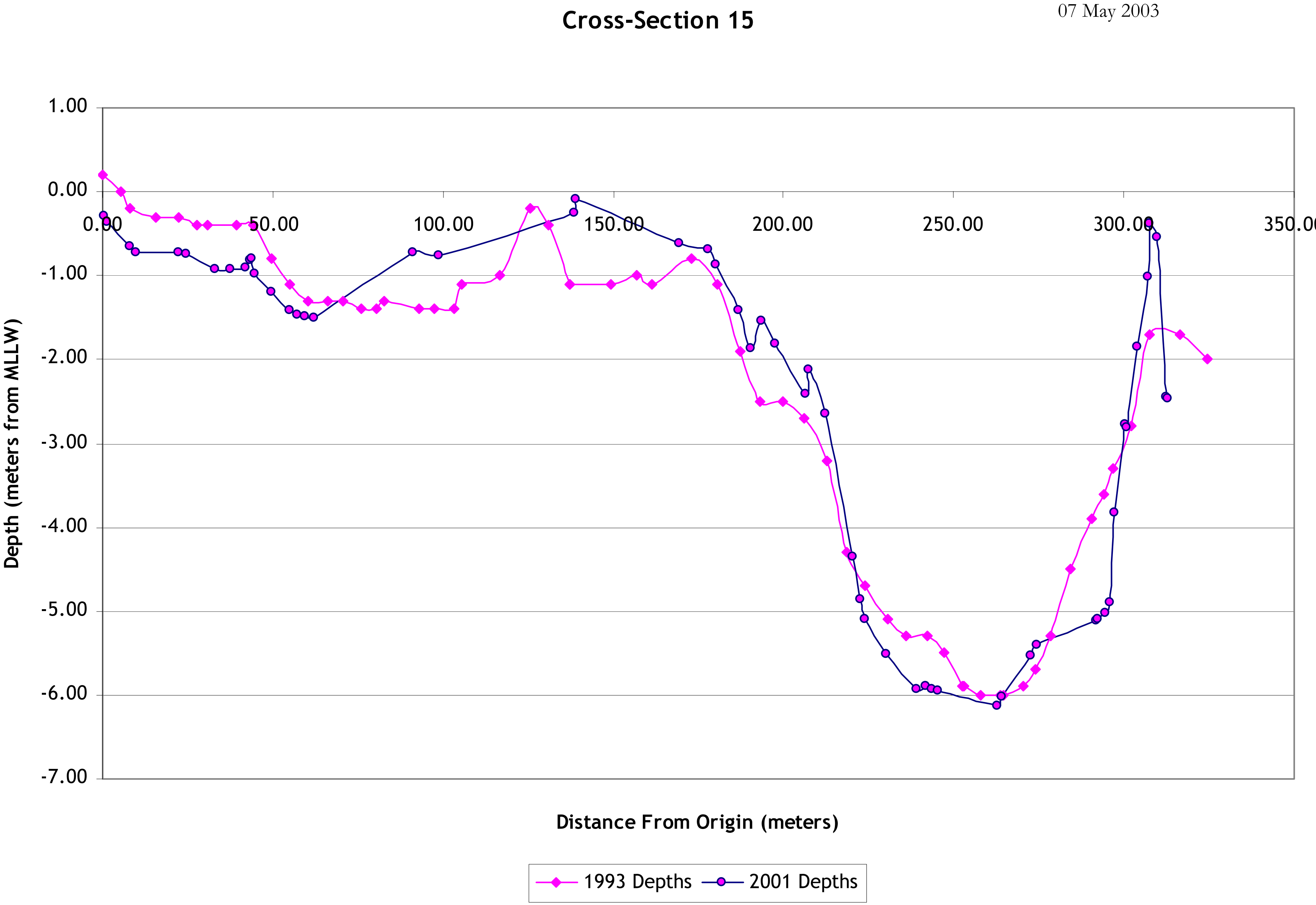
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
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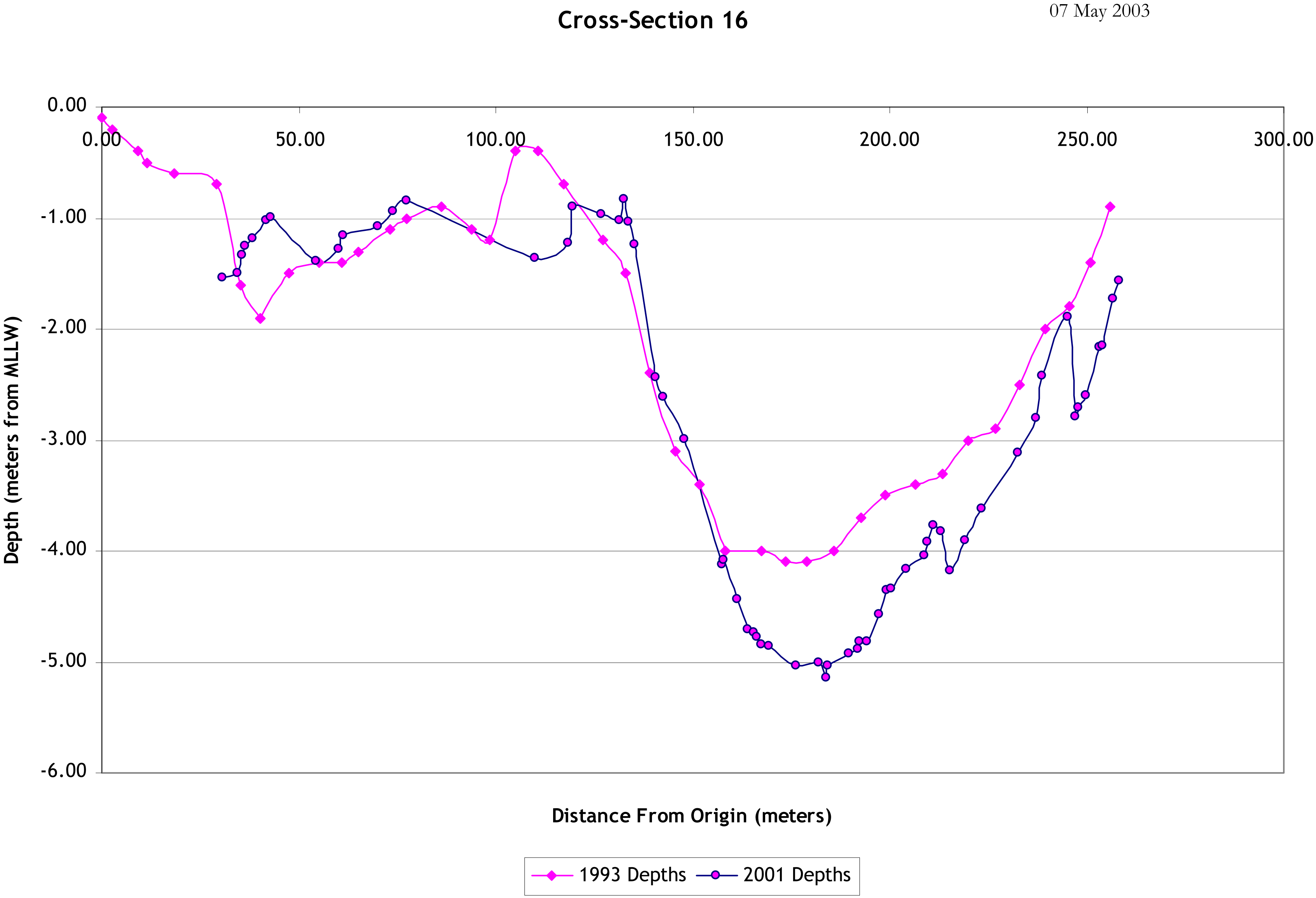
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Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths


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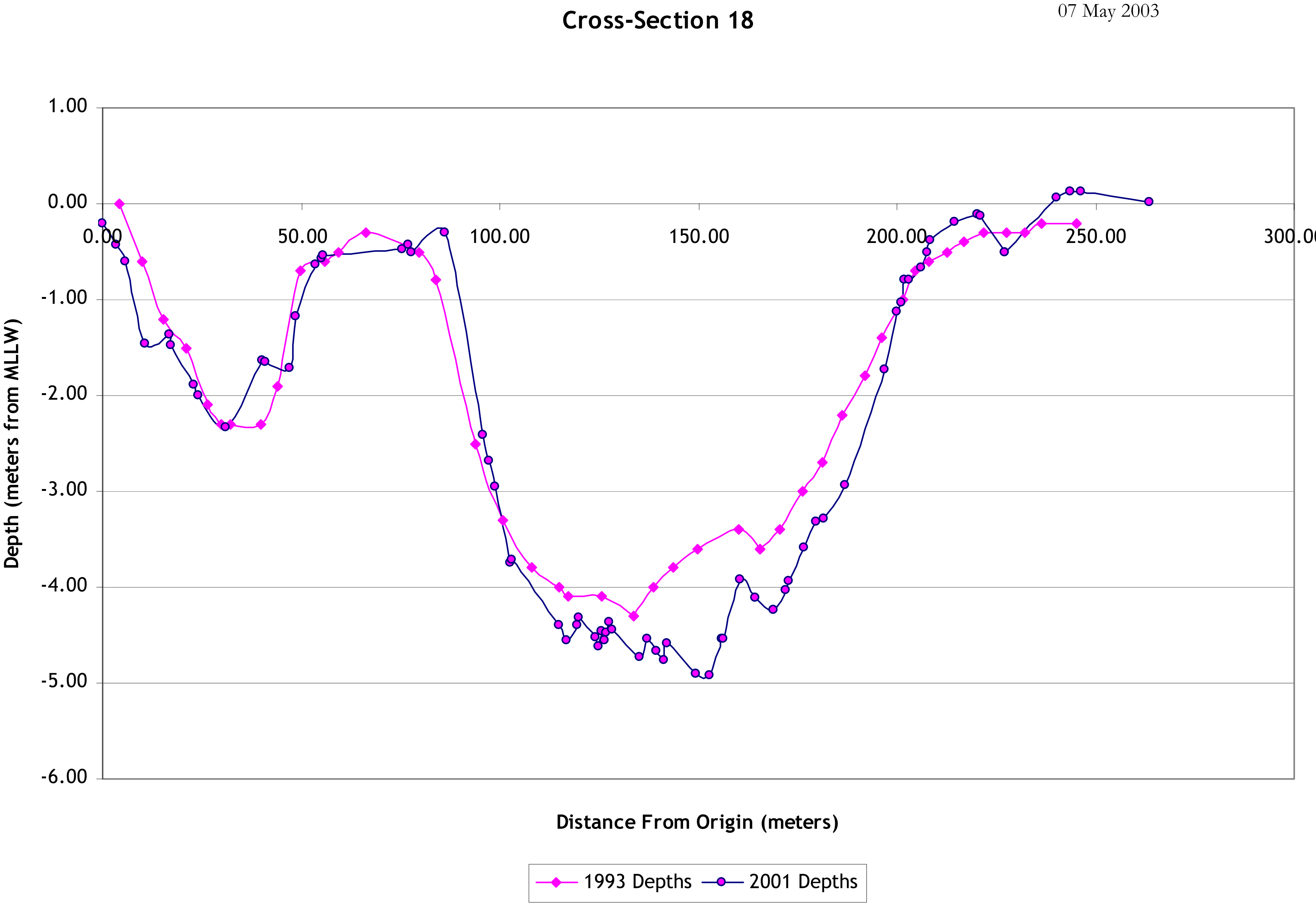
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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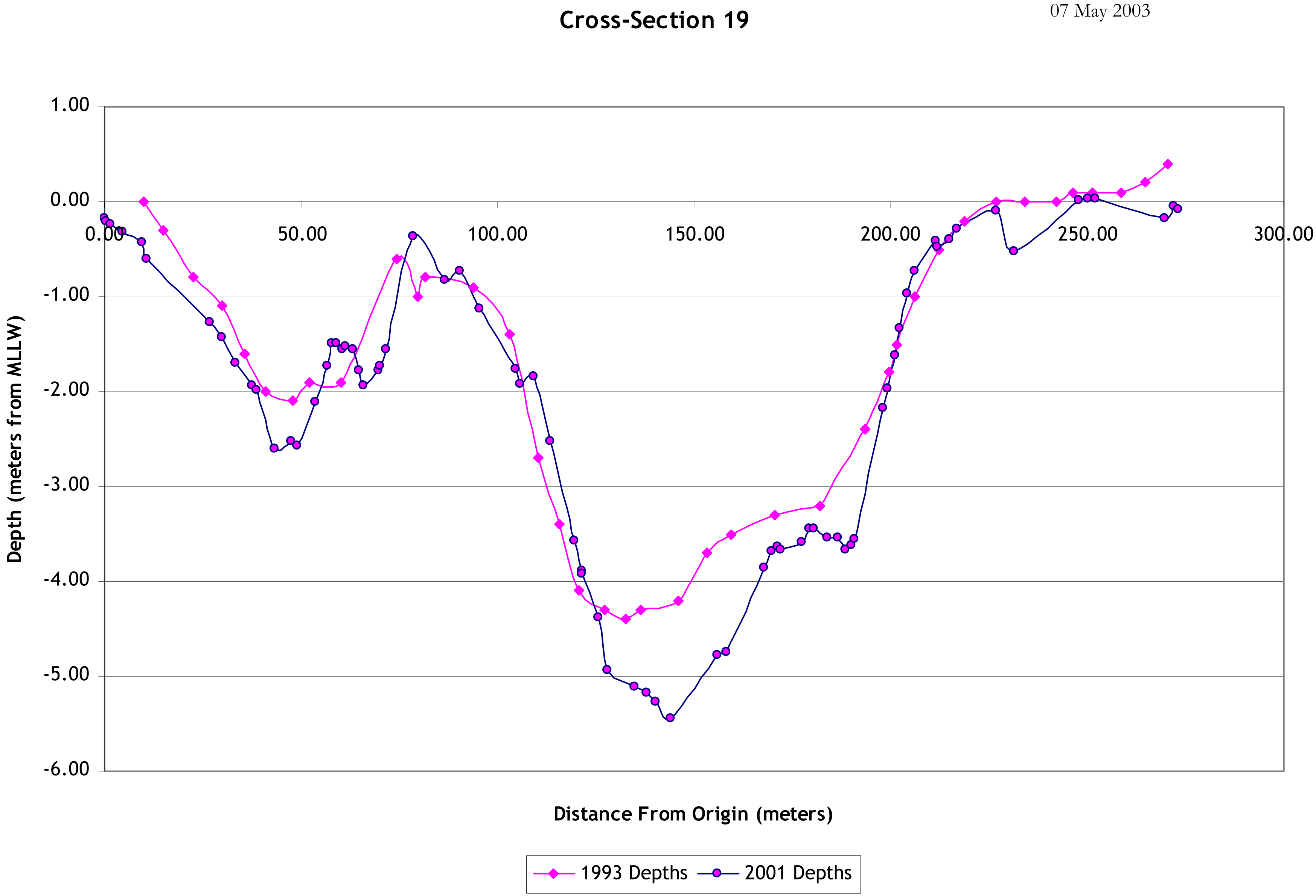
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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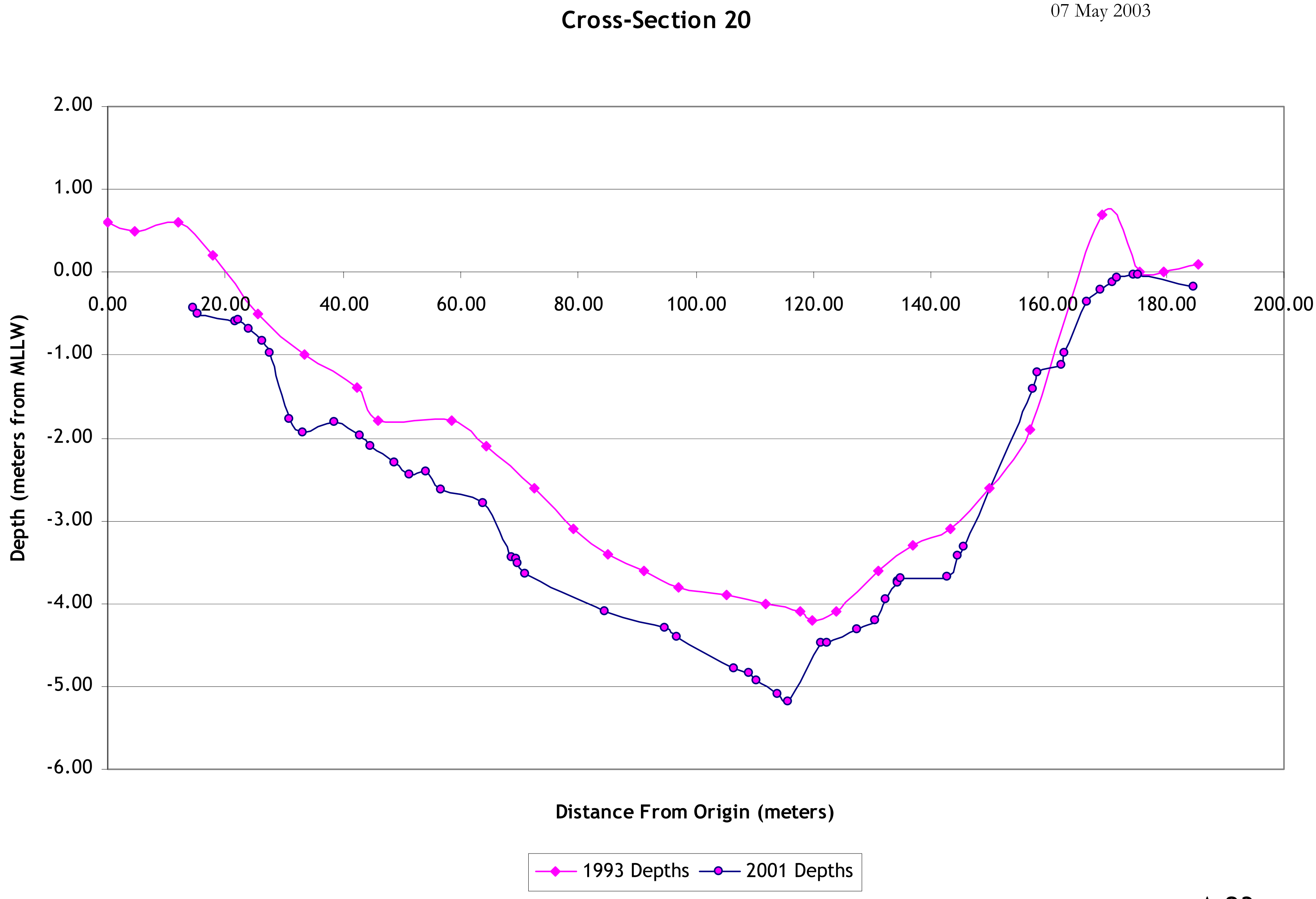
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths


Cross-Section 21
(This cross-section corresponds to CS-2 in Oliver 1988 and Malzone 1999)
Depth (meters from MLLW)
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120.00
140.00
160.00
180.00
Distance From Origin (meters)
1993 Depths
2001 Depths


Cross-Section 22
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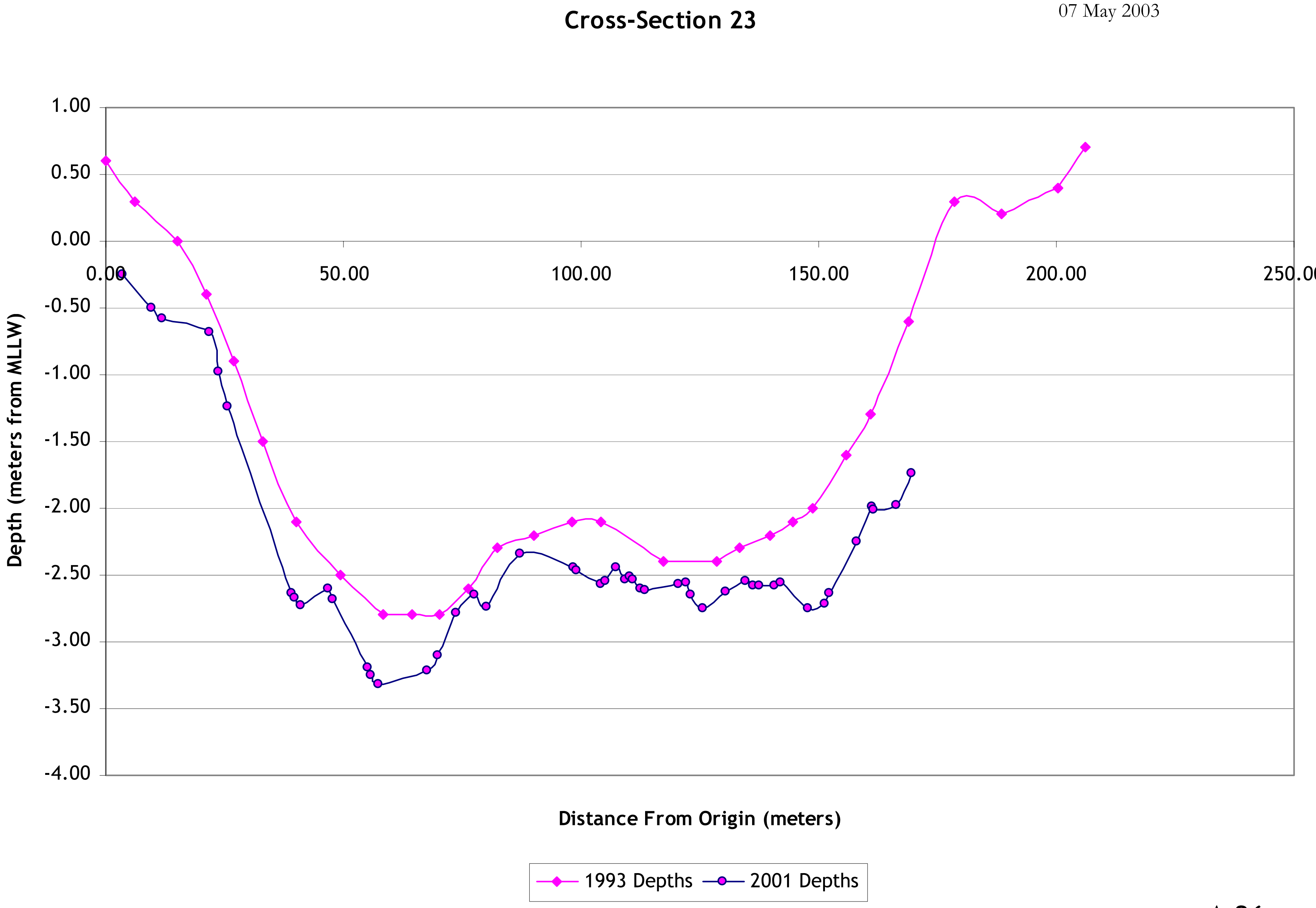
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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-4.00
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100.00
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200.00
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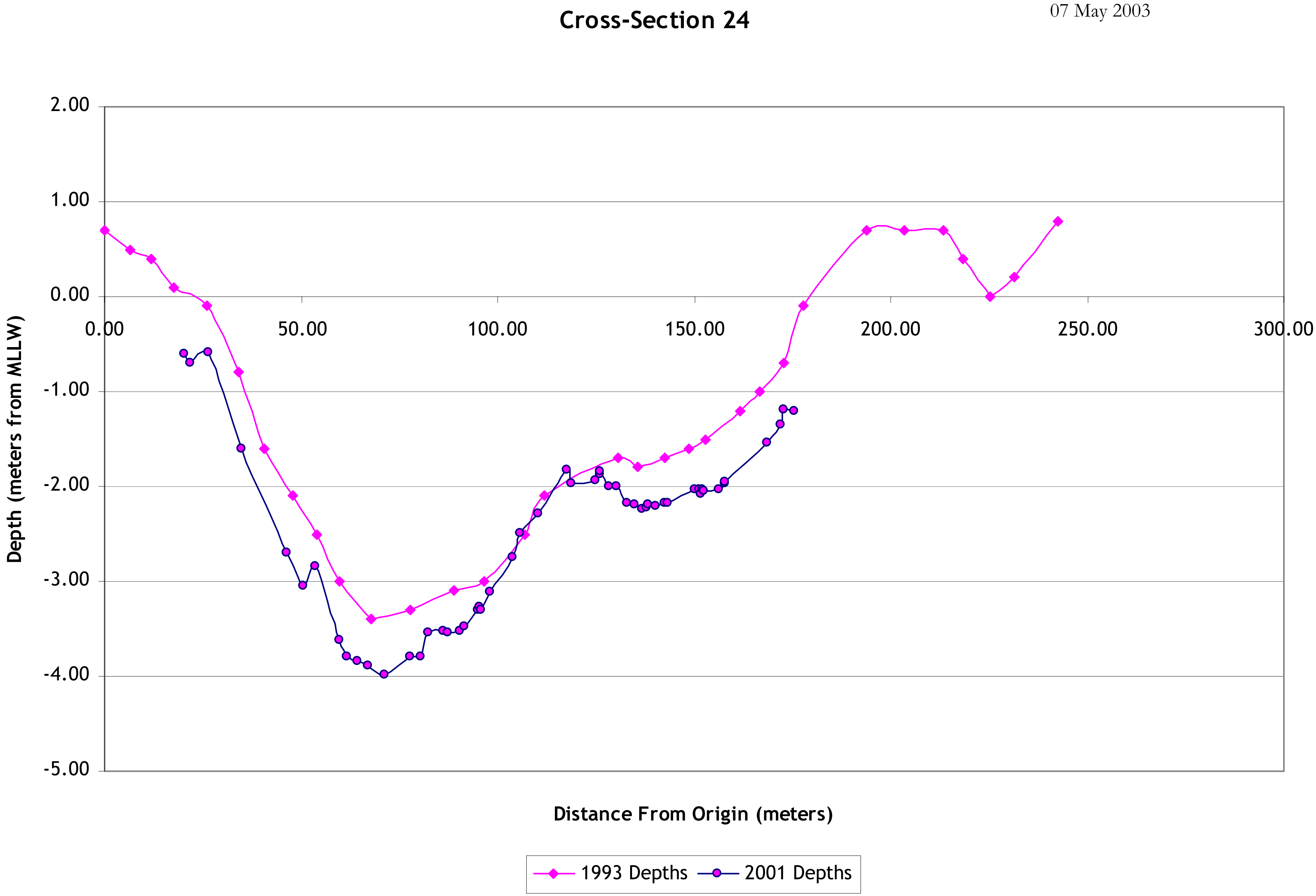
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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Depth (meters from MLLW)
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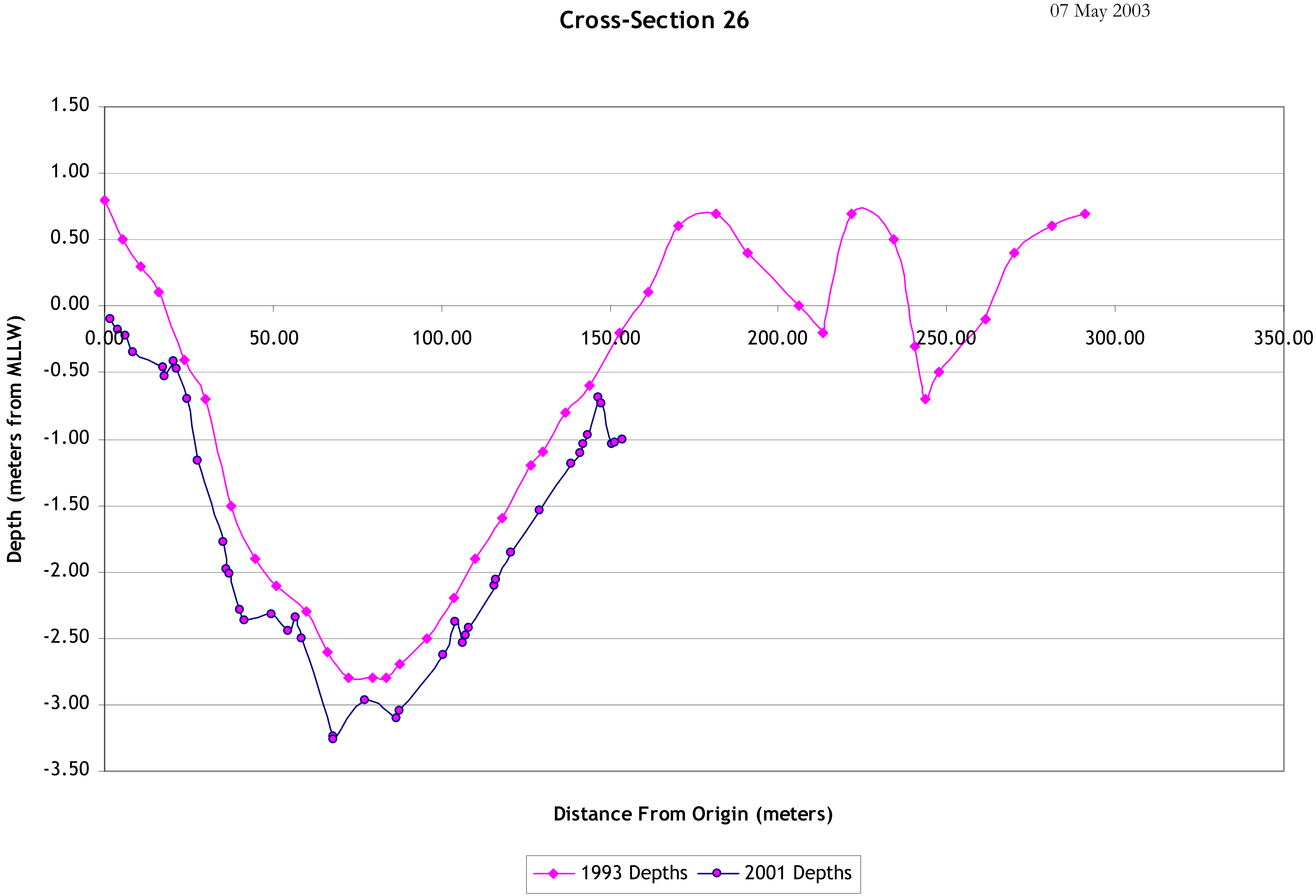
100.00
150.00
200.00
250.00
300.00
Distance From Origin (meters)
1993 Depths
2001 Depths

Edwin Wendell Dean III
Tidal Scour in Elkhorn Slough
07 May 2003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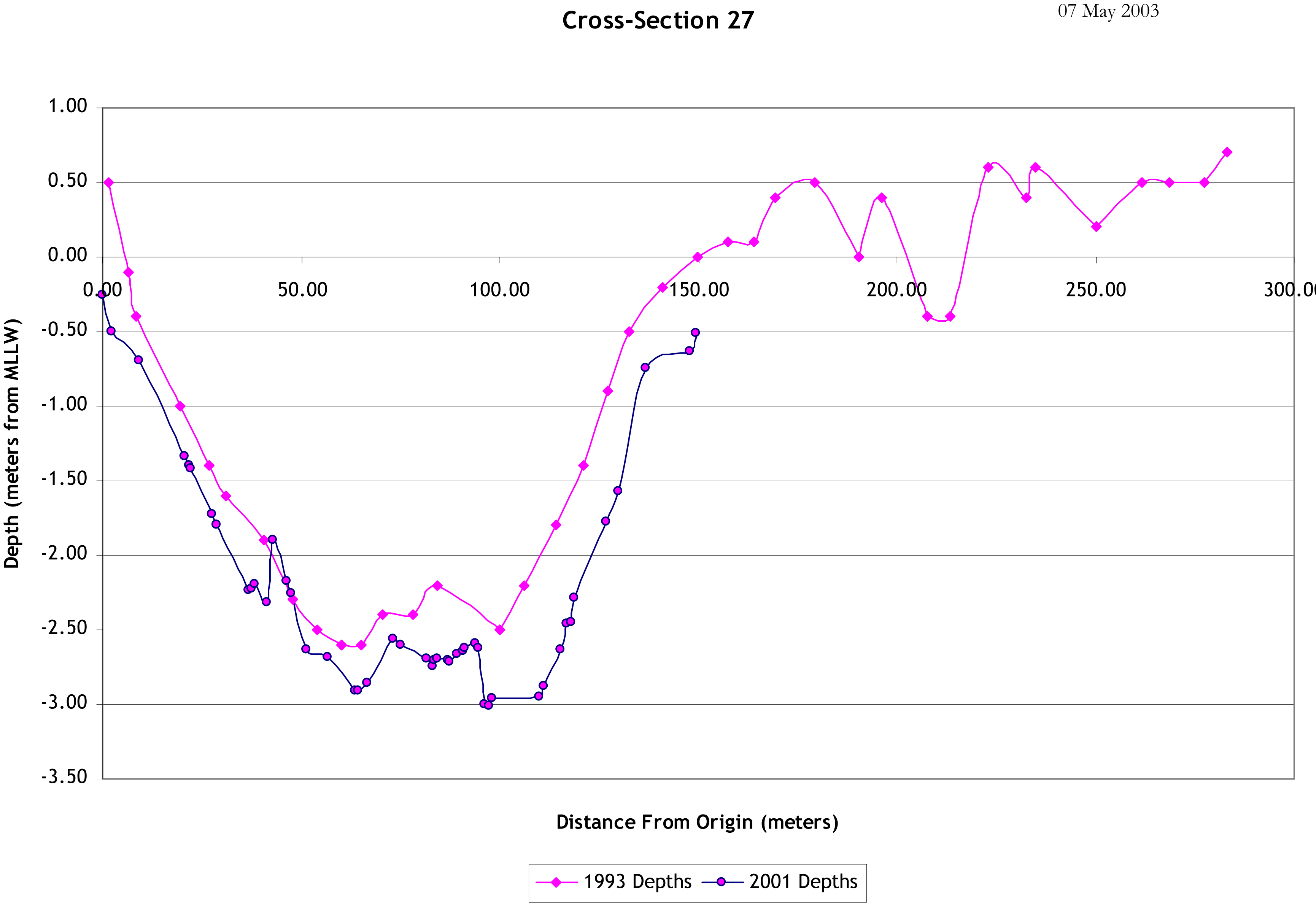
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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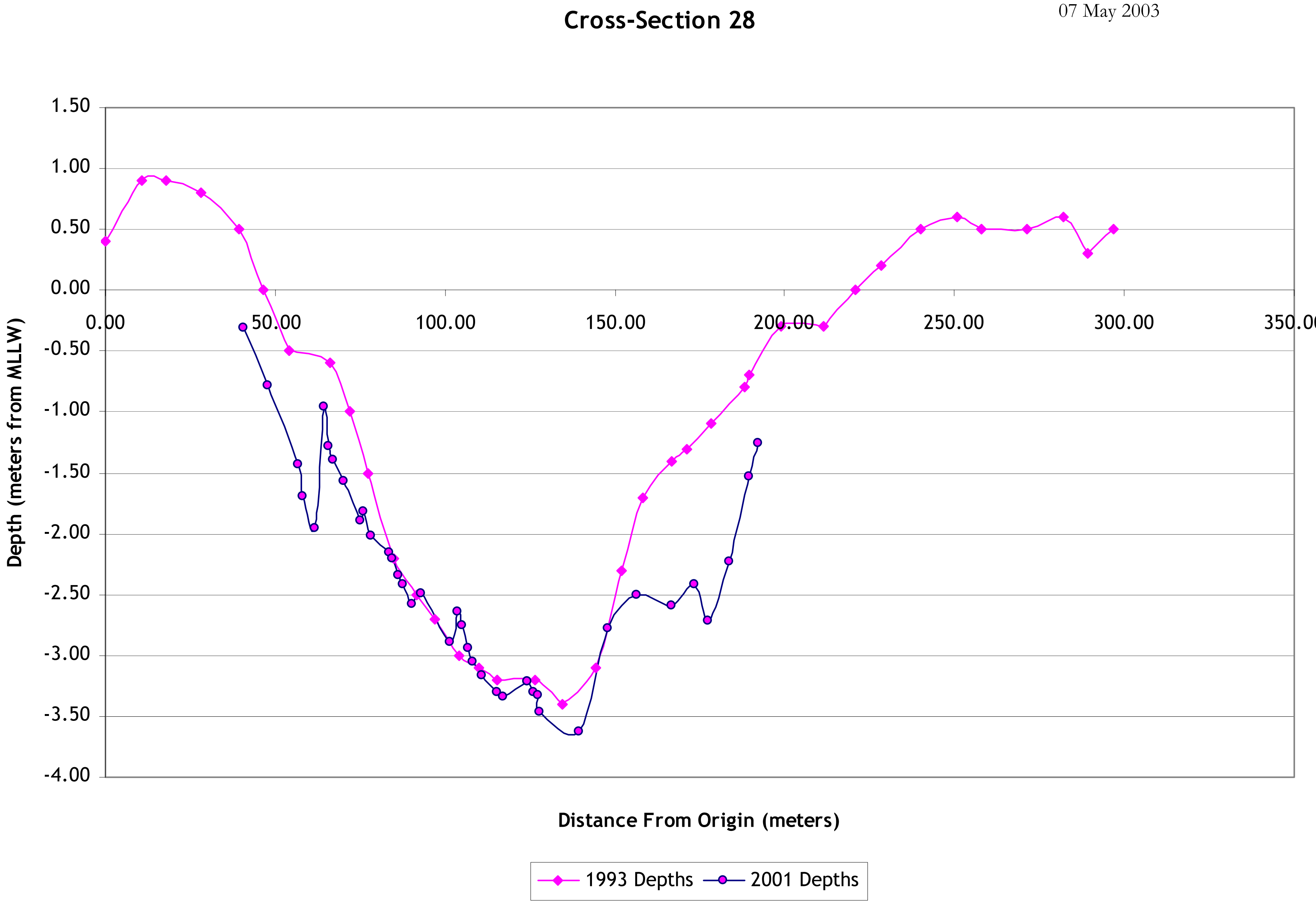
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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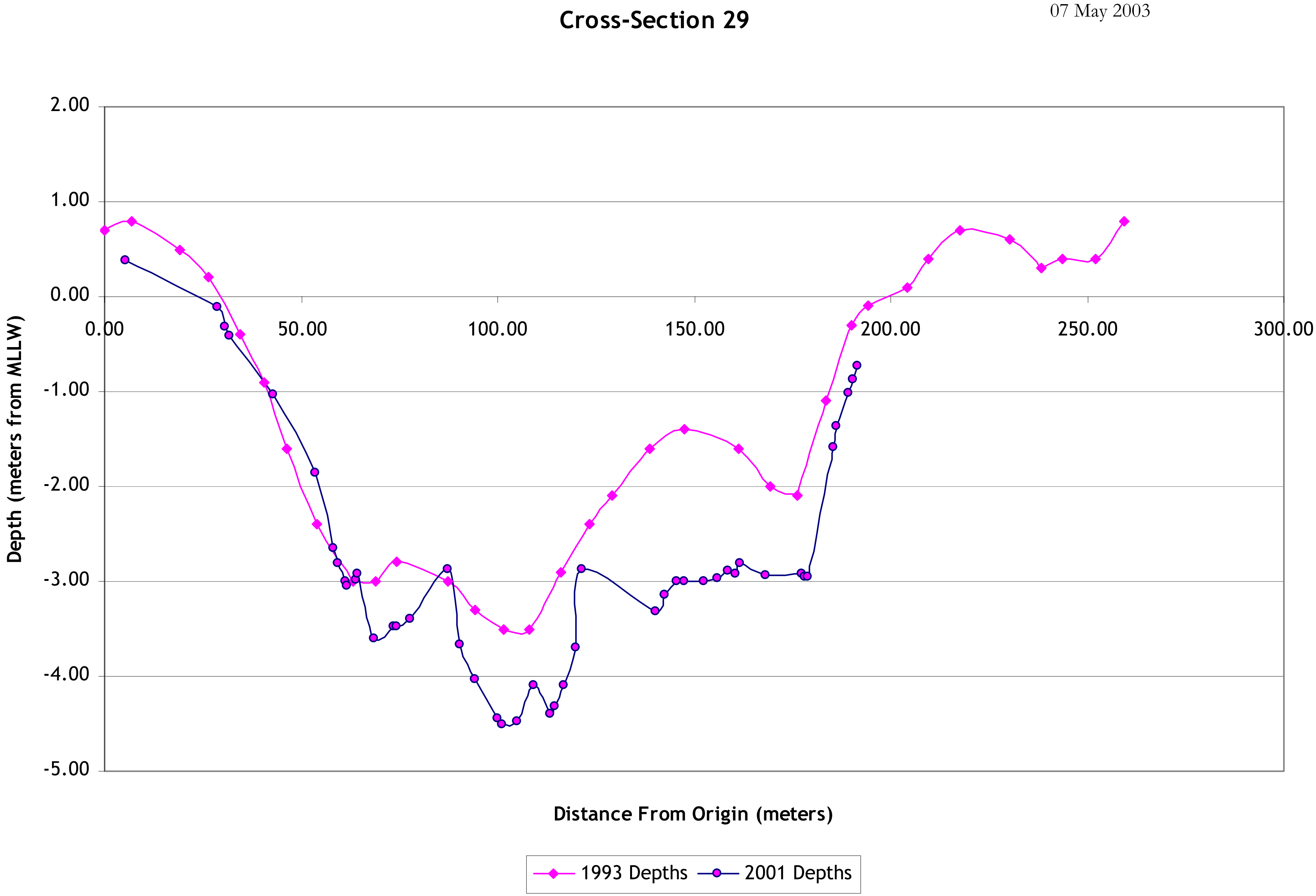
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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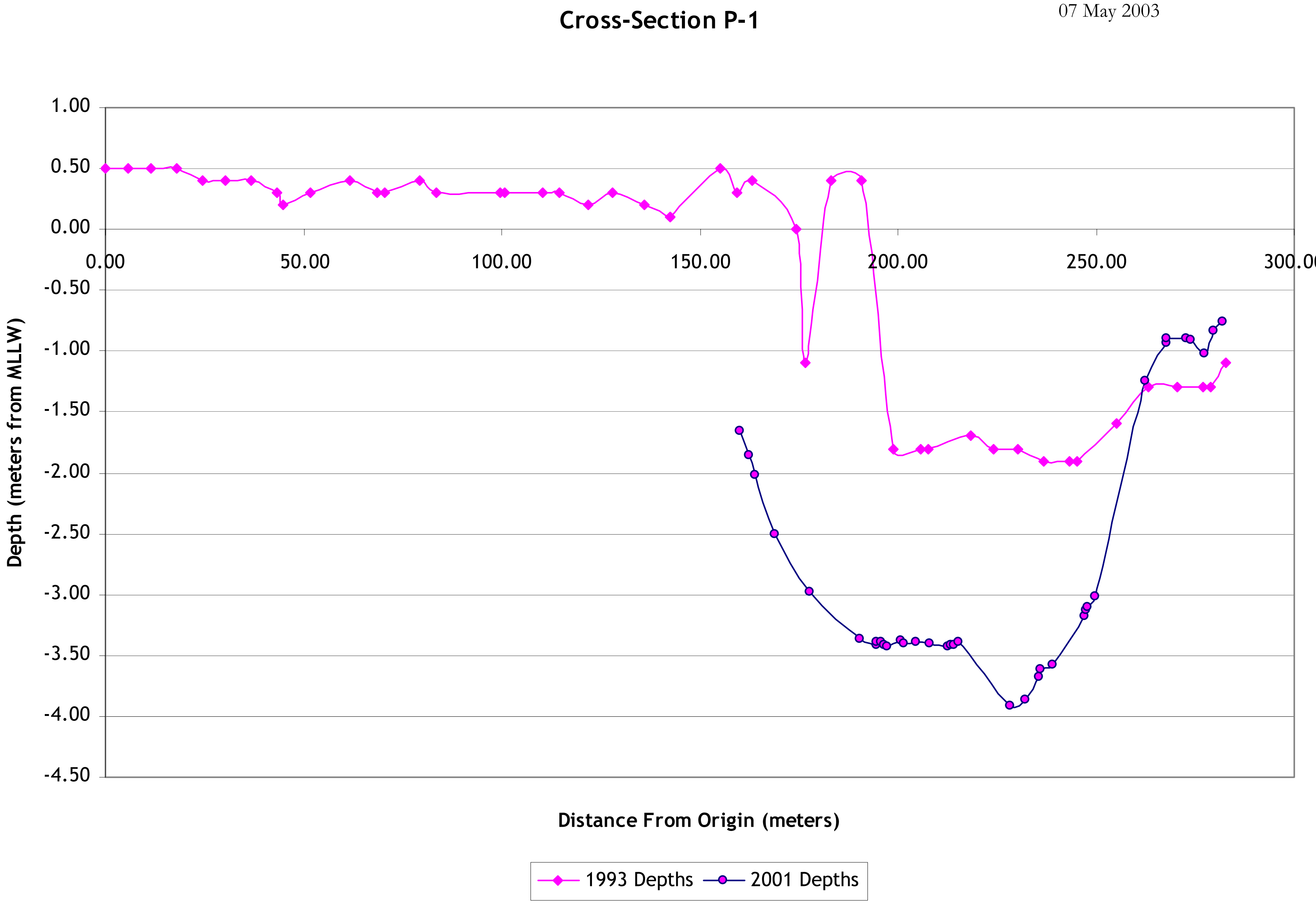
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths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-4.00
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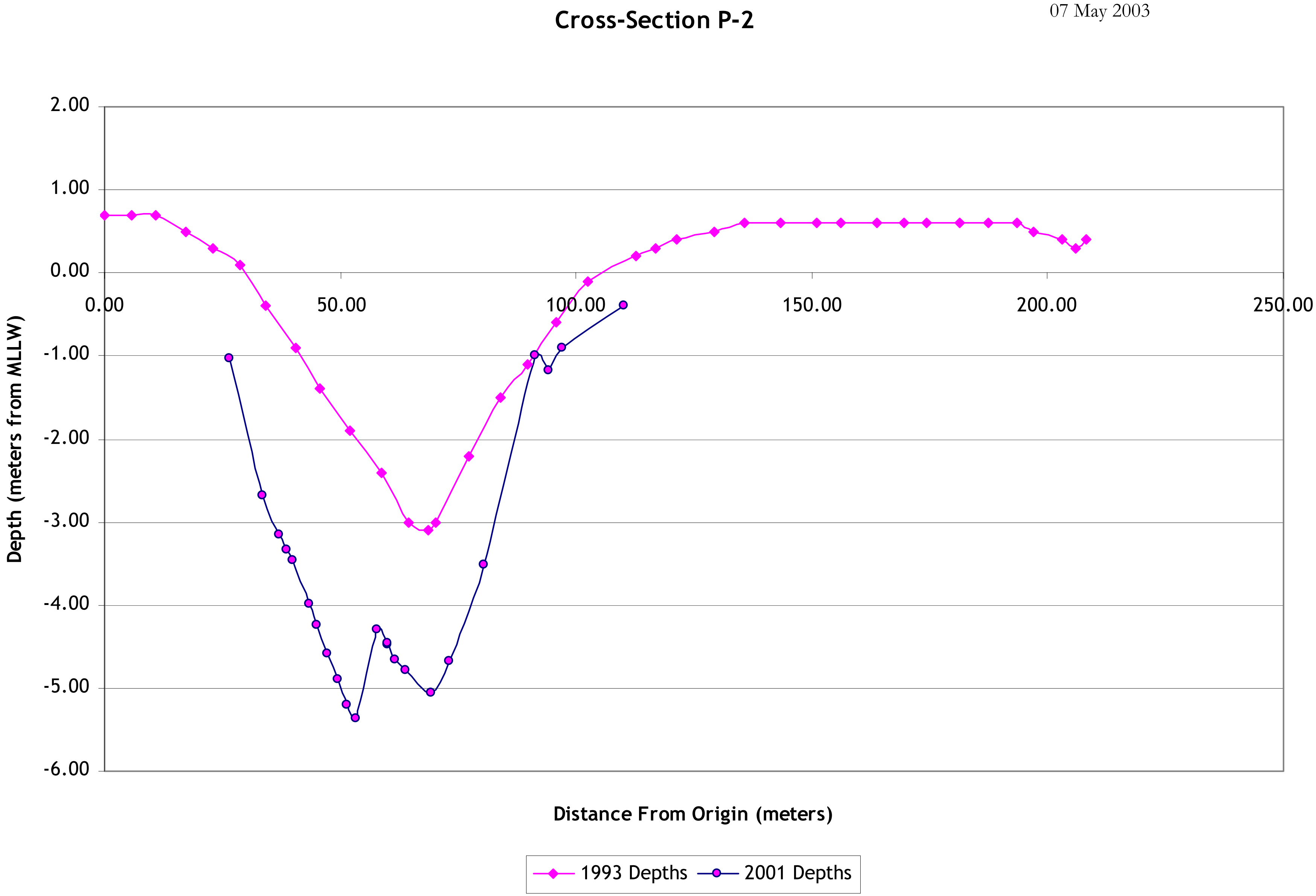
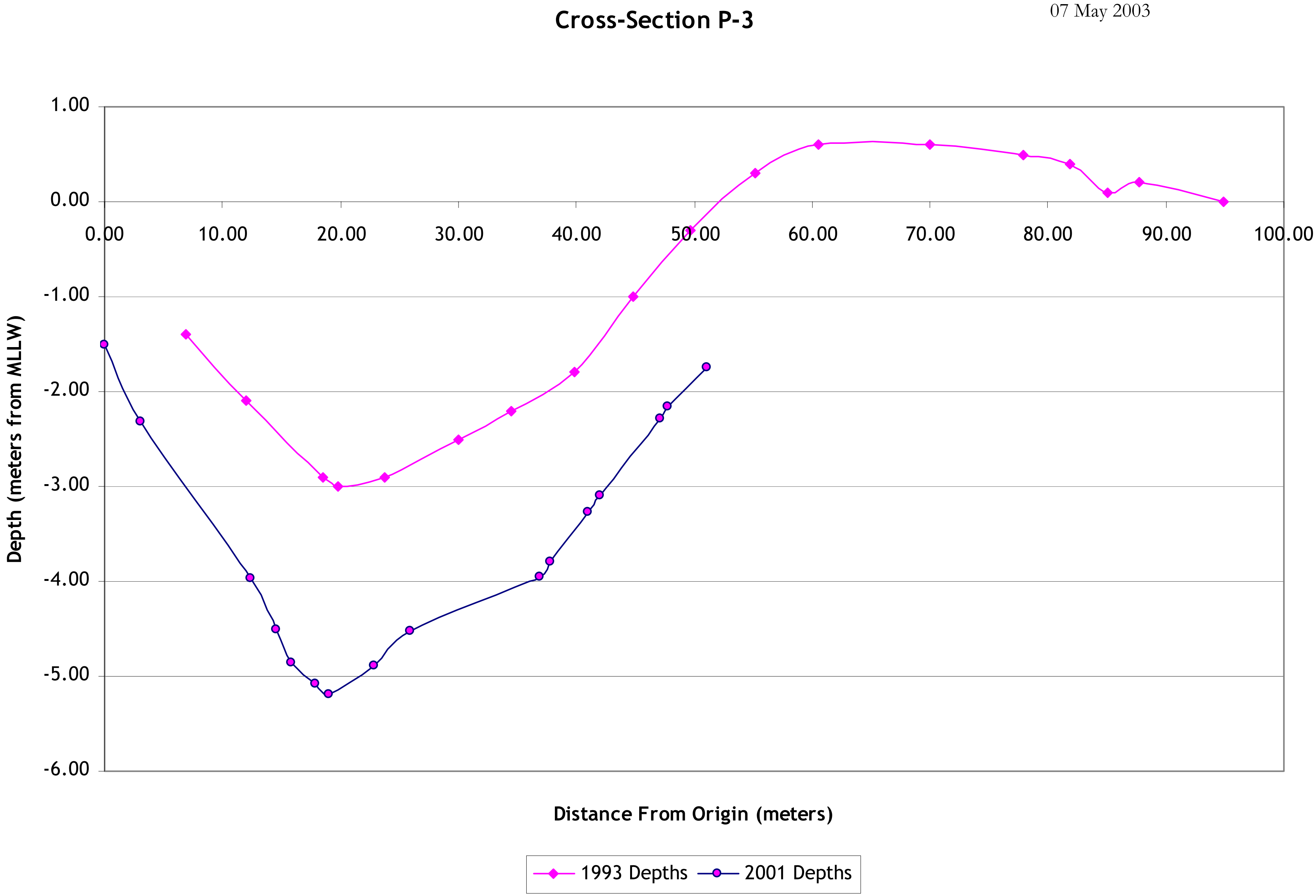
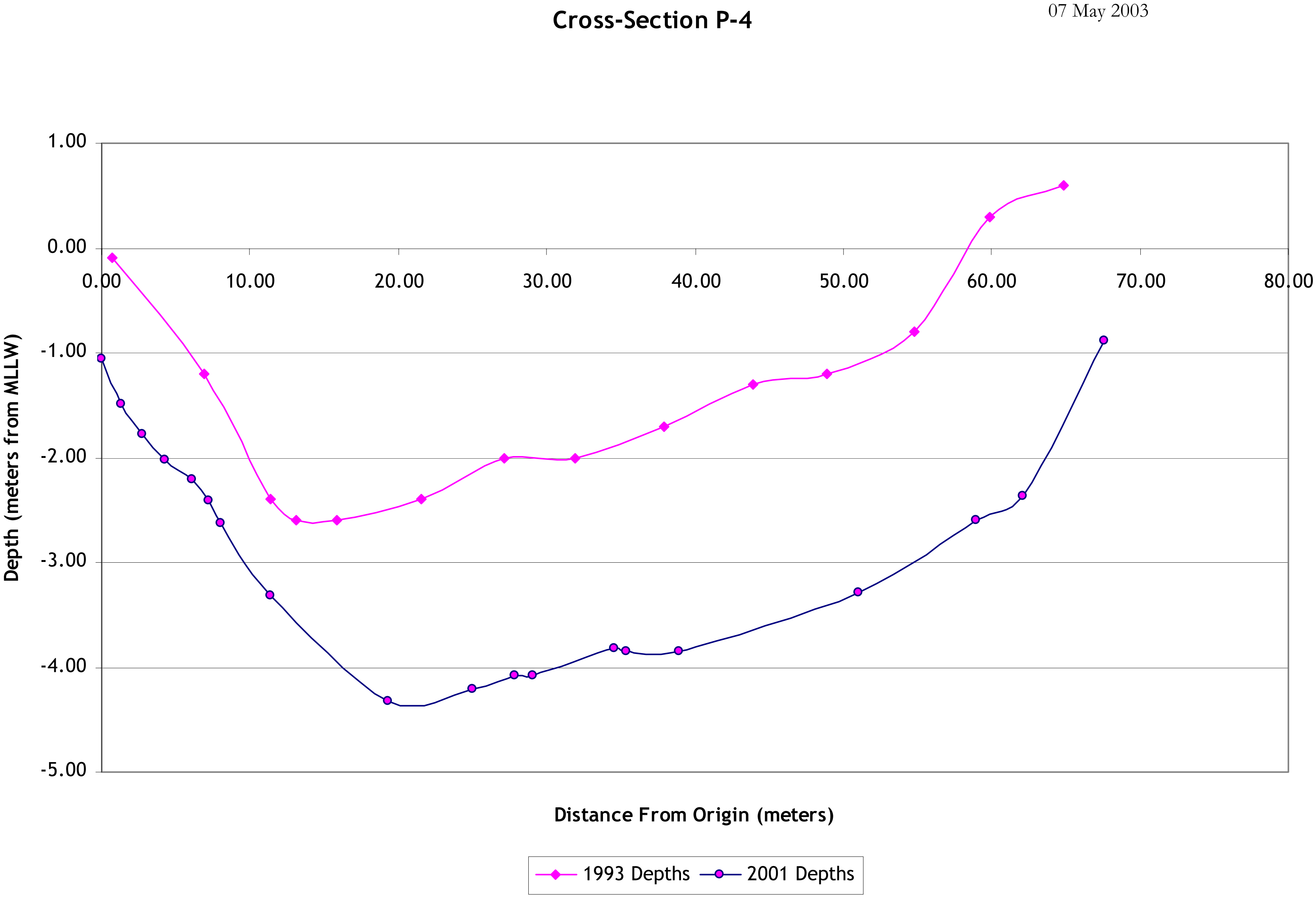
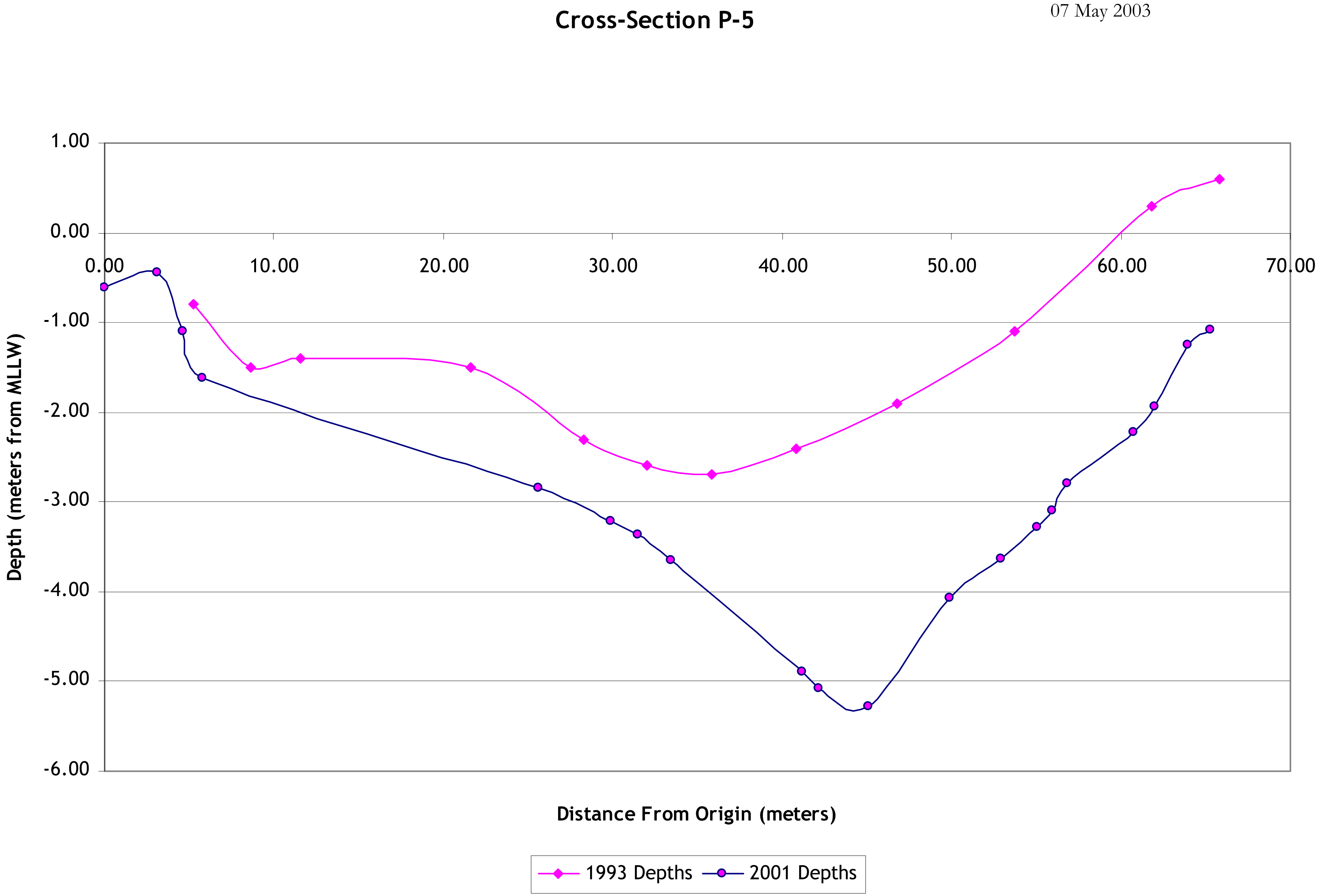
150.00
200.00
250.00
300.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths


Cross-Section P-2
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
0.00
50.00
100.00
150.00
200.00
250.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths


Cross-Section P-3
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths


Cross-Section P-4
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths


Cross-Section P-5
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
-6.00
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths

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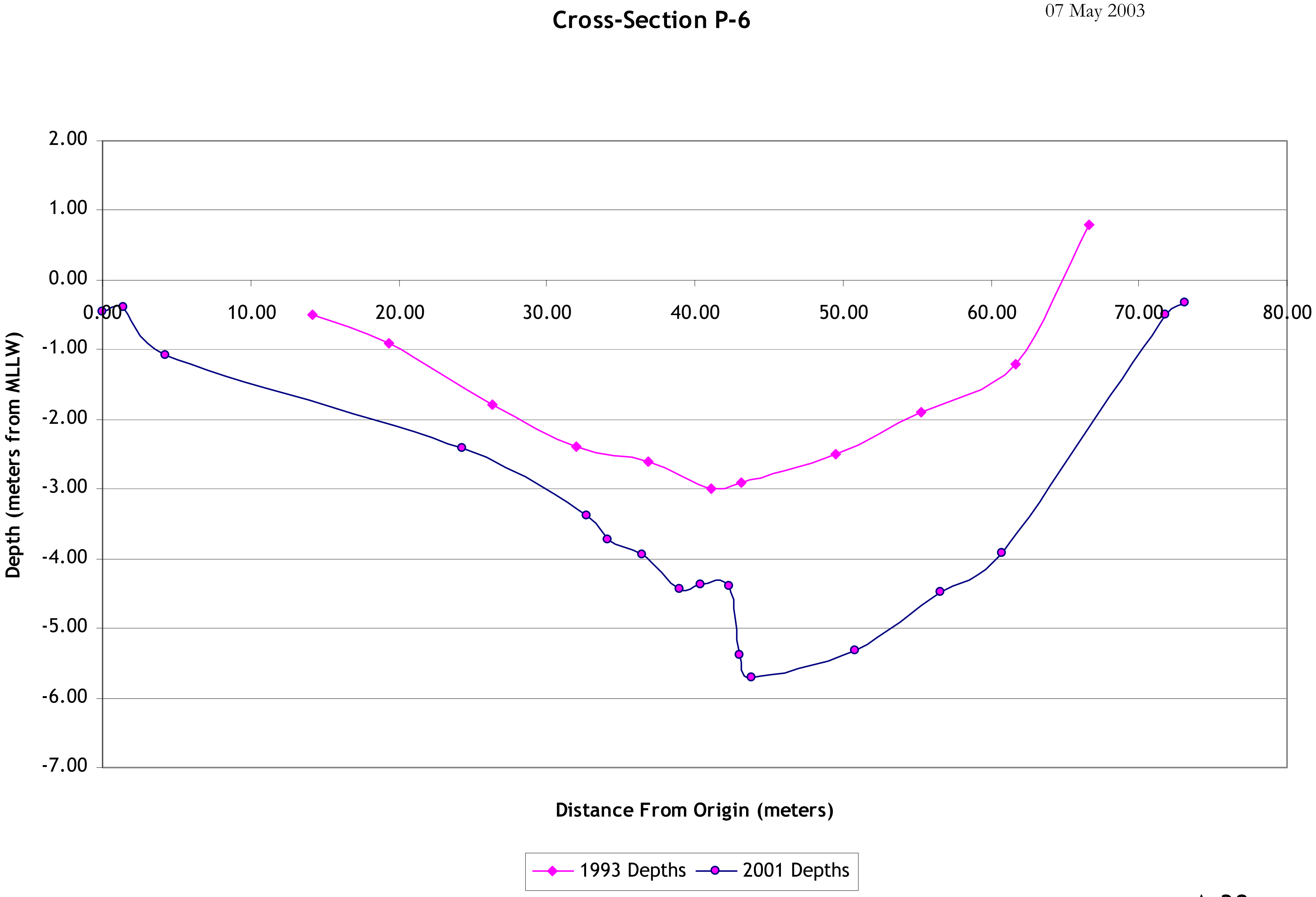
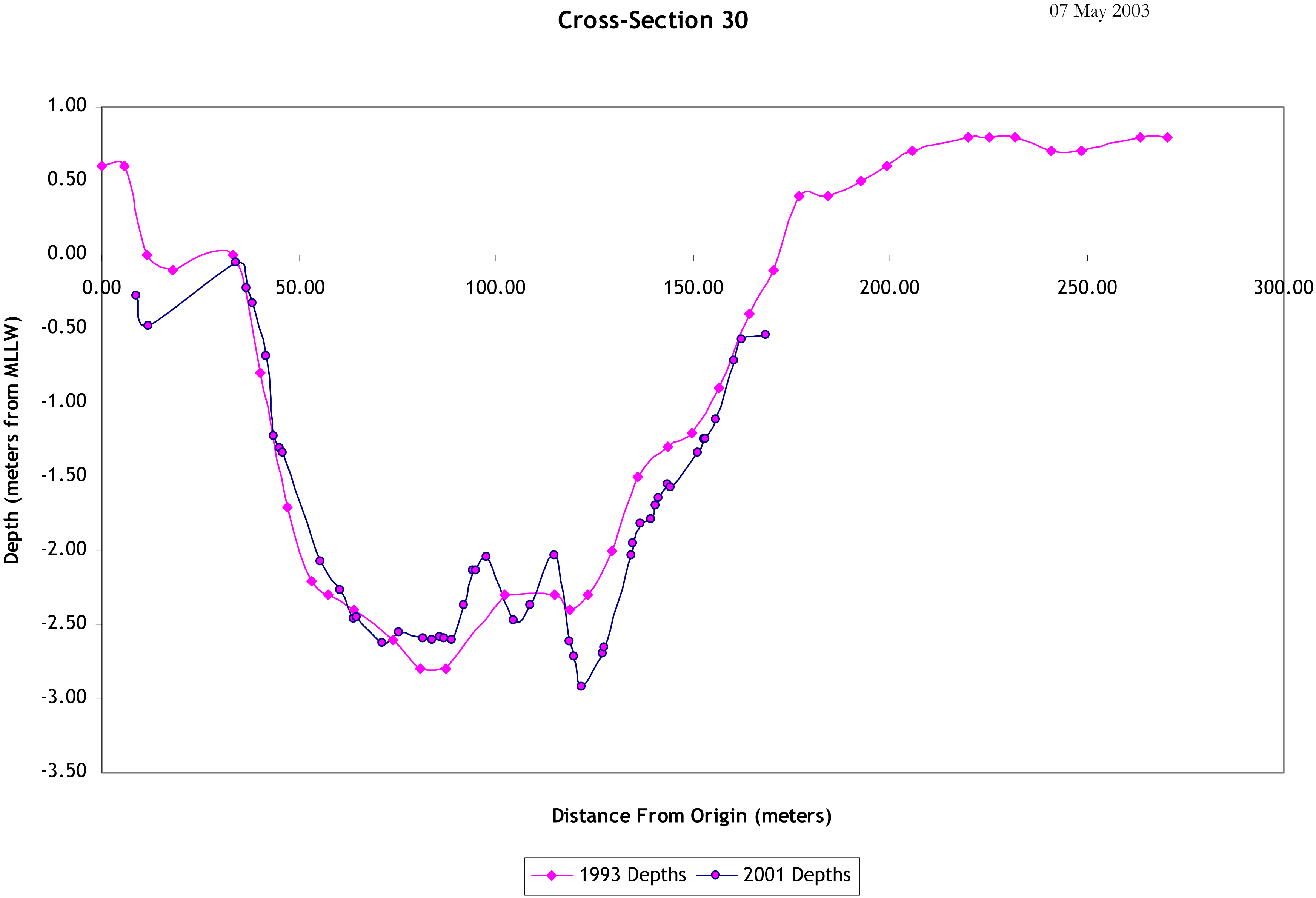
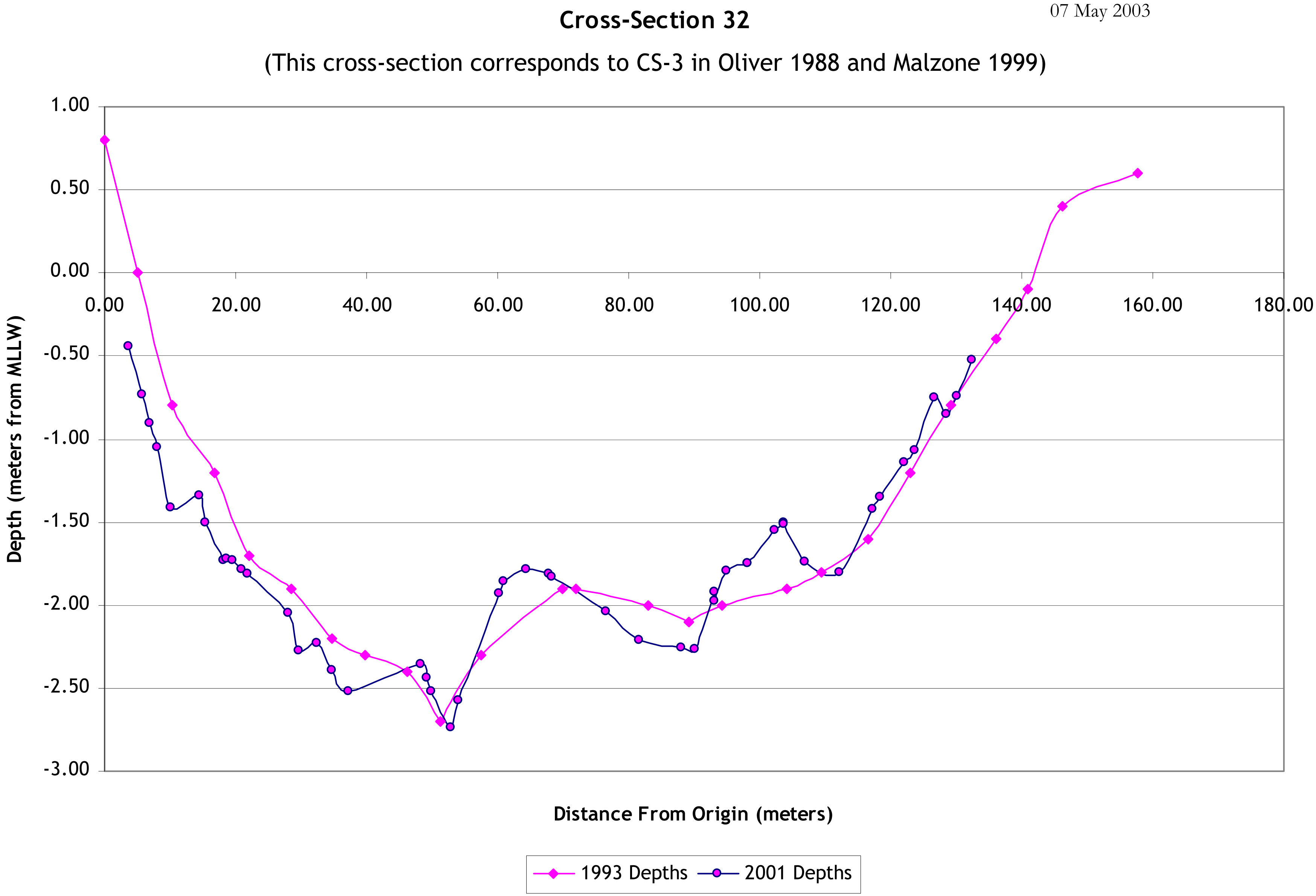



Cross-Section 30
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
0.00
50.00
100.00
150.00
200.00
250.00
300.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths


Cross-Section 31
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
0.00
50.00
100.00
150.00
200.00
250.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths


Cross-Section 32
(This cross-section corresponds to CS-3 in Oliver 1988 and Malzone 1999)
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths

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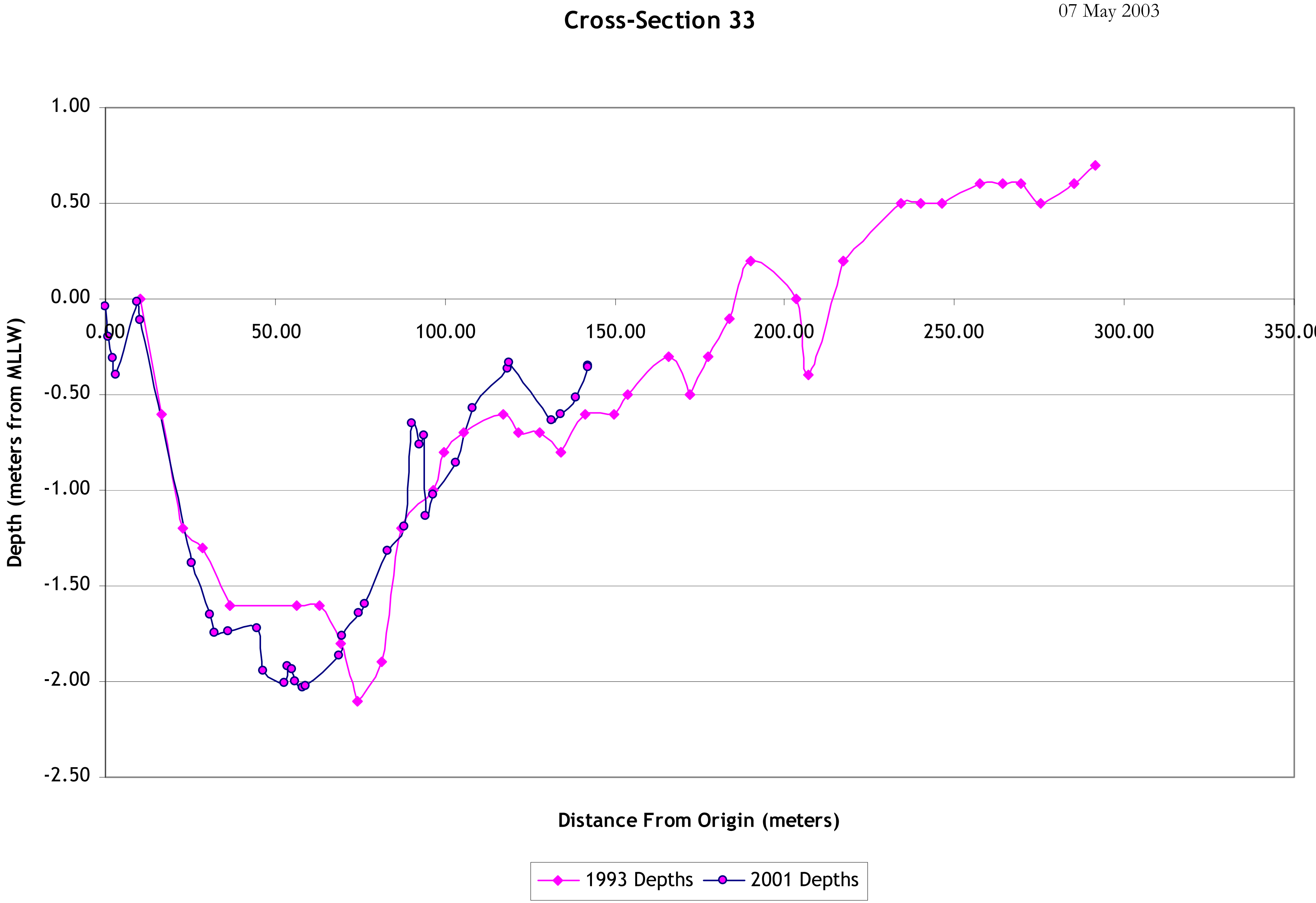

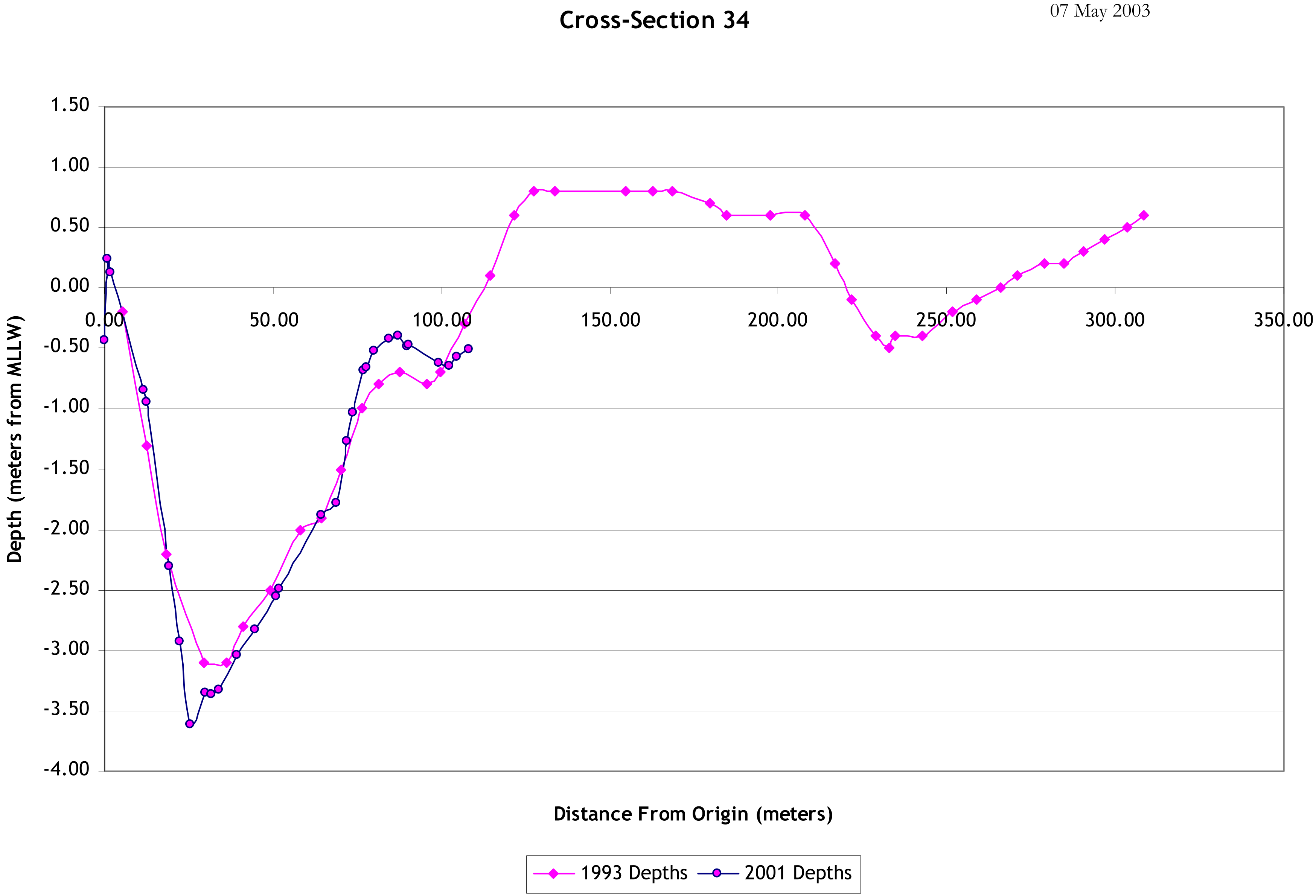
Cross-Section 34
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths

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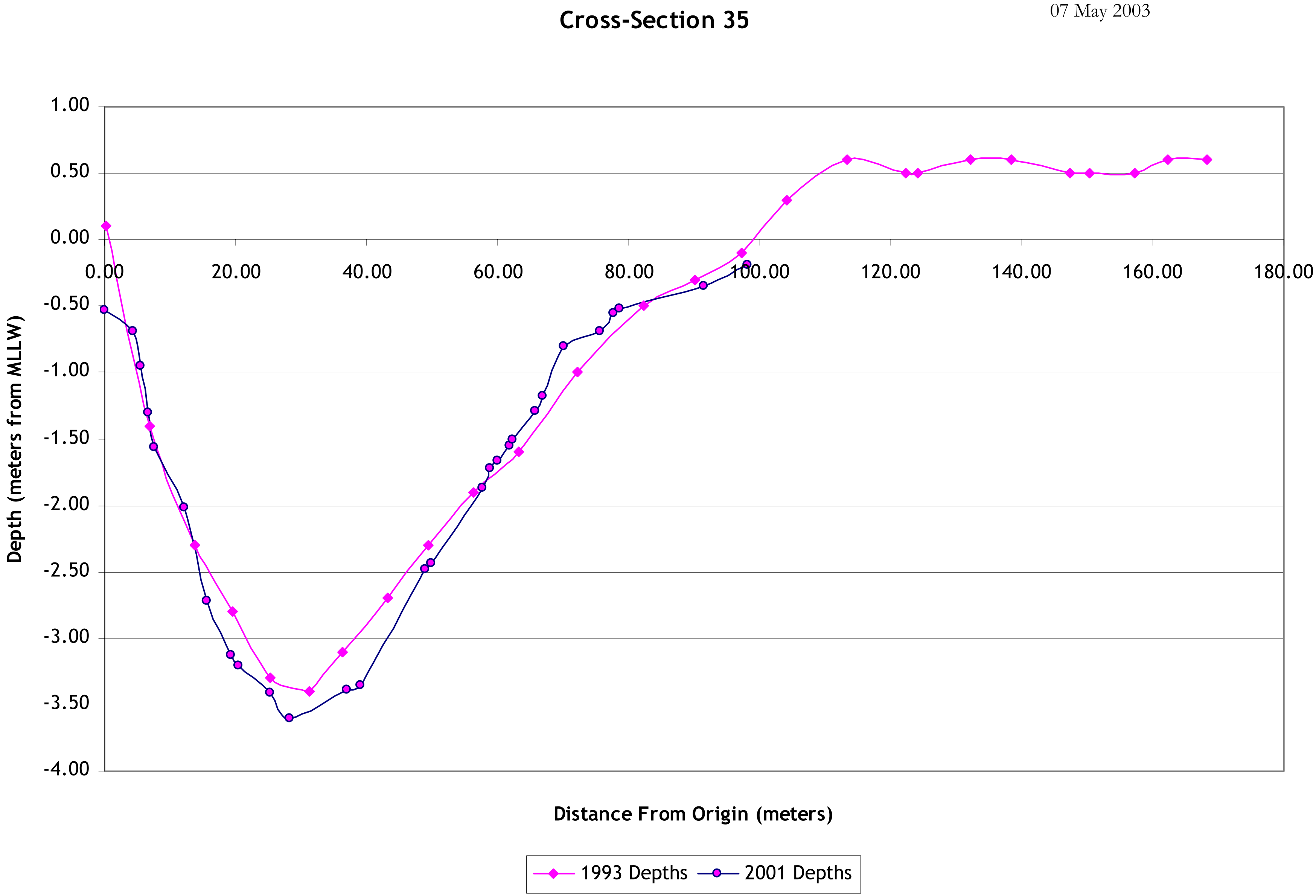
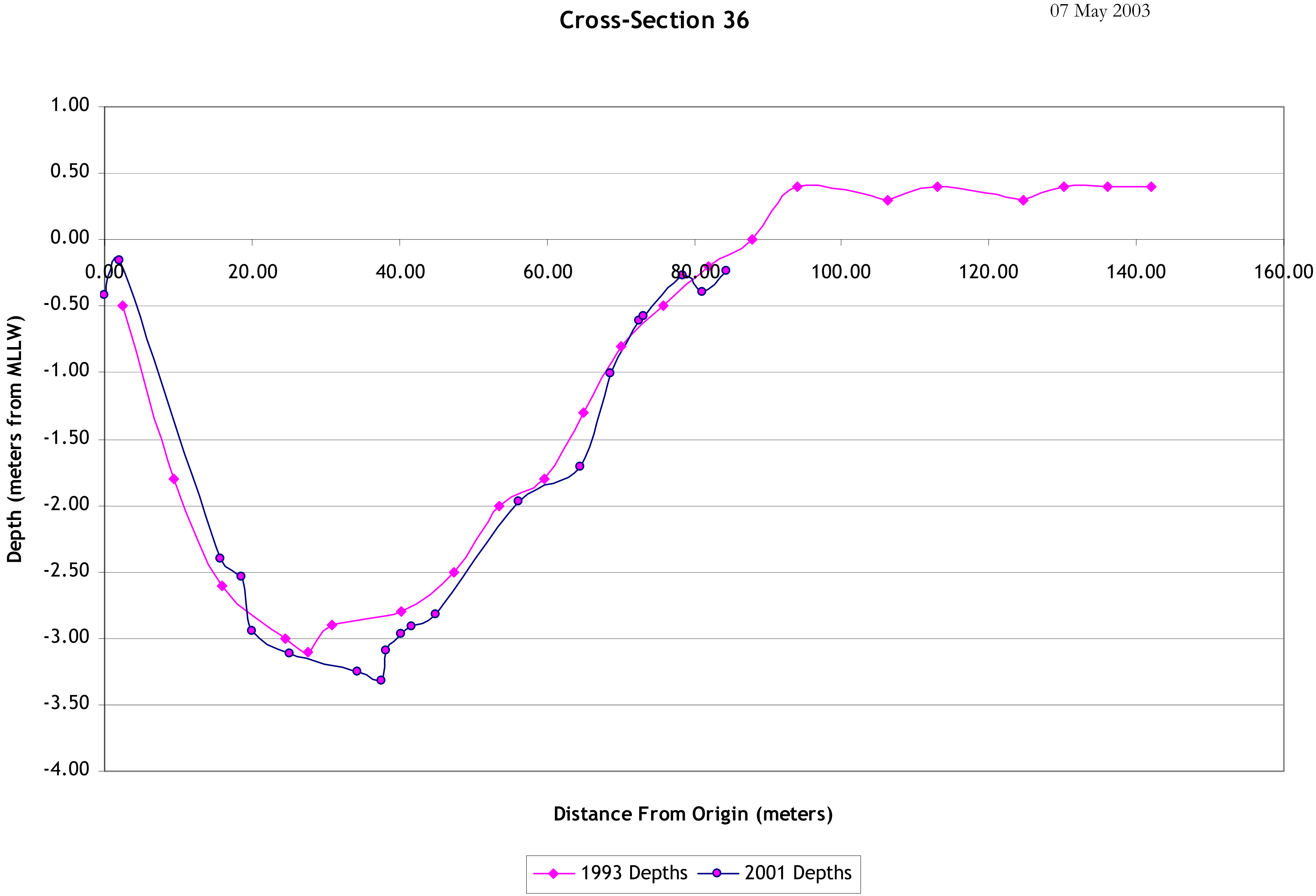
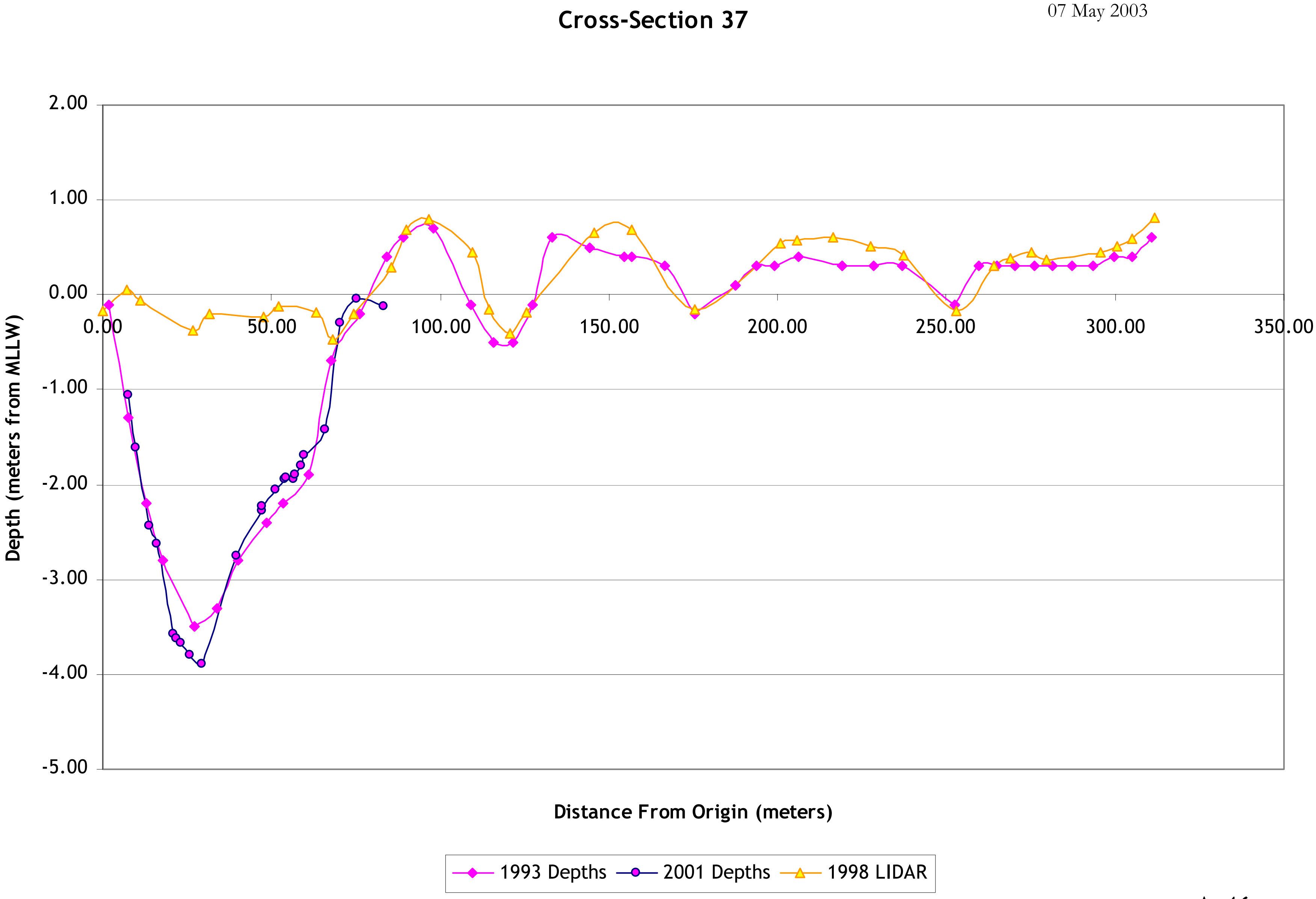



Cross-Section 36
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths


Cross-Section 37
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR

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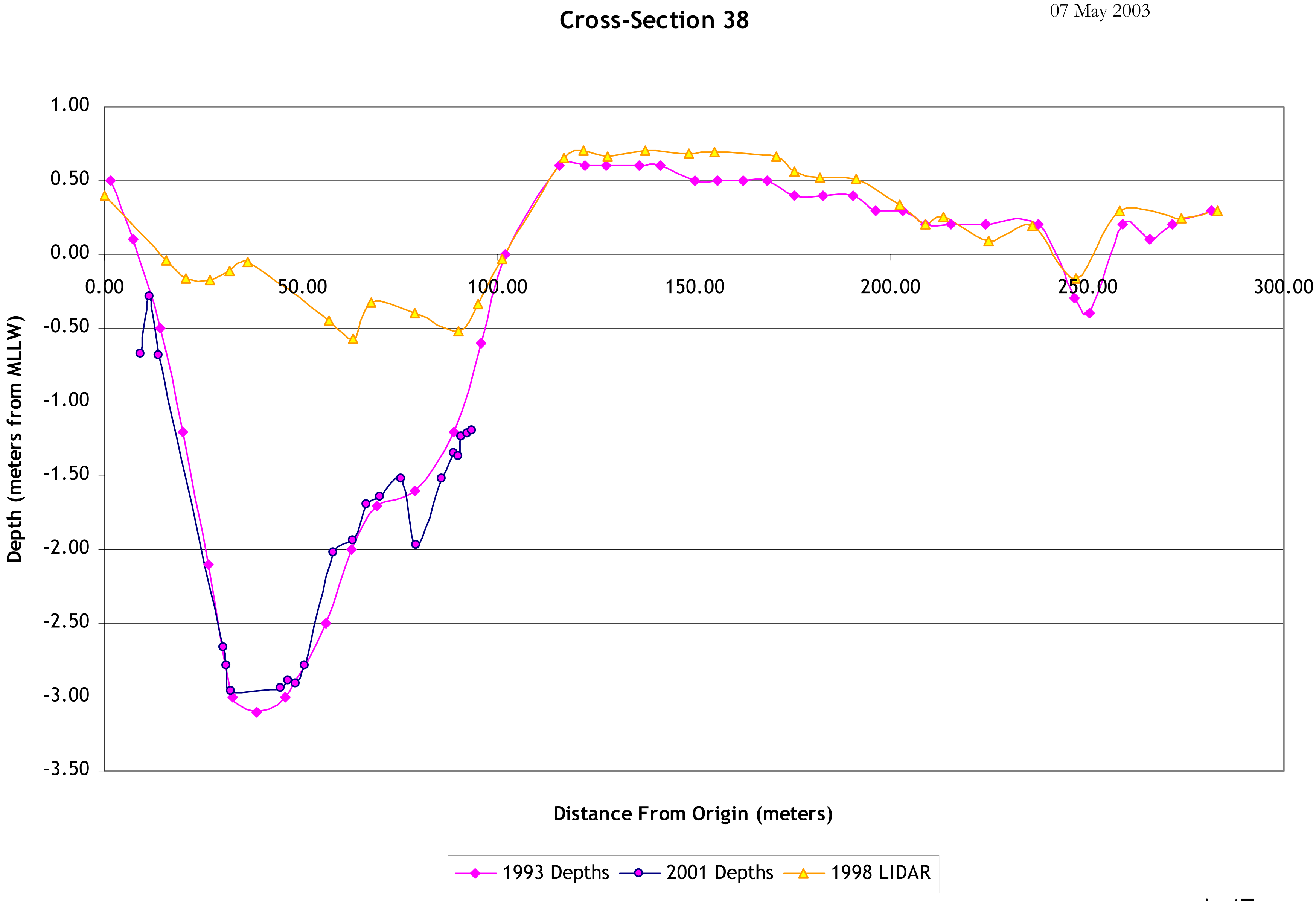

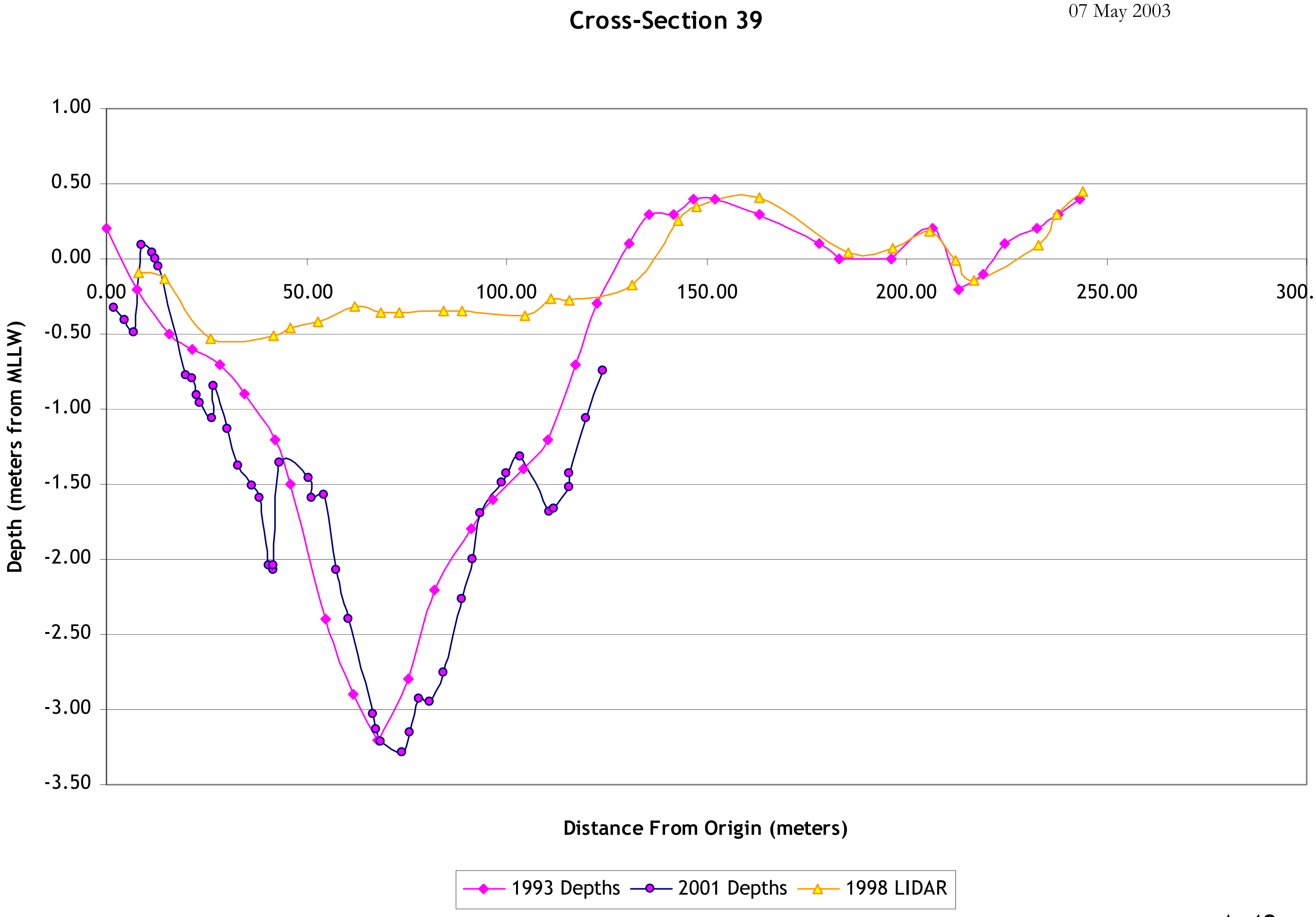
Cross-Section 39
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
0.00
50.00
100.00
150.00
200.00
250.00
300.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR

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Cross-Section 41
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
0.00
50.00
100.00
150.00
200.00
250.00
300.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR

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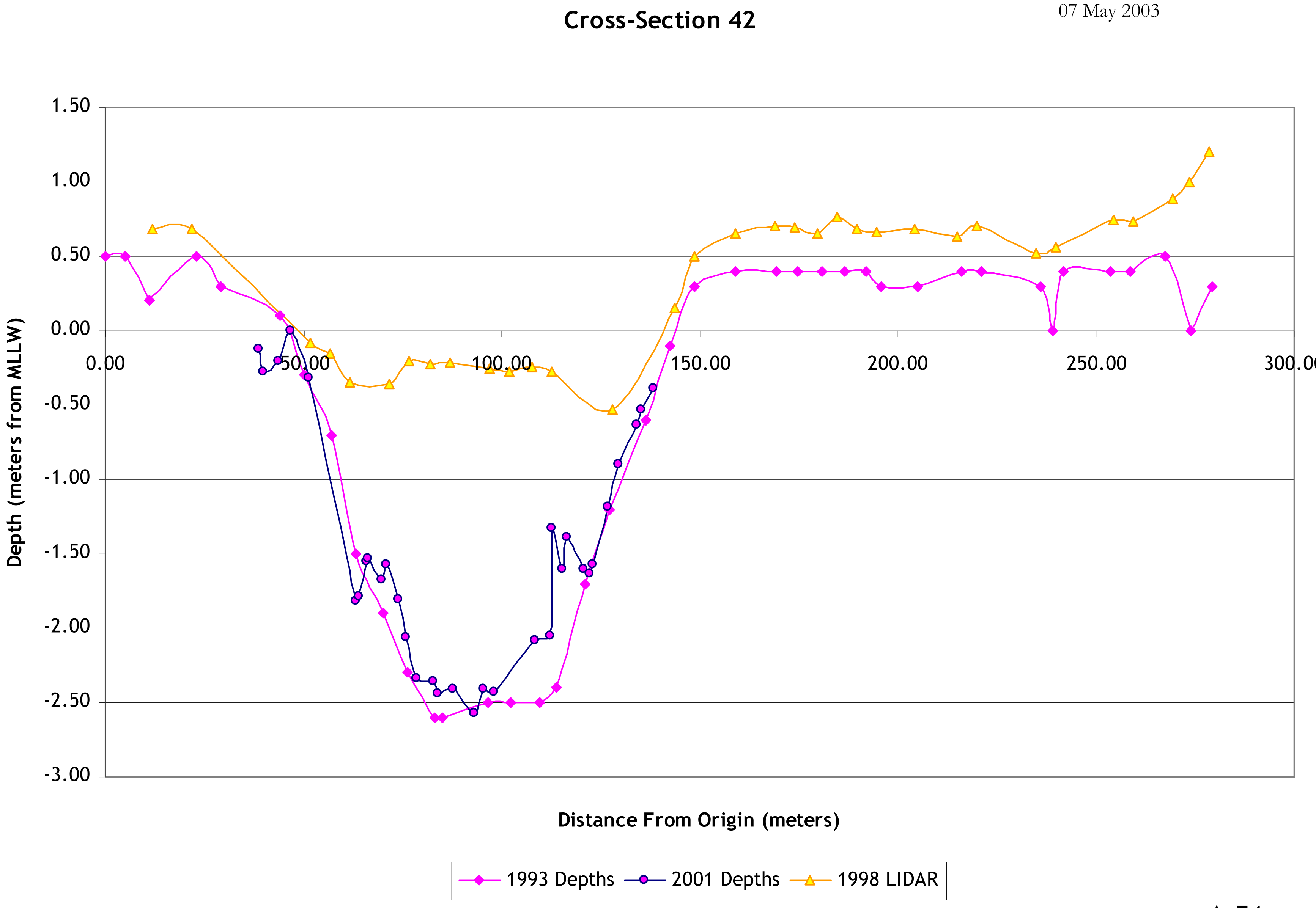
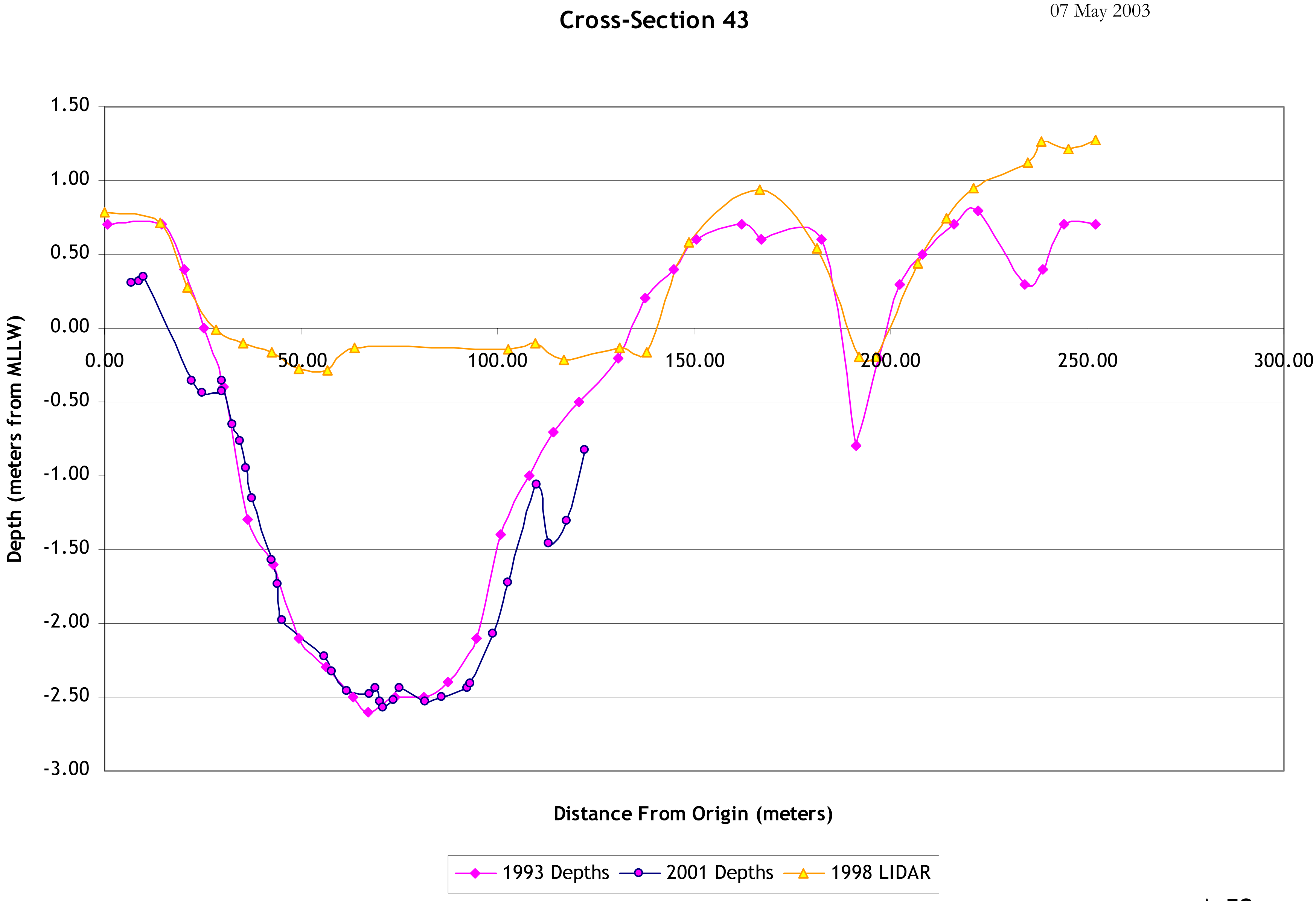
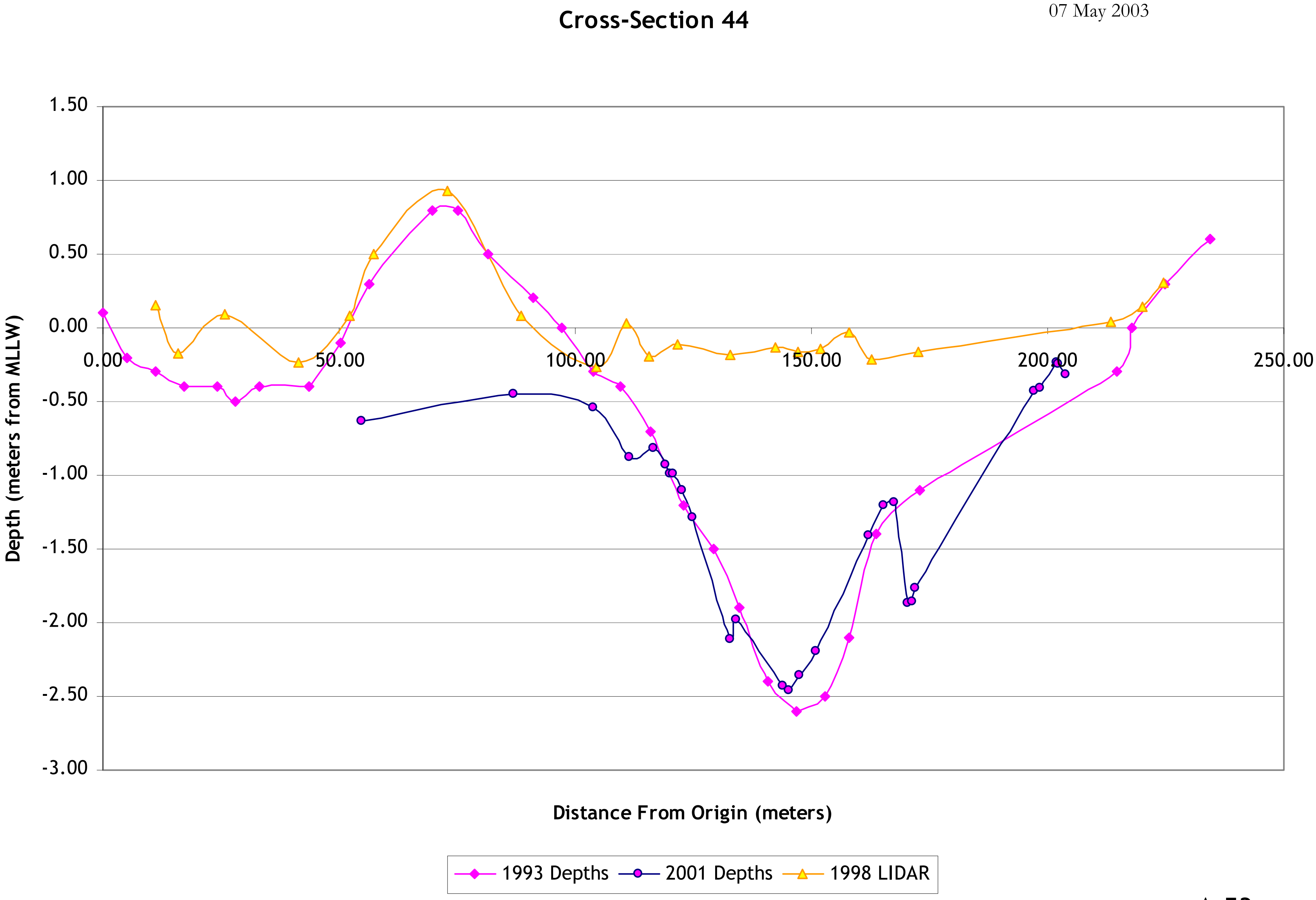
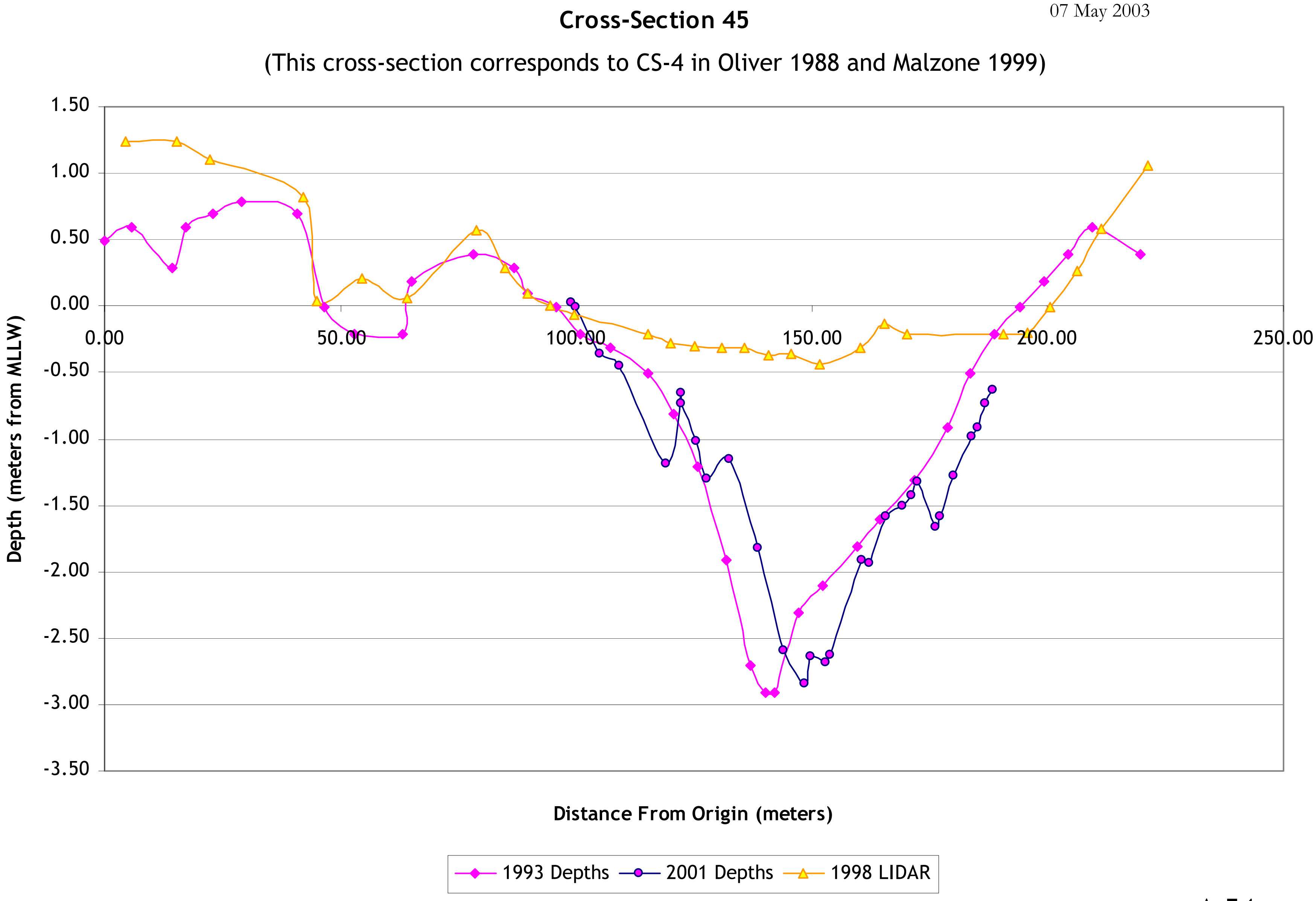


Edwin Wendell Dean III




Cross-Section 44
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
Depth (meters from MLLW)
0.00
50.00
100.00
150.00
200.00
250.00
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR


Cross-Section 45
(This cross-section corresponds to CS-4 in Oliver 1988 and Malzone 1999)
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
0.00
50.00
100.00
150.00
200.00
250.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR


Cross-Section 46
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR

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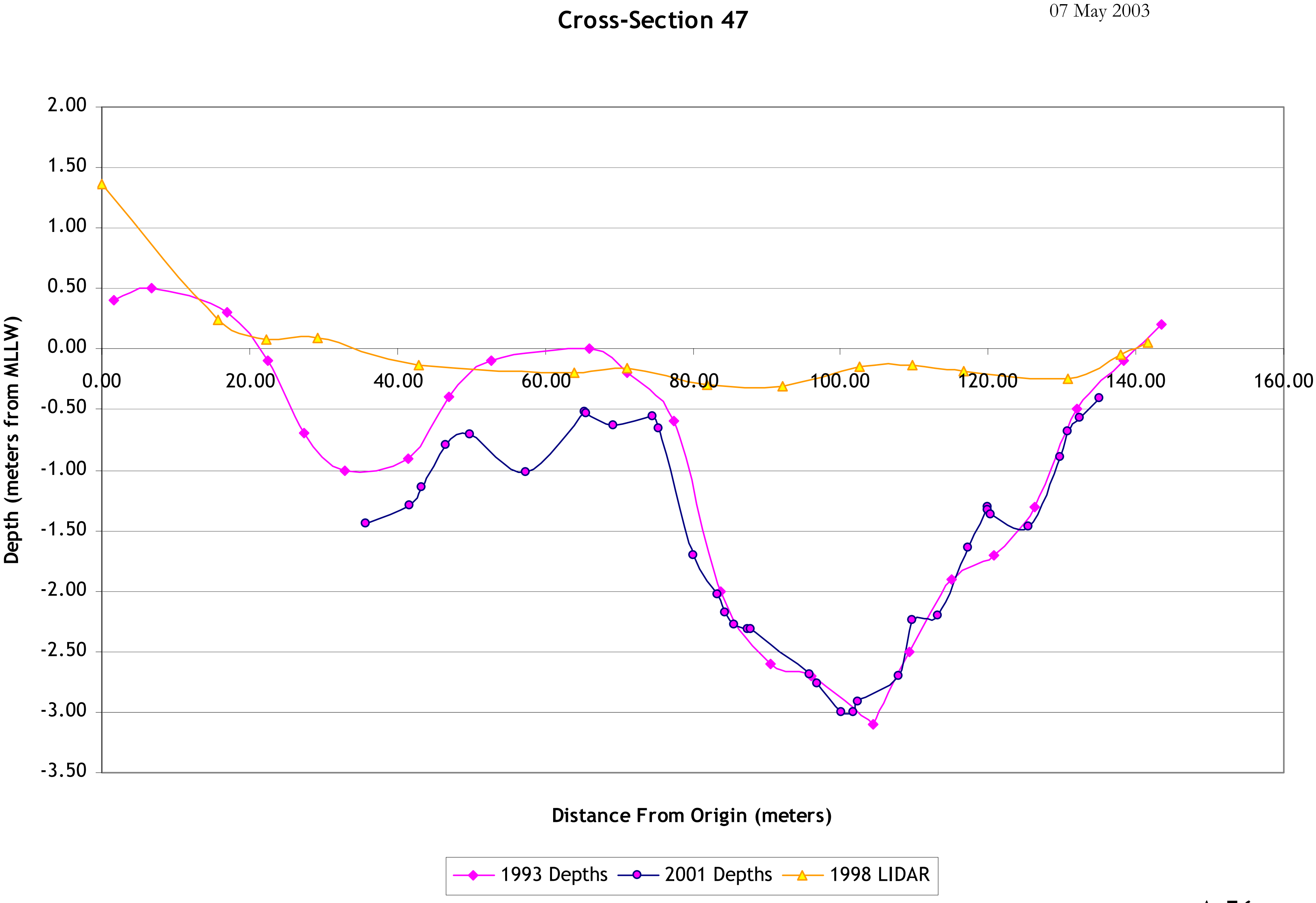

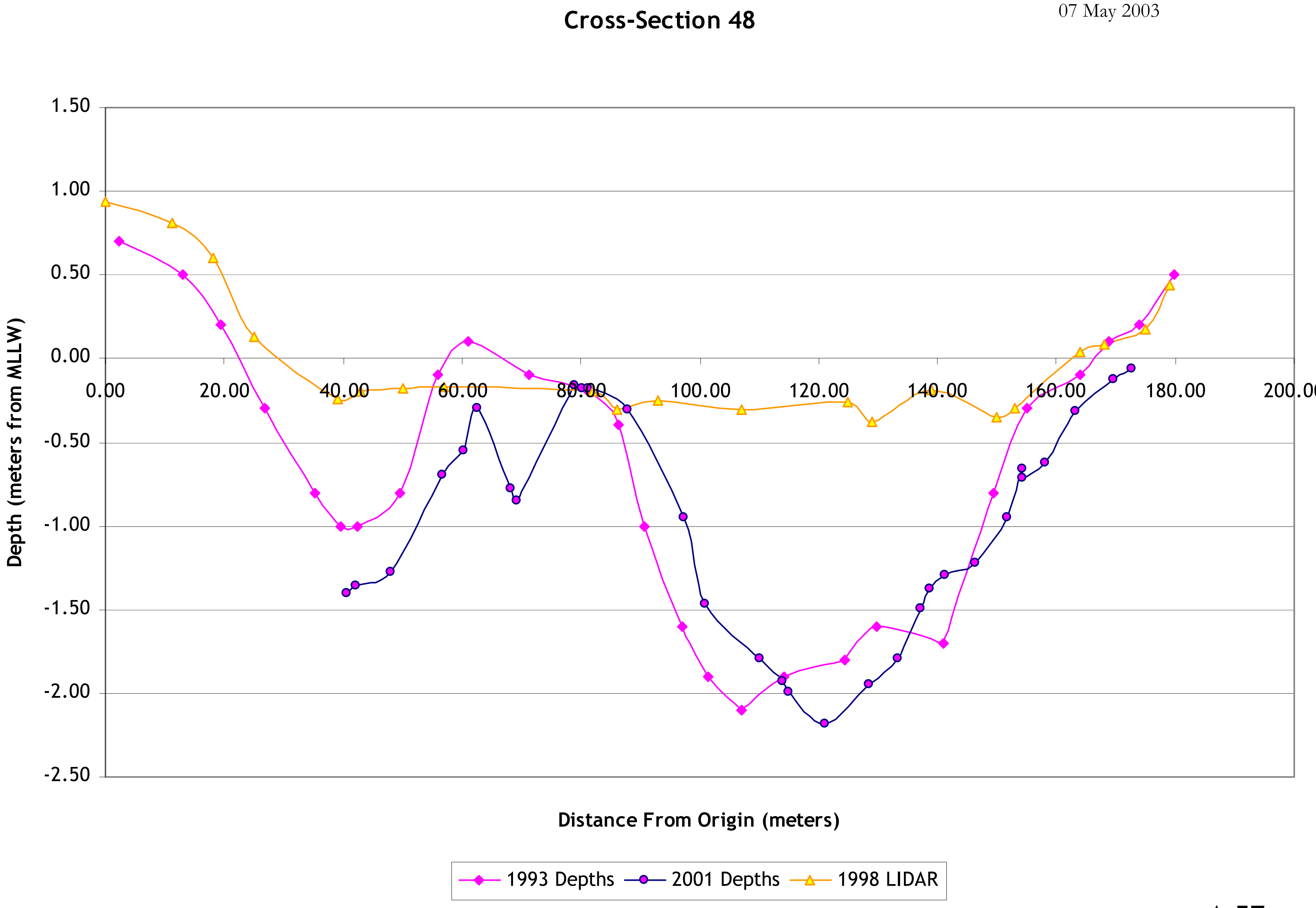
Cross-Section 48
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR

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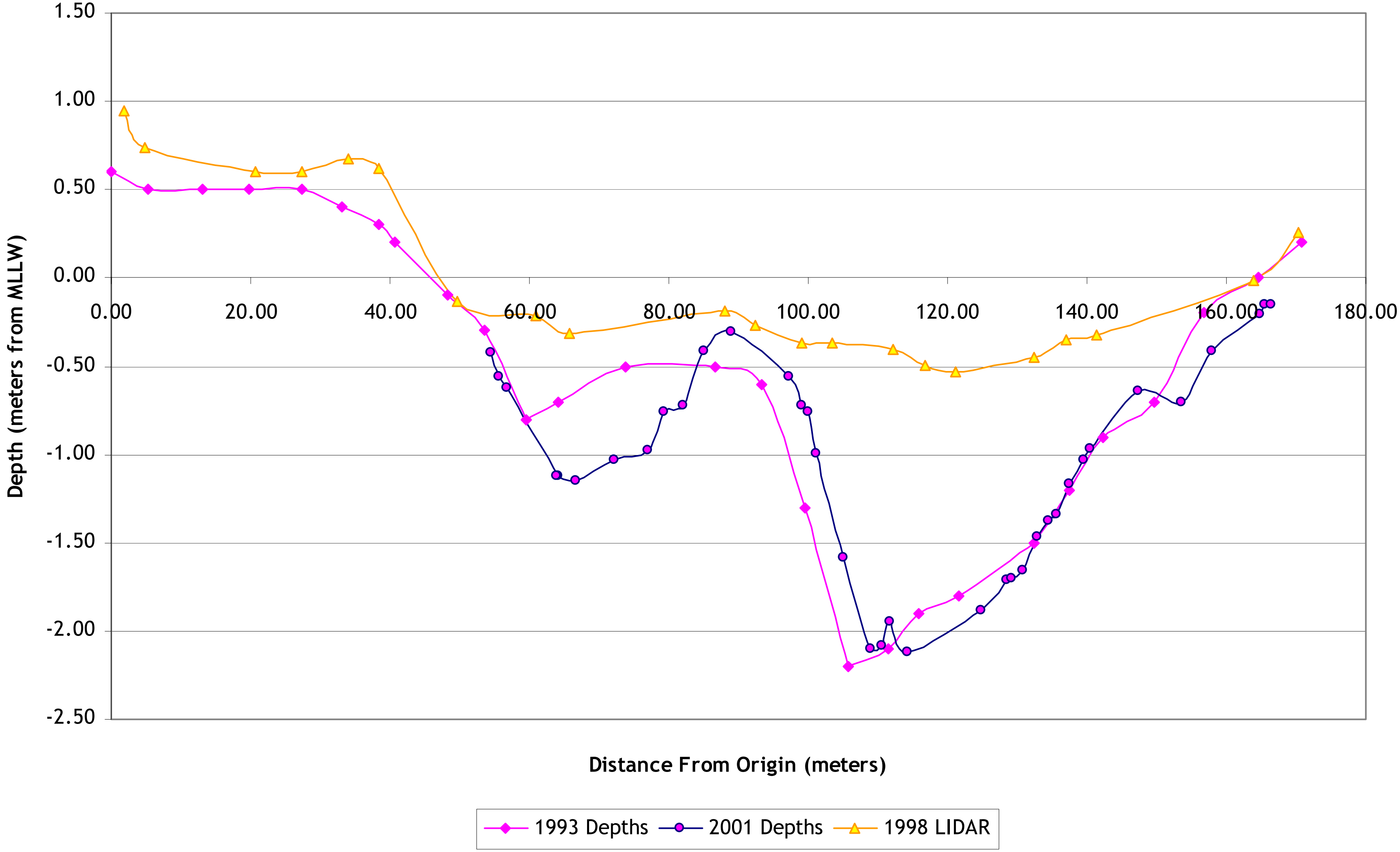
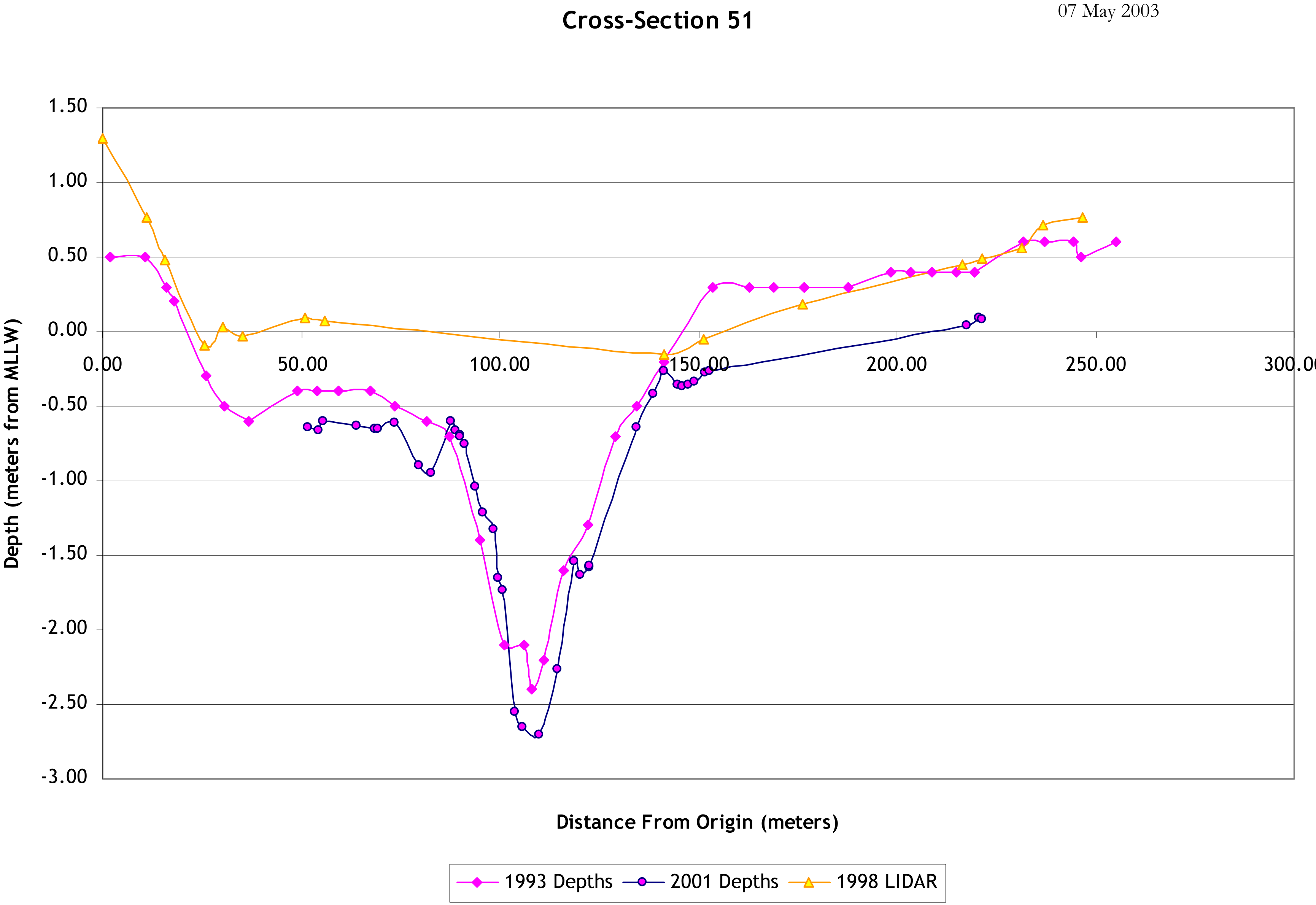
Cross-Section 49



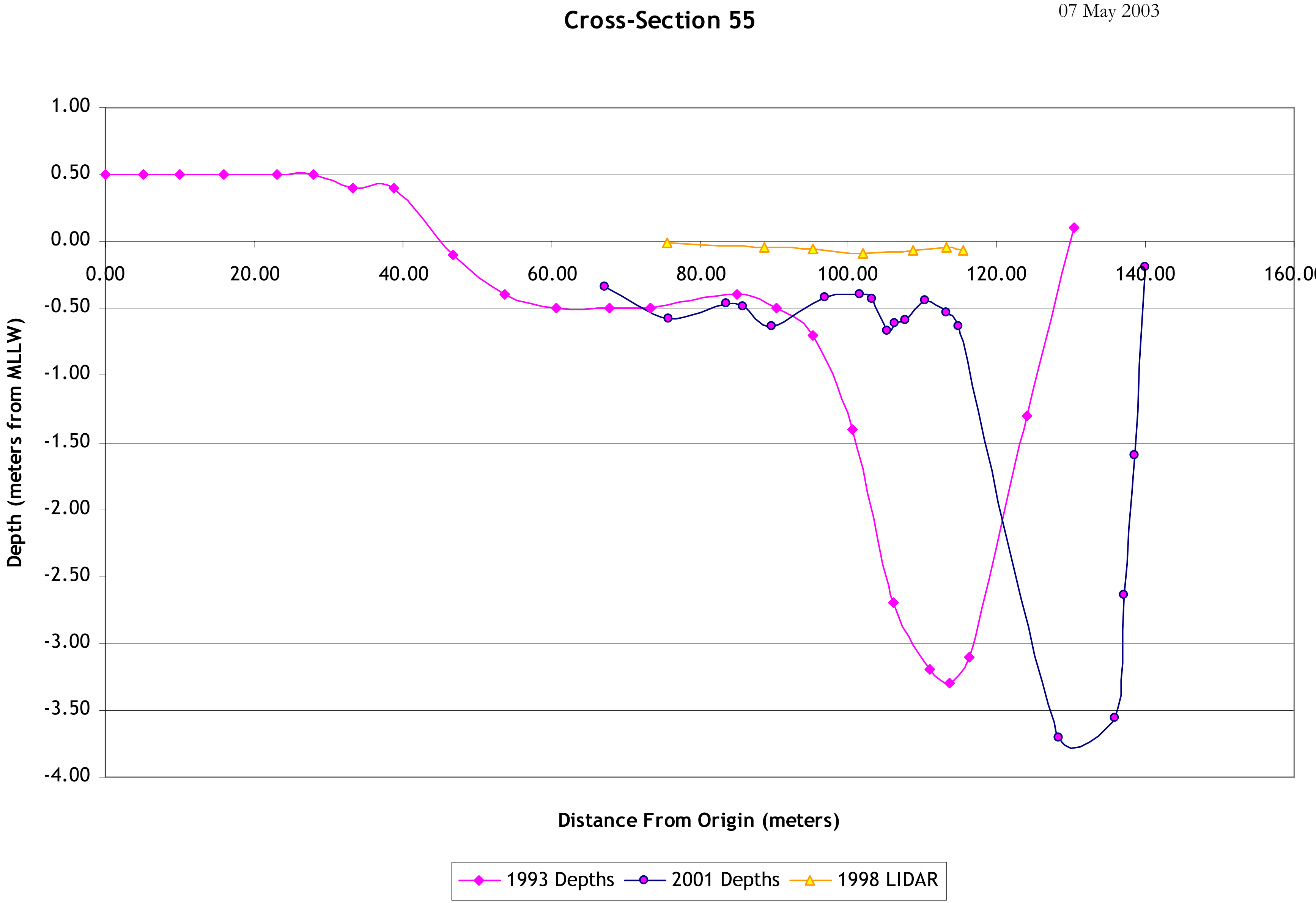

Cross-Section 50
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
Depth (meters from MLLW)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR


Cross-Section 51
Depth (meters from MLLW)
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR


Cross-Section 52
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
Depth (meters from MLLW)
0.00
50.00
100.00
150.00
200.00
250.00
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR


Cross-Section 53
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
-5.00
0.00
50.00
100.00
150.00
200.00
250.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR


Cross-Section 54
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR


Cross-Section 55
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR

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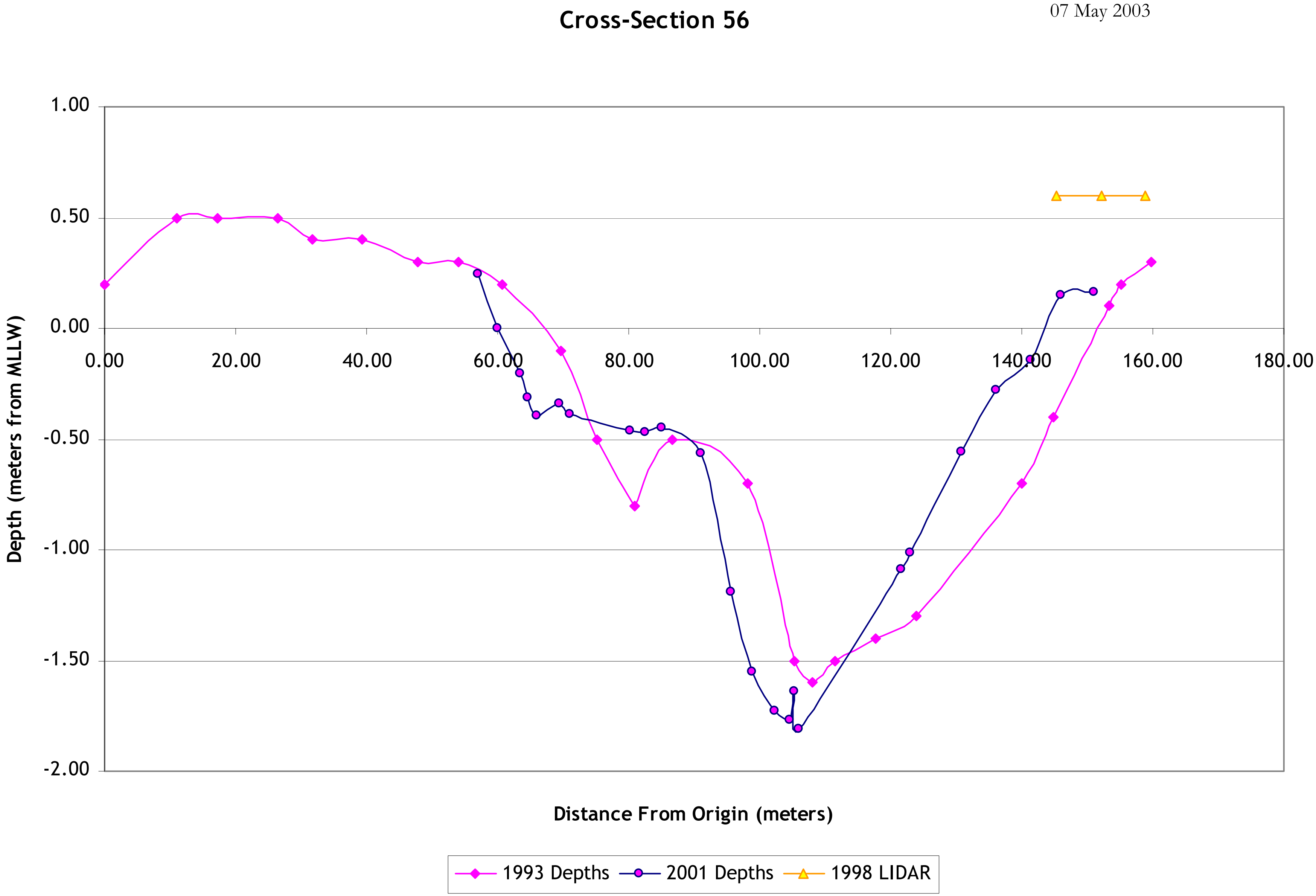
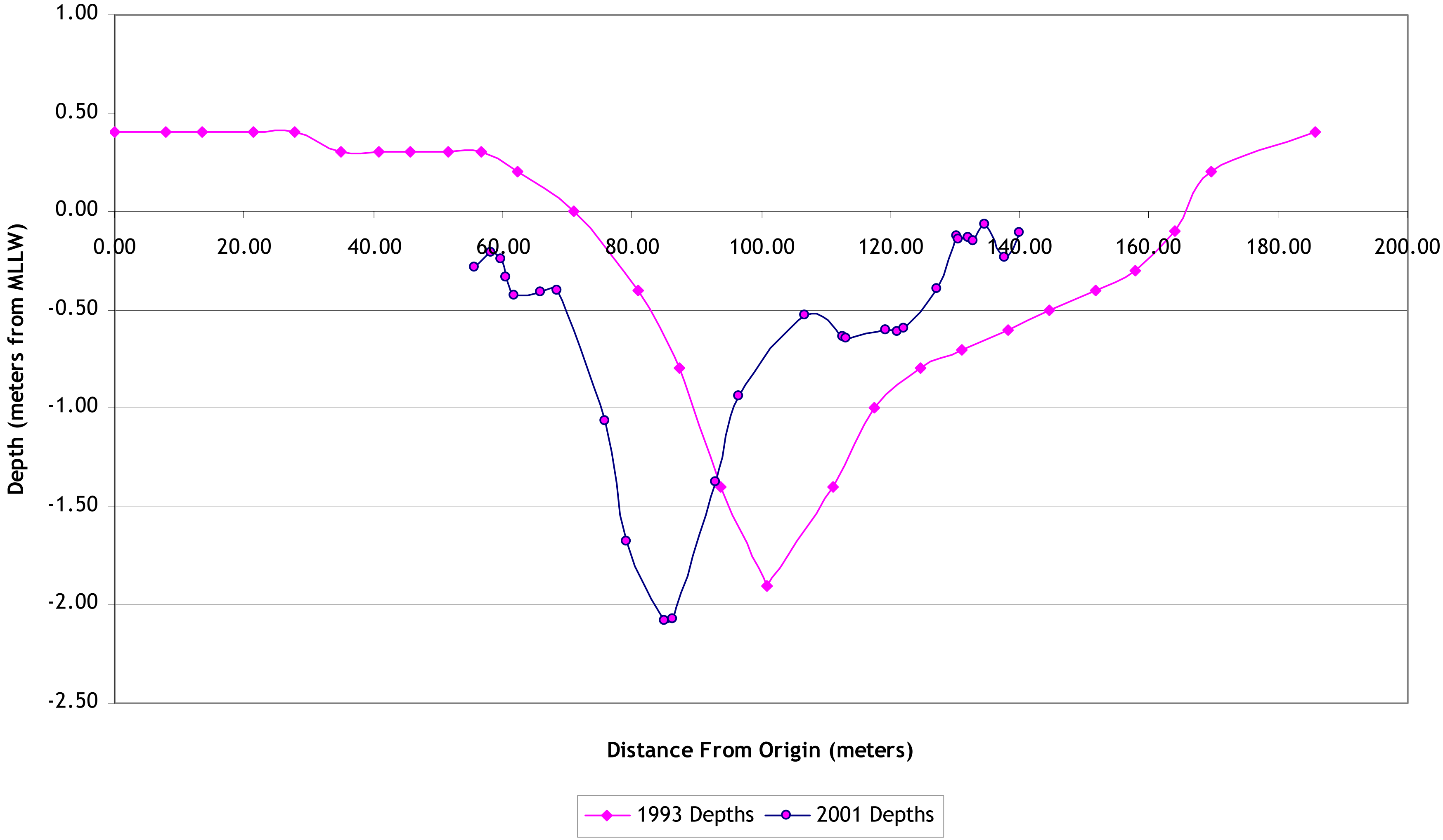
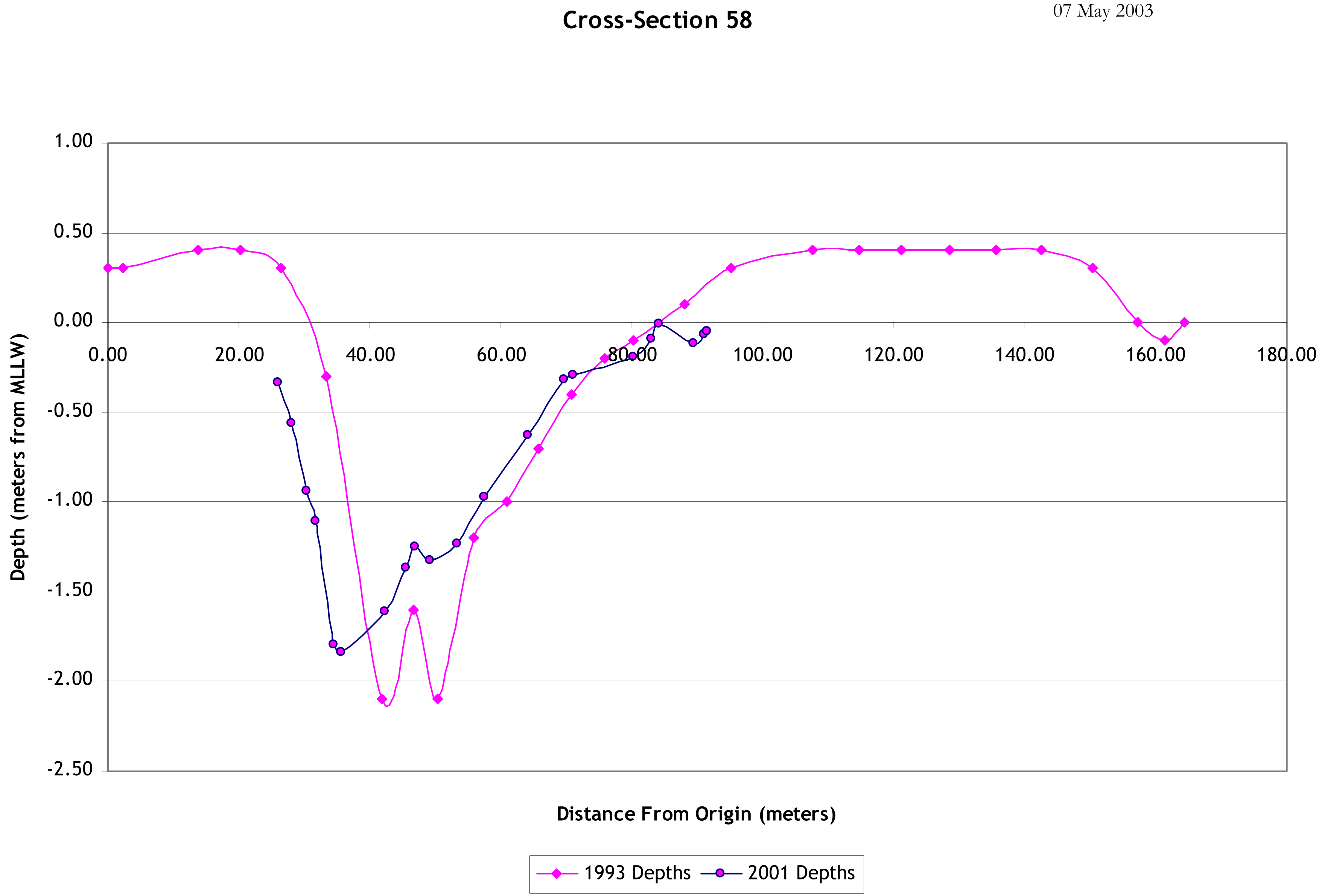


Cross-Section 57

(This cross-section corresponds to CS-5 in Oliver 1988 and Malzone 1999)




Cross-Section 58
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths

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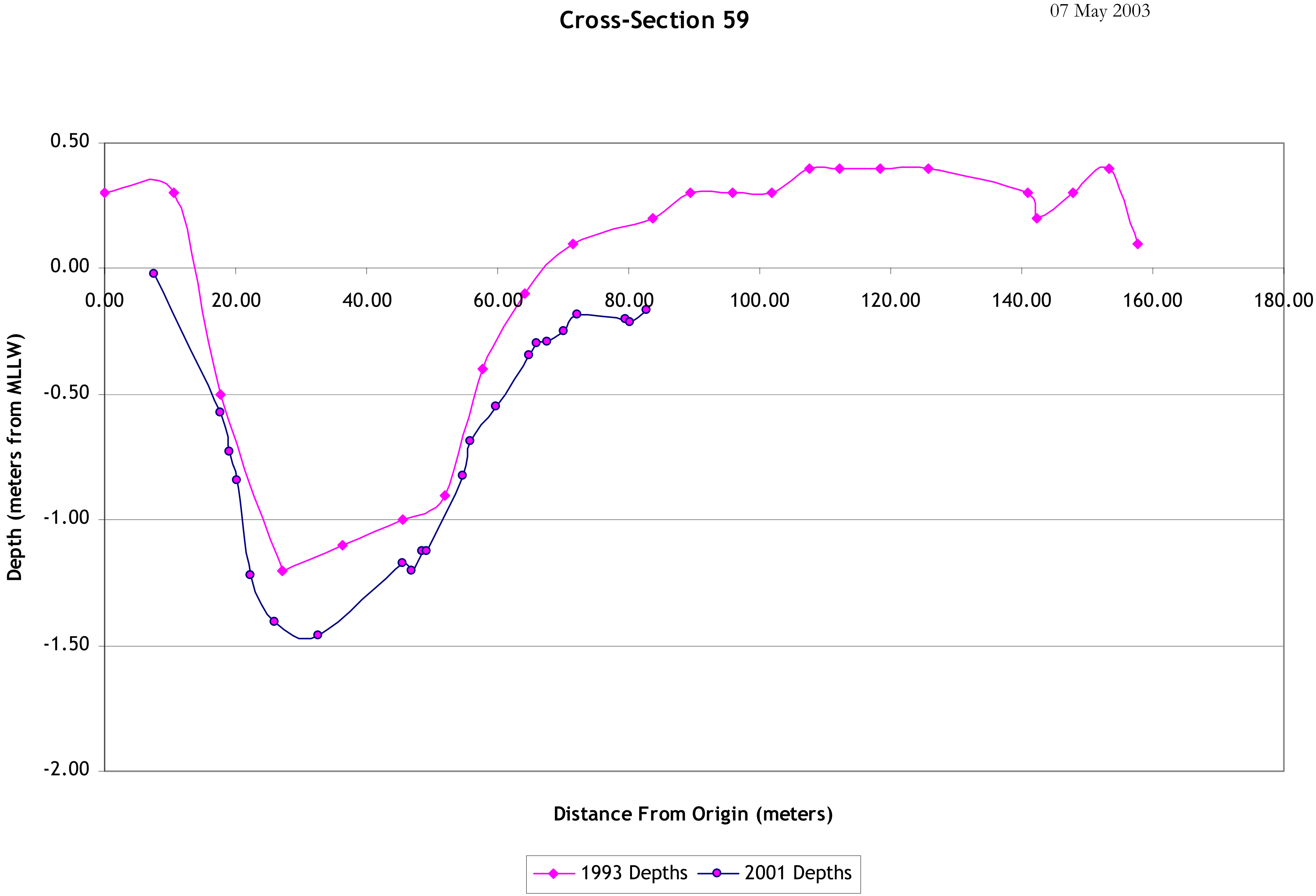
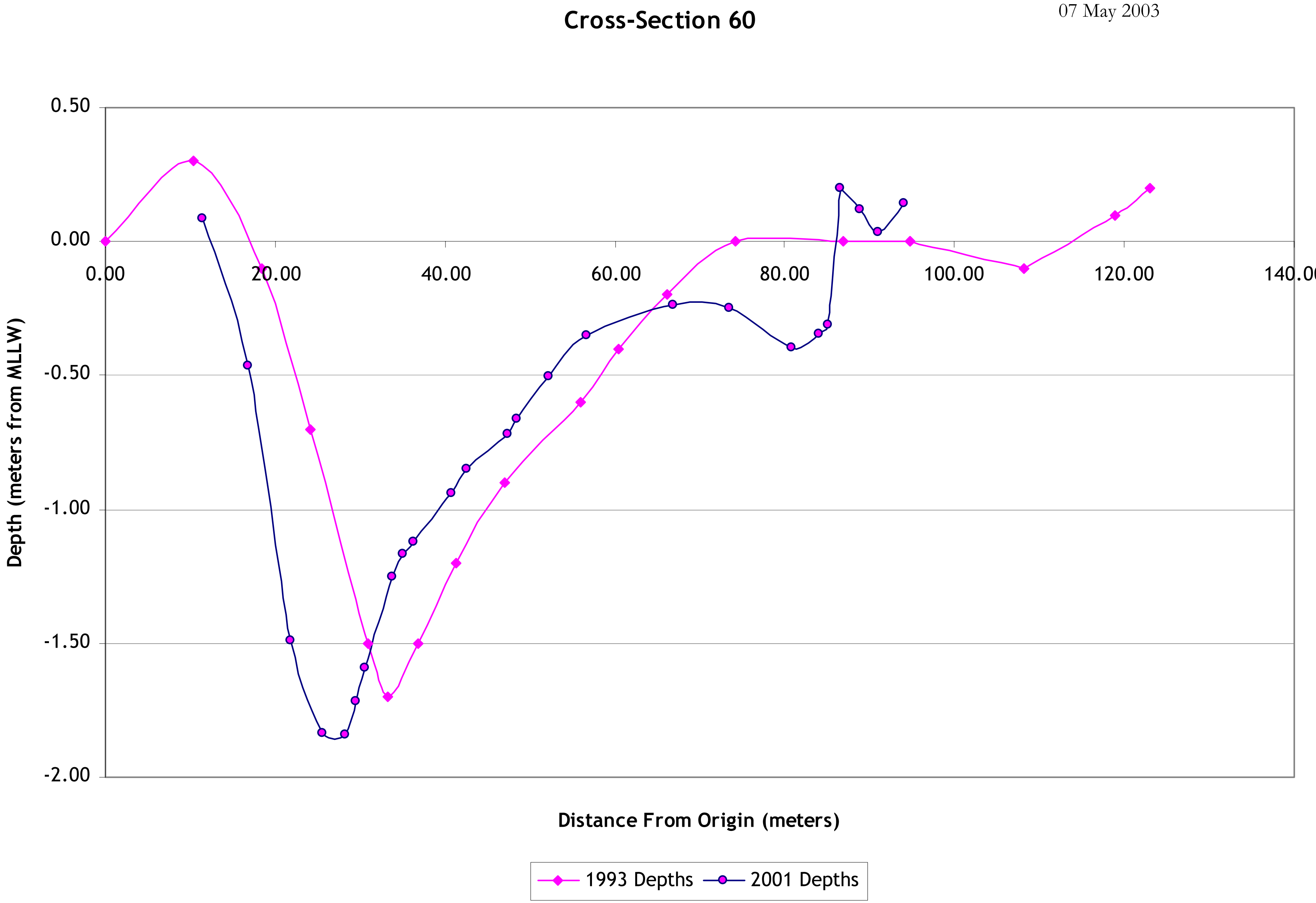
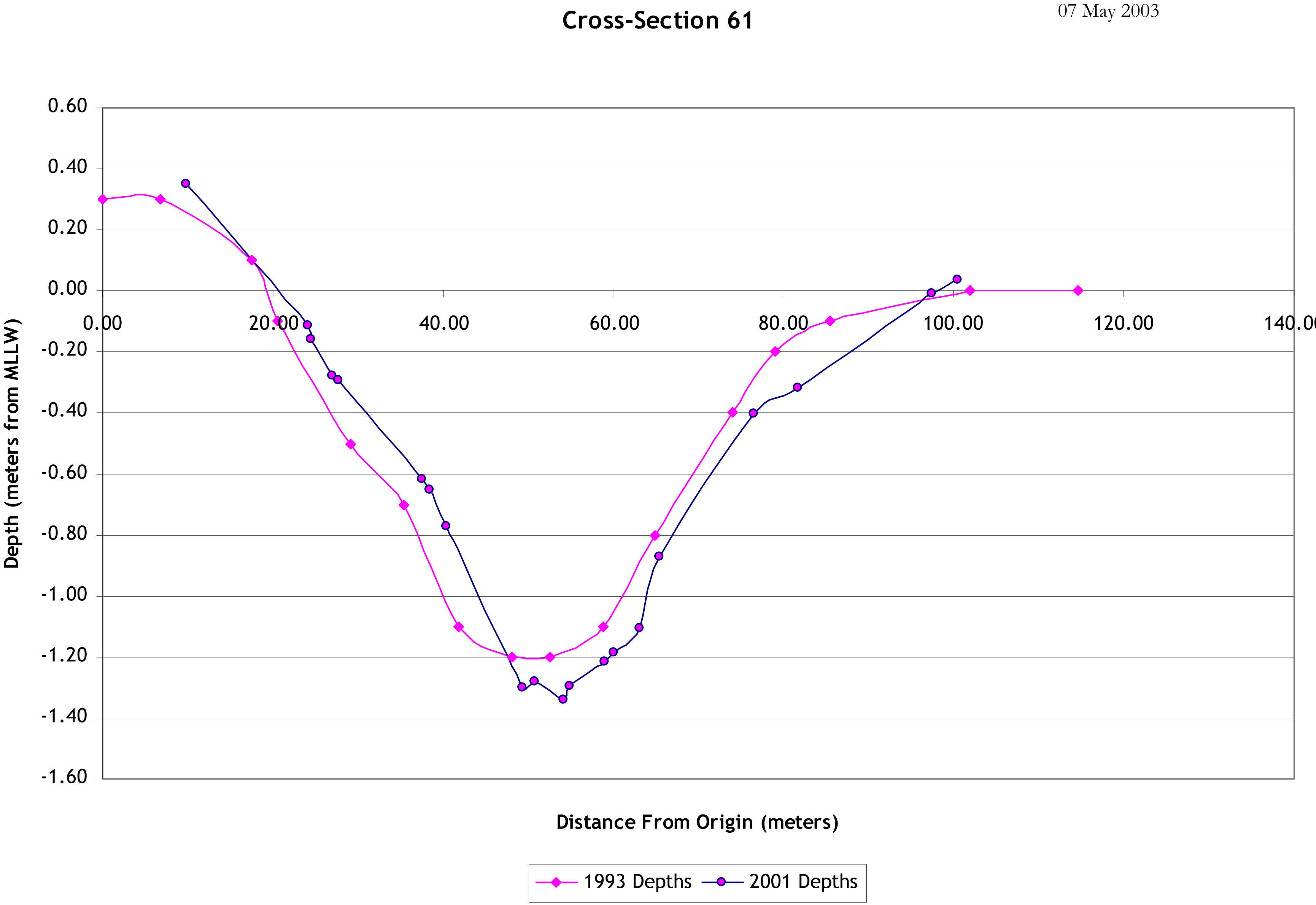



Cross-Section 60
0.50
0.00
-0.50
-1.00
-1.50
-2.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths


Cross-Section 61
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
-1.60
Depth (meters from MLLW)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
Distance From Origin (meters)
1993 Depths
2001 Depths

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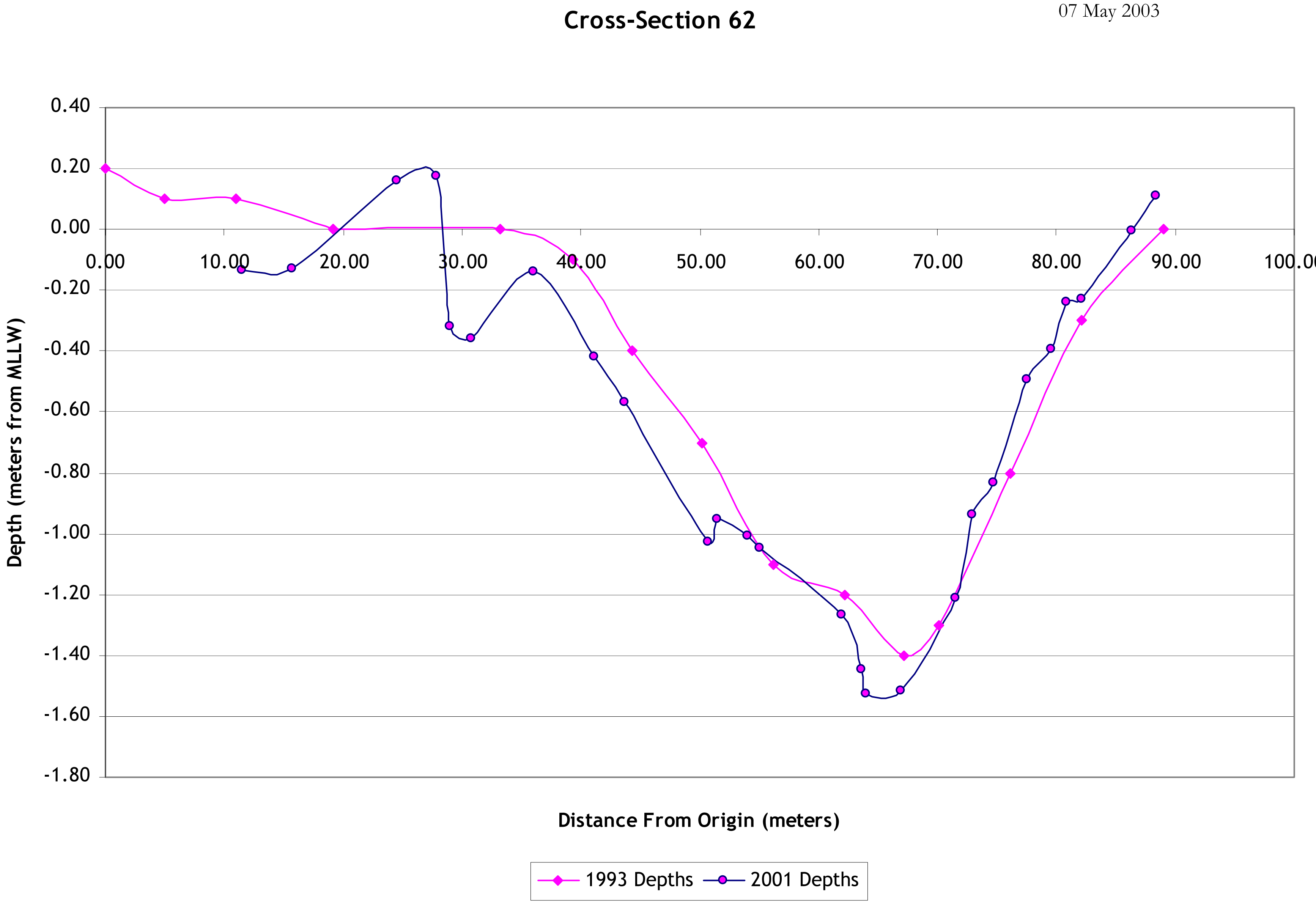

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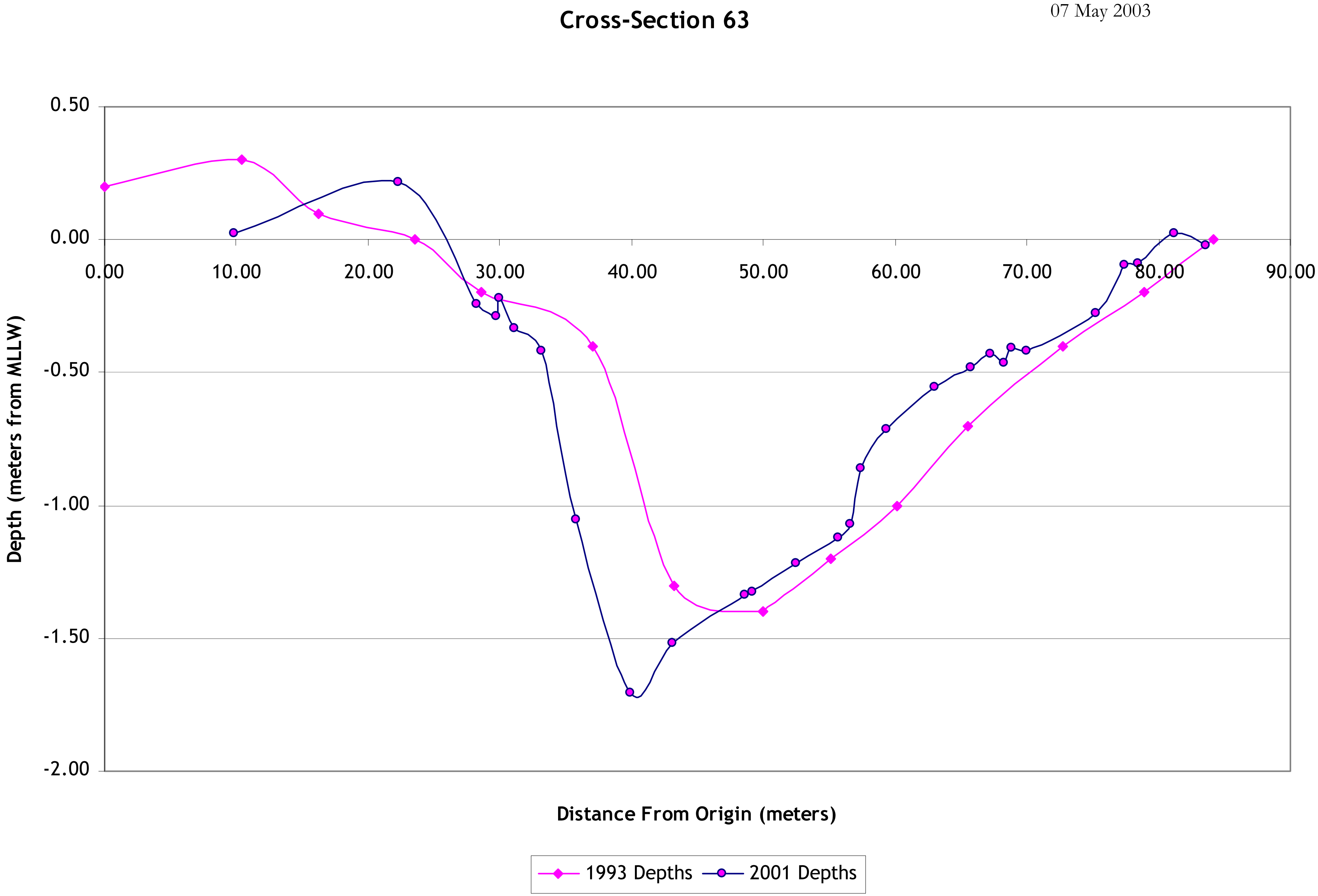

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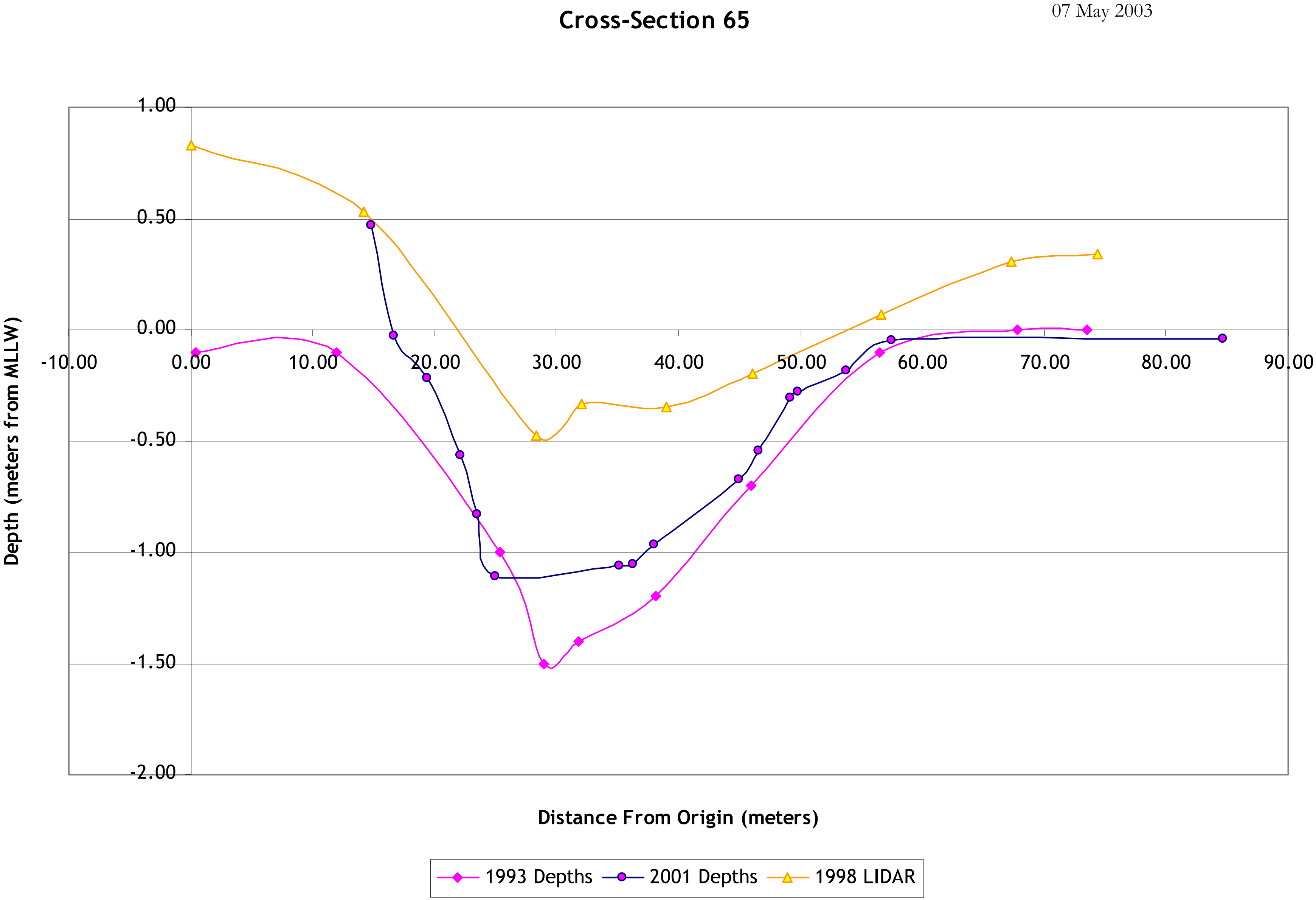
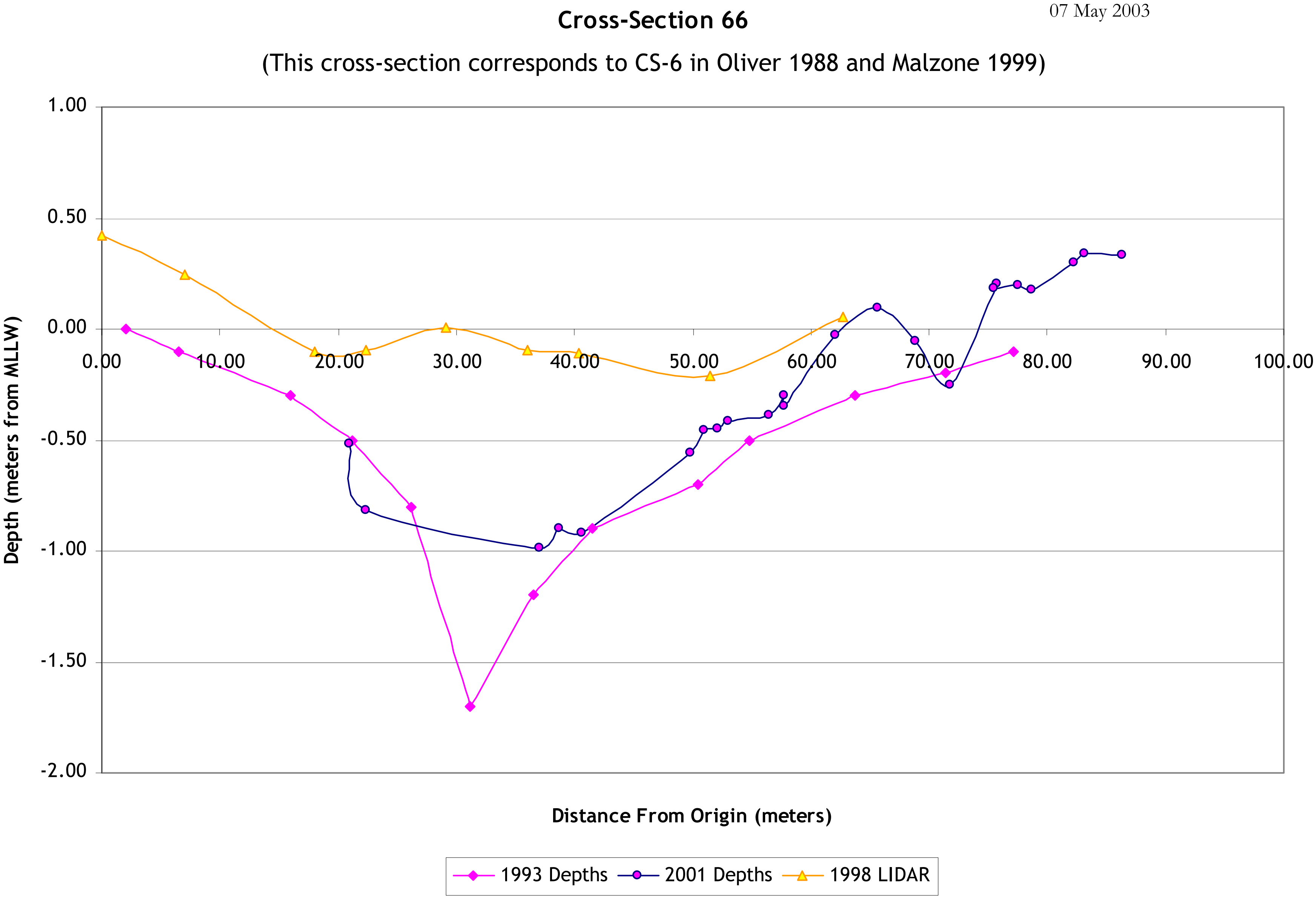

Cross-Section 65
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-10.00
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
Depth (meters from MLLW)
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR


Cross-Section 66
(This cross-section corresponds to CS-6 in Oliver 1988 and Malzone 1999)
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
Depth (meters from MLLW)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
Distance From Origin (meters)
1993 Depths
2001 Depths
1998 LIDAR