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THE HYDRAULIC GEOMETRY OF EPHEMERAL CHANNELS IN A TECTONICALLY ACTIVE...

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The hydraulic geometry of ephemeral channels in a tectonically active landscape: north flank of the San Bernardino Mountains, California

by

Sarah A. Newland

A Thesis

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in

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Lehigh University

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Preface

This paper details research leading to my master's thesis that was completed during the summer of 2000, near the town of Lucerne Valley, California. This study is a component of a larger landscape evolution study undertaken by Martha Cary Eppes, a Ph.D. candidate at the University of New Mexico who has been working in this area as a part of her dissertation. My thesis was written with the intent that it will be submitted to a geologic journal, therefore it is not in traditional masters thesis format. Our project's main objective is to quantify the response of ephemeral streams as they interact with an area of active tectonic uplift. This paper is one of the first steps in remediating the lack of knowledge of ephemeral streams, especially in the context of active tectonics. Our ability to document both quantitative and qualitative aspects of the hydraulic geometry of these ephemeral streams provides a initial step in understanding the important processes that occur in these channels, as well as providing a tool to locate potential areas of tectonic uplift in other arid or semi-arid landscapes.

This paper begins by presenting the reasons why this particular field site was chosen for our study, followed by our hypothesis. Ephemeral streams on the north flank of the San Bernardino Mountains will have a quantifiable, measurable response to changes in gradient imposed by actively rising structures. The geologic setting is clearly laid out, so that the reader will be spatially located, and understand the evolution of the Transverse Ranges, as well as the stratigraphy that is key to this study. A brief description of the evolution of the soils on the piedmont will key the reader in as to why the soils are so important to the topographic expression of active tectonics, and why this study worked so well in this location.

A section entitled "Fluvial Expression of Active Tectonics" will provide the reader with an understanding of the distinction between ephemeral and perennial streams, and the difficulties in making comparisons between the two. The concept of hydraulic geometry is discussed, and utilized in describing the results from previous research on perennial streams in active tectonic settings. Later, the Methods section describes how the field area was divided, and how we actually measured the aspects of hydraulic geometry of these ephemeral channels.

The Results and Discussion sections are divided into three sub-topics: channel pattern morphology, transverse drainage development, and tectonic transition. The channel pattern morphology sections describe the visible quantitative and qualitative aspects of how the ephemeral streams respond as they traverse actively uplifting structures. The transverse drainage development sections describe and present data collected that illustrates three phases of transverse drainages, and later presents a model to explain how these drainages evolve. The tectonic transition sections put the specific field area into the larger perspective of the entire north flank of the San Bernardino Mountains, and the tectonic uplift of the Transverse Ranges. The utility of ephemeral channels as a tool to locate areas of active tectonics that may have previously been overlooked is discussed. And finally, a geologic map and observations of ephemeral streams are presented to illustrate that structures exist in other areas of the piedmont where the topographic expression of these structures may not be preserved. This necessitates the consideration that each individual blind thrust fault may be longer than what is expressed topographically as a fault-propagation-fold.

Abstract

The north flank of the San Bernardino Mountains provides an ideal field location to investigate the response of ephemeral alluvial channels to possibly active, Quaternary fault propagation folding. In this study, the primary response of transverse streams to a fault-propagation-fold is to change their channel pattern morphology from a single channel to a braided channel immediately upstream of the fold axis, and then incise, preserving a terrace in the axis of the fold and preserving bars of sediment further downstream. This stream response is documented for topographically obvious fault-propagation-folds, as well as for folds that have not been recognized as structures. The Cougar Buttes anticline also provides insight on the development of transverse drainages; some channels may be antecedent, whereas others are clearly subsequent. Antecedent streams head in the mountain front and are spaced at wider intervals in comparison to subsequent streams that head on the alluvial fan surface.

These observations help constrain a model for fault/fold-ephemeral stream interaction that proves useful in identifying previously unrecognized active (?) Quaternary structures. The Cougar Buttes anticline extends 1 km further west beyond its current topographic expression; the response of the ephemeral channels allow the true length to be measured. Because the streams are accurate recorders of the locations of tectonic deformation, I can use the streams to locate areas of deformation along the piedmont, and gain some understanding of the seismic hazards associated with potential ruptures along these faults. Collectively, these structures represent a complicated zone of strain partitioning between the Big Bear and the Mojave blocks.

Introduction

Blind thrust faults occur in many compressional tectonic settings, and they are capable of generating large damaging earthquakes, such as the 1994 M 6.7 Northridge and the 1987 M 6.1 Whittier Narrows earthquakes. Sometimes these features have no historic seismicity and no obvious geomorphic expression, so their relative activity and associated seismic hazards are unknown. In southern California there is previous excellent work, including Bullard and Lettis, (1993), Burbank and Verges, (1994), and Keller et al., (2000), that have focused on the active uplift and geomorphic response to the Wheeler anticline, a well-known actively growing fold atop a blind thrust, that has a recurrence interval of 300 to 600 years (Keller, et al., 1998). Their research has opened the door to subsequent investigations of how a growing fold interacts with the fluvial system in an arid landscape. However, convergent tectonic settings where blind thrusts commonly interact with fluvial systems in arid landscapes are not restricted to southern California. The approach of using the geomorphic response of the fluvial system to help identify and understand tectonic deformation is equally applicable in humid settings with perennial streams, as it is in arid settings with ephemeral streams, such as southern California.

Geomorphologists know from many perennial alluvial channel studies (Ouchi, 1985; Schumm et al., 1987) that these channels *do* adjust to active tectonics. Contemporary deformation tends to modify channel gradients, and these gradient changes are accommodated by measurable adjustment of channel metrics such as sinuosity. In contrast, the response of ephemeral alluvial channels to active tectonics is much more poorly known. The processes and characteristics of ephemeral channels in arid settings differ from perennial channels in many ways. Most notably, ephemeral channels are characterized by both fluvial and debris flow processes (Bull, 1997). These differences suggest that in response to tectonic deformation, ephemeral channels can respond in a different manner than previously documented for perennial channels.

Upwards of ~30 % of the worlds' active compressional tectonic settings lie in arid and semi-arid lands (Moores and Twiss, 1995). Geomorphic analysis is the primary means of assessing the seismic hazard potential, growth, and activity of folds and structures within these settings (e.g. Bullard and Lettis, 1993; Keller et al., 1998, 1999, 2000). To date, there has not been a major study directly related to ephemeral channel response to active tectonics. If important insights into convergent tectonic processes are to be made using geomorphic techniques, then it is clear that ephemeral channel-tectonic interactions must be defined and characterized.

This paper details a field study conducted along the north flank of the San Bernardino Mountains of southern California, near the town of Lucerne Valley (Figure 1) that illustrates how ephemeral channels interact with blind thrust faults and active tectonics in arid landscapes. The underlying premise in this study is that ephemeral streams should have a quantifiable, measurable response to subtle or large changes in gradient imposed by actively rising structures. First, I document that response in an area where topographic criteria clearly indicate the location of an active structure. Using this documentation, I am then able to recognize actively rising structures in adjacent areas where topographic expression is equivocal or absent. To date, ephemeral channels have been described primarily in qualitative terms (Bull, 1991). This research seeks to

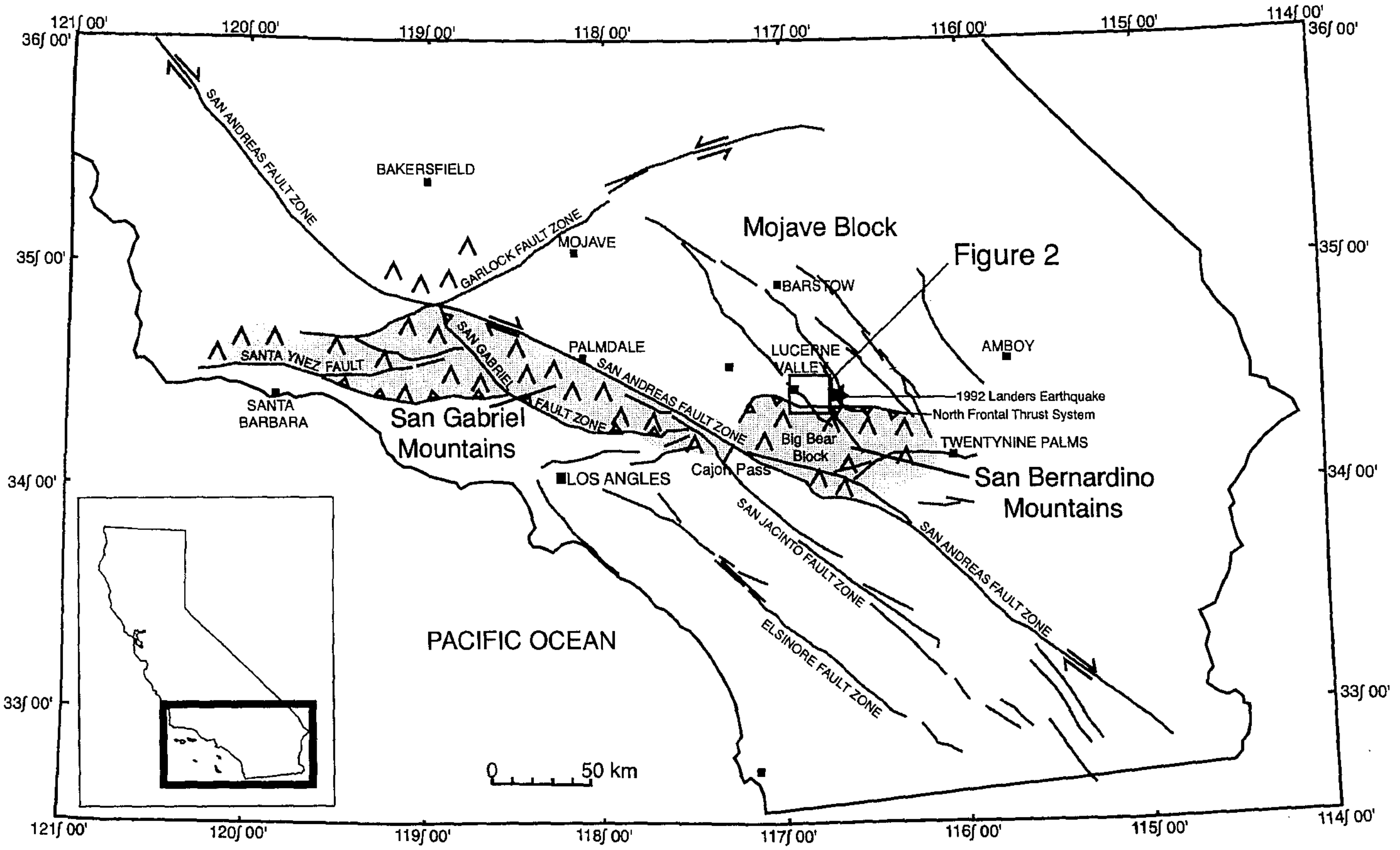

Figure 1. Tectonic map of southern California showing major faults and generalized mountainous topography. Area of Figure 2 is shown by the box in the Lucerne Valley: Modified from Miller, 1987.

quantitatively characterize ephemeral channels in the context of active tectonics, and thus fill a major gap in the understanding of these fluvial systems.

The paper will discuss the specific suite of field methods necessitated by this particular setting, present some quantitative and qualitative data on channel metrics, define the range of channel behaviors in this setting, and draw some insights into fault and fold behavior in this specific convergent setting. From this study we gain a better understanding of the seismic hazards in Lucerne Valley, because the fluvial system has compelled us to consider a series of blind thrusts that may be longer than previously believed. The study also has implications for the development and significance of transverse drainages, the behavior of ephemeral channels as they respond to active uplifts, and the complex strain partioning across structures marking the transition from the Big Bear block to the Mojave block.

Geologic and Tectonic Setting

Southern California tectonics are dominated by the right-lateral San Andreas Fault Zone. As the San Andreas Fault completes its "big bend" from south of Los Angles to Santa Barbara, the right-lateral motion causes a broad band of transpression, across which the Transverse Ranges are uplifting (Figure 1). The large crustal block that is bound to the south by the Transverse Ranges, and to the north by the left-lateral Garlock Fault Zone is the Mojave block. This block is disrupted with northwest-trending right-lateral strike slip faults synthetic to the San Andreas, that are estimated to accommodate between 9 and 23% of the relative motion between the Pacific and North American Plates (Southern California Earthquake Center, 2001). Some of these northwest-trending faults are presently seismically active, as demonstrated by the 1992 magnitude 7.3 Landers earthquake that ruptured portions of the Johnson Valley, Landers, Camp Rock and Homestead Valley faults (Figure 1). The north flank of the San Bernardino Mountains marks a complex transition between the northward-driven shortening of the Transverse Ranges and the right-lateral strike-slip offset across northwest-striking faults in the Mojave block (Figure 1).

The field area for this study is located along the piedmont of the north flank of the San Bernardino Mountains, the range that marks the southern boundary of the Mojave desert. The piedmont receives on average 5 inches of precipitation a year, with the majority received during the winter months. The study site encompasses an area beginning just south of the town of Lucerne Valley, CA, and extending 10 km east, to the edge of the Blackhawk landslide (Figure 2). Elevation varies between 3000 feet at the northern edge and 3700 feet at the southern edge of the study site. The topographic presence of fault cored anticlinal structures along the piedmont, and regional record of seismic activity suggest that the north flank has recently experienced tectonic deformation.

The San Bernardino Mountains are believed to have been uplifted in two distinct phases (Meisling and Weldon, 1989). The first phase began in the late Miocene to earliest Pliocene (between 9.5 and 4.1 Ma) as crystalline rocks of the ancestral San Bernardino Mountains were thrust southward along the Squaw Peak thrust system. Predating, and concurrent with the first phase of uplift, the regional drainage system flowed from north to south, draining the Mojave block directly across what is now the San Bernardino

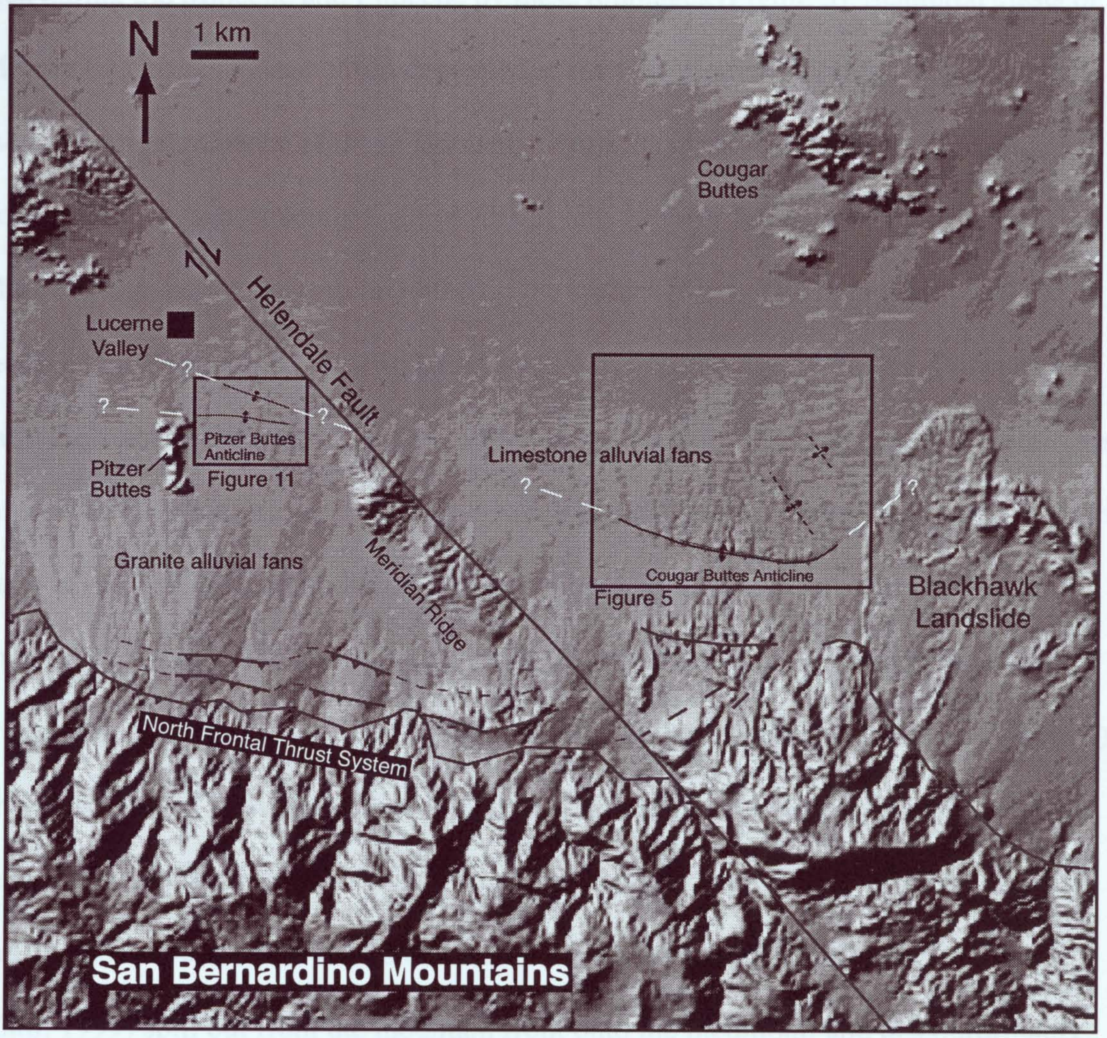

Figure 2. Map of the Lucerne Valley and northern flank of the San Bernardino Mountains expressed as a shaded relief Digital Elevation Model.

Mountains. Poorly consolidated continental redbed siltstones and sandstones of the Old Woman Springs Formation (Meisling and Weldon, 1989) were deposited across the study area during the Miocene and Pliocene by these drainages (Figure 3). Scattered clasts of Mojave block provenance basalt deposited in the Old Woman Springs Formation attest to the northern provenance of these sediments. Portions of the Old Woman Springs Formation have subsequently been reworked into younger fan deposits, allowing the Mojave block basalt clasts to be found on the surface today. The main portion of the modern San Bernardinos, the Big Bear block, was uplifted during the late Pliocene and early Pleistocene (between 2.0 and 1.5 Ma) along the North Frontal Thrust System. This thrust system is comprised of a series of south-dipping reverse faults that bound the north flank of the San Bernardino Mountains and form a 70 km long escarpment. This new phase of thrusting is evidenced by the reversal of the Old Woman Springs Formation drainage and accompanying deposition of the Cushenbury Springs Formation (Figure 3). This mostly early Pleistocene unit is a gray and tan coarse fanglomerate and sandstone shed northward from the actively uplifting Transverse Ranges (Shreve, 1968; Meisling and Weldon, 1989). From the San Bernardino escarpment, alluvial fans (Powell and Matti, 1999) spill out from the mountain front onto the piedmont, and disconformably overlie the Cushenbury Springs Formation. These fan units range in age from middle Pleistocene to Holocene, and interfinger with basin deposits in Lucerne Valley (Figures 1 and 2).

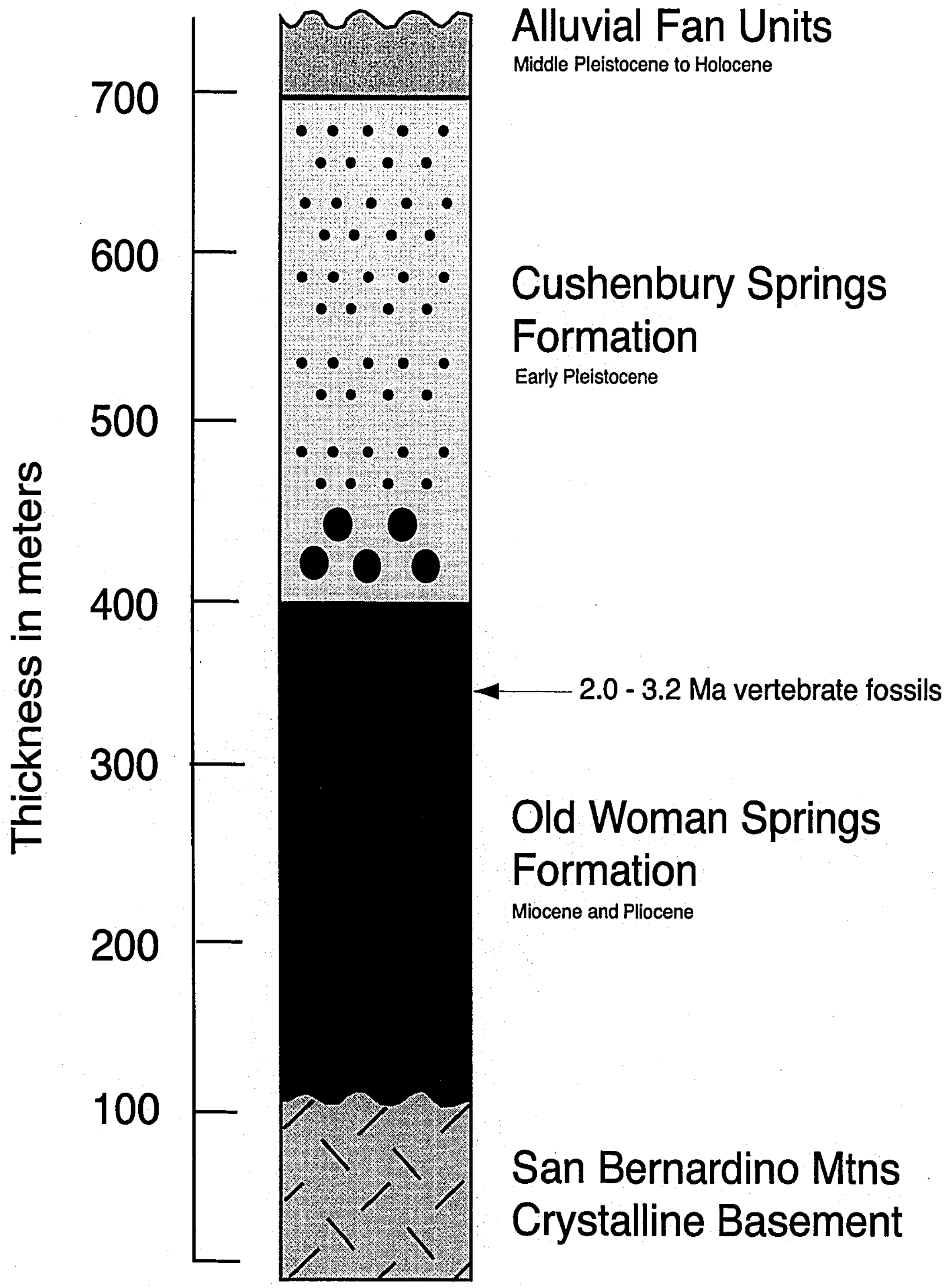

Figure 3. Stratigraphic column showing the geologic units of the north flank of the San Bernardino Mountains near the town of Lucerne Valley, CA (modified from Meisling and Weldon, 1989). Scale is in meters.

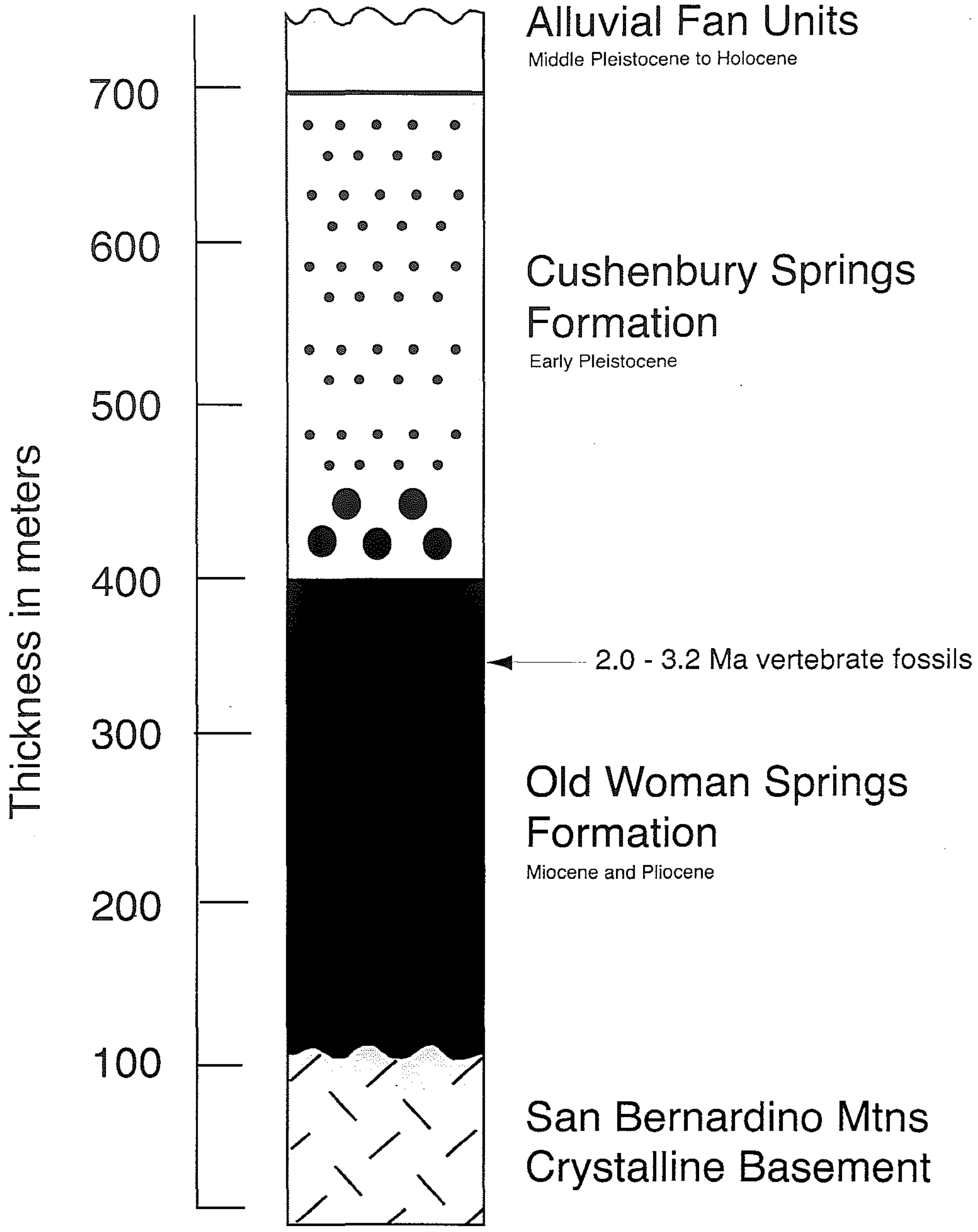

Figure 3. Stratigraphic column showing the geologic units of the north flank of the San Bernardino Mountains near the town of Lucerne Valley, CA (modified from Meisling and Weldon, 1989). Scale is in meters.

Uplift of the San Bernardinos continues today, as evidenced by many Holocene fault scarps along the piedmont. The thrust front appears to have propagated northward, away from the North Frontal Thrust System as a complex zone of blind, or recently emergent south-dipping thrust faults. Thrust faults are often manifest as fault propagation folds in the medial piedmont, where alluvial fans are often warped into anticlinal ridges. Incision through these anticlines by transverse drainages exposes underlying Cushenbury Springs and Old Woman Springs Formations. The most distal of these anticlines, including the Cougar Buttes and Pitzer Buttes anticlines, represent some of the most youthful expressions of shortening across the San Bernardinos (Figure 2).

The Helendale fault, a northwest-trending right-lateral fault of the Mojave block trends roughly perpendicular to the North Frontal Thrust System and strikes directly through the town of Lucerne Valley, CA. Although these two faults intersect, it is unclear which actually dominates. It is believed that these two fault systems might both be active (Spotila and Sieh, 2000). East of the Helendale fault, the mountain front is composed primarily of Paleozoic marbles and meta-sediments that are exposed as roof pendants to Mesozoic plutons, resulting in a carbonate provenance for the mid-Pleistocene alluvial fans mantling the piedmont in front of this part of the mountain range. A calcic soil, interpreted to be 300 – 700+ ka has developed on these limestone fans (Eppes et al., 2000). The soil has a 2-3 meter thick, cemented petrocalcic horizon that is highly resistant to erosion. In places, the soil has been eroded down to the petrocalcic horizon, which is now unconformably overlain by younger fan deposits. At the Cougar Buttes anticline (Figure 4), the petrocalcic horizon is at the surface where it forms and protects

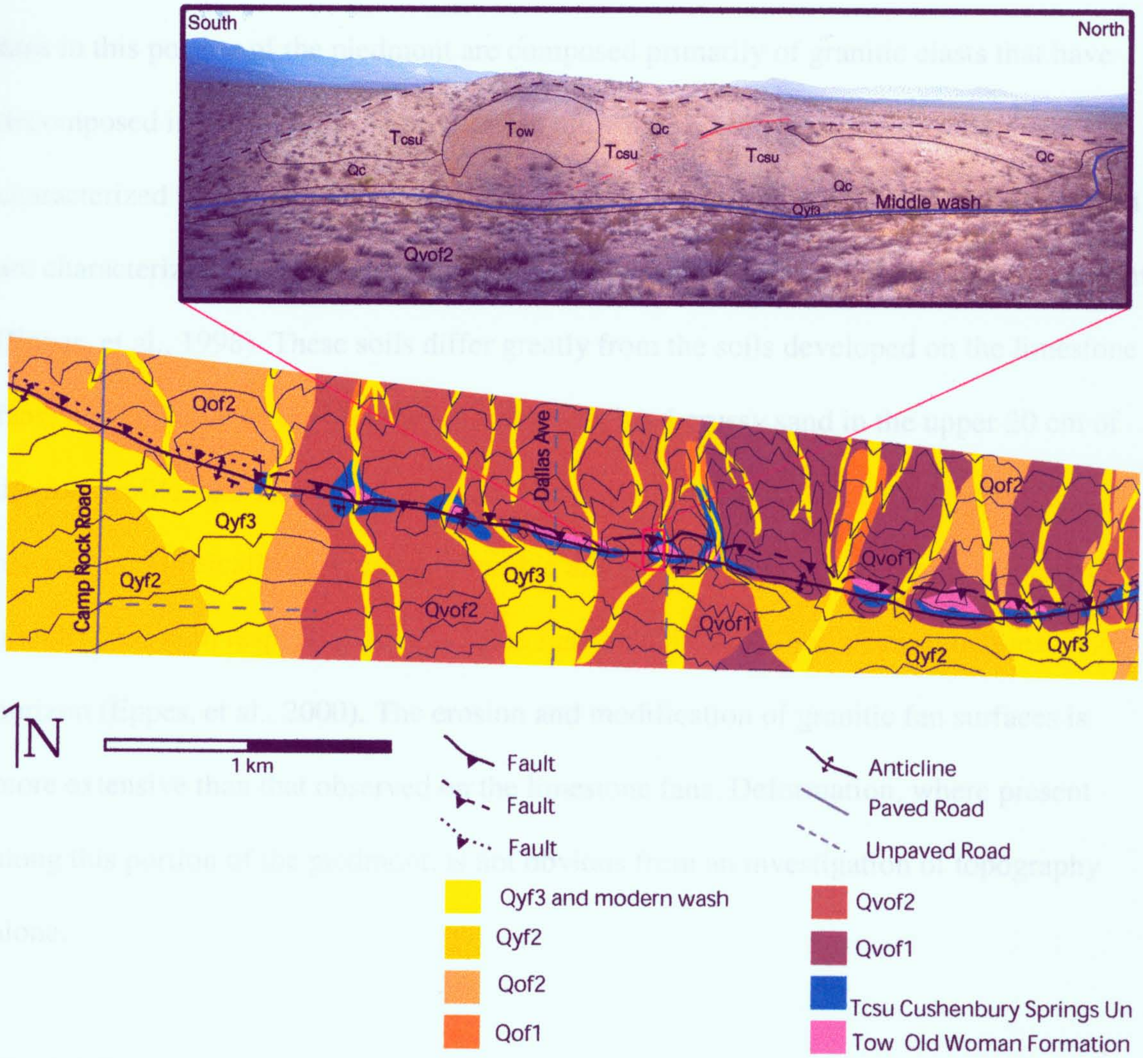

Figure 4. Geologic map of Cougar Buttes anticline (Eppes, et al., in prep.). Photo (view looking west) shows the fold cut by Middle wash. The fault plane (solid line), Tertiary Old Woman Springs (Tow), Tertiary Cushenbury Springs (Tcsu), Quaternary colluvium (Qc), Quaternary very old fan (Qvof2), Quaternary young fan (Qyf3), and the base of a middle (?) Pleistocene pedogenic calcic horizon (dashed line) are shown.

the flanks of the anticline from erosion (Eppes et al., 2000). In contrast, the mountain front west of the Helendale fault is dominated by Mesozoic granitic batholiths. Alluvial fans in this portion of the piedmont are composed primarily of granitic clasts that have decomposed into grus. The majority of fan units in this portion of the piedmont are characterized by the development of soils that are interpreted to be less than 20 ka which are characterized by reddened horizons, with less than stage I calcic horizon development (Eppes, et al., 1998). These soils differ greatly from the soils developed on the limestone fans, most notably by the presence of unconsolidated grussy sand in the upper 20 cm of the soil profile, and the lack of a resistant petrocalcic horizon. The genesis of this soil results in dramatically different geomorphic and erosional behavior of the surface of the granitic fans with respect to the limestone fans, mainly due to the absence of a resistant horizon (Eppes, et al., 2000). The erosion and modification of granitic fan surfaces is more extensive than that observed on the limestone fans. Deformation, where present along this portion of the piedmont, is not obvious from an investigation of topography alone.

Fluvial Expression of Active Tectonics

This study focuses on a series of ephemeral streams that traverse the Cougar Buttes anticline and continue north into the Mojave block. These streams head on both the alluvial fans of the piedmont and within the mountain front. Based upon the results from many previous studies of perennial alluvial channels (as reviewed in Schumm, 2000) I anticipate seeing a response in the ephemeral channels as they encounter the actively rising fold. Although the majority of previous research has focused upon documenting the response to active tectonics for perennial channels, I enter this research with the working hypothesis that ephemeral channels will also respond, but in an unknown manner. The response is unknown because ephemeral and perennial channels have vastly different discharge and sediment transport characteristics.

A perennial alluvial channel is free to mutually adjust its dimensions, shape, pattern, and gradient in response to external factors such as climate, tectonics, or sediment supply. The perennial channel bed and banks are composed of the material transported by the river under prevailing flow conditions (Schumm, et al., 1987). As discharge increases downstream, the depth of the channel increases, and the gradient of the stream decreases, both proportionally to discharge (Leopold and Maddock, 1953). In contrast to the perennial streams, the depth of ephemeral streams in semi-arid regions will increase less rapidly and gradient will decrease less rapidly in the downstream direction, due to the high water loss and increase in suspended sediment concentration in the downstream direction (Schumm, et al., 1987). Additionally, ephemeral streams in arid regions tend to become clogged with debris flow lobes, the result of frequent hyper-concentrated flows, and debris flows during times when the stream has discharge. These debris lobes are usually very coarse grained, armor the channel, and thus greatly increase the response time of the channel to adjust to a tectonically-induced change in gradient. These differences in sediment transport render it unlikely that ephemeral channels will respond by making the same subtle changes in channel sinuosity that has been documented for low gradient perennial channels.

I proceed on the premise that ephemeral channel response will be expressed primarily by changes in both channel hydraulic geometry (Leopold and Maddock, 1953), and in general channel pattern. Hydraulic geometry is an expression of the balance between form and process in the fluvial system, and includes channel metrics such as: width, depth, velocity, sinuosity, and average channel bed grain size. These metrics mutually adjust in response primarily to changes in discharge, and secondarily to changes in slope. Slope refers to both channel slope and valley slope, in which the sinuosity of the channel is the compensation between the two. Ouchi (1983) documented a useful example of channel hydraulic geometry and channel pattern changes for a braided, perennial stream that encounters a zone of uplift. Upstream of the uplift the channel tends to aggrade, experience a thalweg shift, and have many submerged bars. In the axis of uplift, the channel tends to incise, have single bars, and forms terraces. And downstream of the uplift, the channel tends to aggrade.

Methods

Six transverse channels were chosen to cover the along strike exposure of the Cougar Buttes anticline. From east to west they are Blackhawk wash, Doubleknob wash, East Middle wash, Middle wash, Slick wash and Control wash (Figure 5). Each stream was divided into 5 reaches, A through E, each approximately 0.5 km in length, with reaches A and B being upstream of the fold, D and E downstream of the fold, and reach C corresponding to the axis of the fold. The channels were divided in this manner so that each reach would correspond to a particular location relative to the fold axis; distal upstream (A), proximal upstream (B), the fold axis (C), proximal downstream (D), and distal downstream (E).

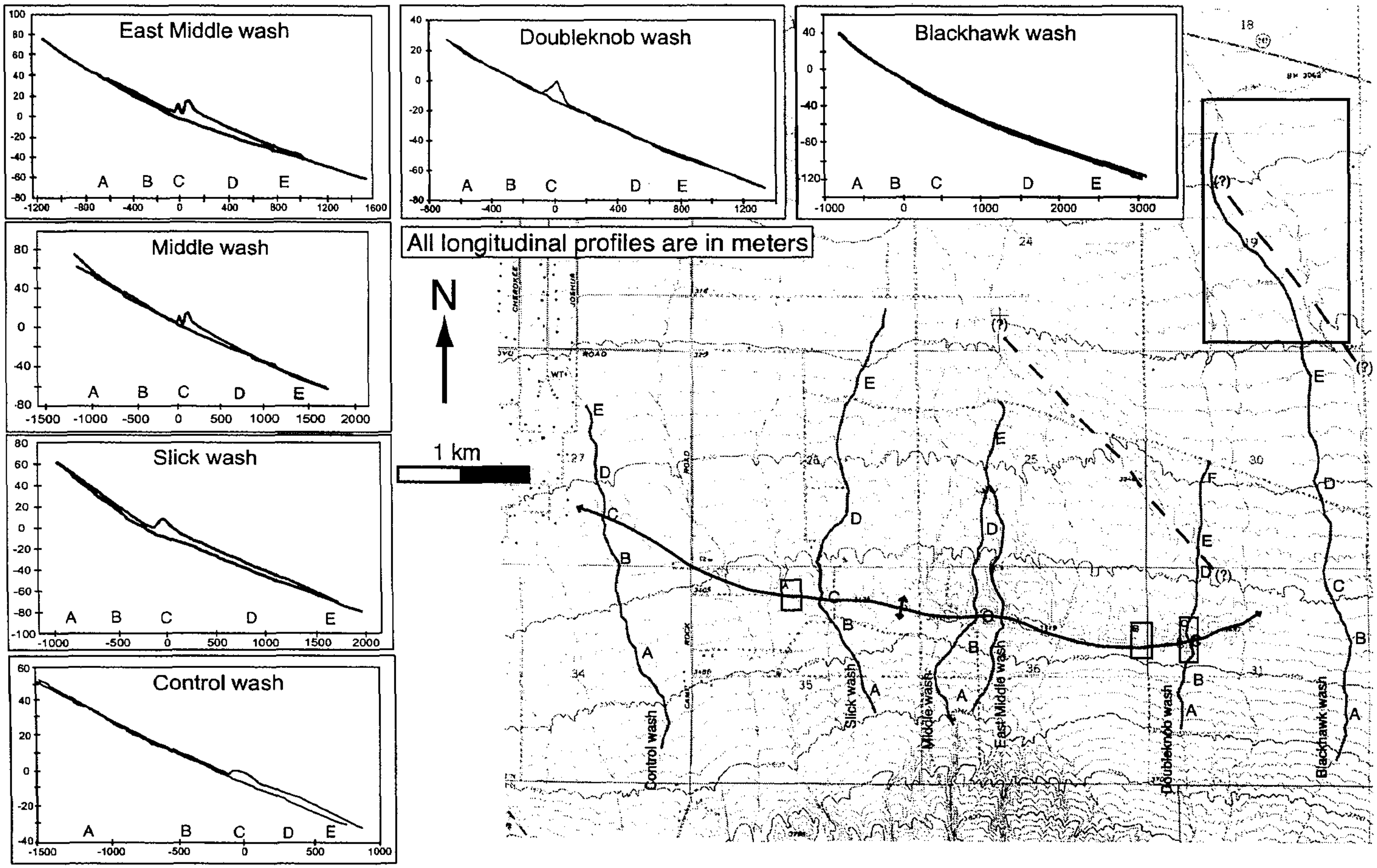

Figure 5. Topographic map of Cougar Buttes anticline showing the locations of the six channels and reaches A through E for each channel. Map is 1:24,000 with a contour interval of 20 feet. Longitudinal profiles for each channel are also shown. The upper line is the interfluve profile, and the lower line is the channel profile. Scale is in meters.

A high-resolution survey of each channel and interfluve adjacent to the channel was made using a Sokkia laser theodoliite. From these surveys, longitudinal profiles were plotted to illustrate the gradient of the channel normal to the rising structure. The interfluve profiles for Middle and East Middle washes appear to have a double peaked anticline, however, it is merely the development of a strike-parallel drainage in the easily erodable Cushenbury Springs and Old Woman Springs Formations that have been exposed in the core of the anticline.

A representative cross section of the entire valley width was also surveyed for each reach (Figure 6). From these cross sections, the width (w) and depth (d) of the channel was measured, allowing the width to depth ratio (w:d) to be calculated (Table 1).

$$w{:}d = w/d \quad (1).$$

The width to depth calculation is a good example of a problem that I faced while trying to quantify these channels. In the field, it is often very ambiguous where the channel bed stops and the fan surface begins. Channel geometry is so variable, that it is difficult to decide where discharge is actually channeled. In an effort to be consistent, the width of the channel is defined by an observable change from a sandy channel bottom to a coarser fan surface, recorded in field notes taken while surveying. The depth is defined by the difference in elevation between the lowest elevation in the channel and the elevation of the closest flat fan surface.

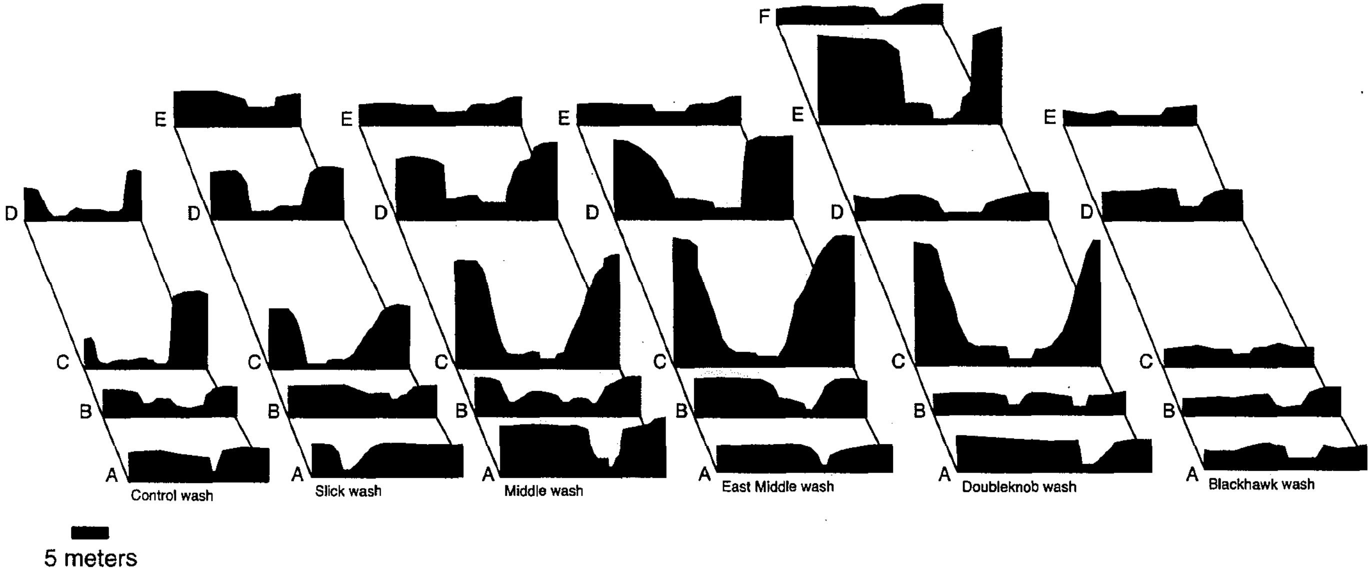

Figure 6. Schematic showing a representative cross section for each reach (A-E) of each stream. Doubleknob wash extends to reach F in order to capture the channel response as it crosses a northwest-trending structure in reach E.

TABLE 1. CALCULATED AND MEASURED ASPECTS OF HYDRAULIC GEOMETRY FOR STREAMS NORMAL TO THE COUGAR BUTTES ANTICLINE

		Control	Slick	Middle	East Middle	Double-knob	Black-hawk
	sinuosity						
no trend ↓	A	1.10	1.12	1.10	1.06	1.15	1.10
	B	1.11	1.15	1.12	1.16	1.19	1.20
	C	1.08	1.08	1.17	1.09	1.25	1.15
	D	1.16	1.16	1.07	1.17	1.31	1.13
	E	1.12	1.10	1.10	1.10	1.08	1.06
	entire	1.10	1.17	1.14	1.14	1.18	1.15
	average grain size (in mm)						
	debris lobe in reach B			65.8			
decrease ↓	B			38.4			46.2
	C			32.1			44.0
	D			30.6			38.0
	w:d						
increase ↓	A	0.83	0.31	0.13	0.52	0.84	1.49
	B	6.41	0.59	13.3	1.39	1.64	dns*
decrease ↓	C	0.30	0.37	0.29	0.12	0.13	2.31
increase ↓	D	5.51	0.52	0.42	0.72	1.41	2.05
	E	dns*	5.77	3.83	3.83	0.89	1.40

*dns = did not survey.

Channel sinuosity (P), the length of the surveyed channel (l_c) divided by the length of the valley (l_v), was calculated for entire streams, as well as for individual reaches (Table 1):

$$P = l_c/l_v \quad (2).$$

Using a strategy inspired by the Wolman method (Leopold et al., 1964), the grain size of the alluvium from the bed of Blackhawk and Middle washes was sampled (Table 1). The Wolman method provides a sampling strategy that produces an objective measure of a channel's average bed grain size. Using this method, the B-axis of 100 sediment grains from a single reach of the channel is measured. A measuring tape is placed longitudinally in the channel, and the grain that is nearest every 0.5 m interval on the tape is measured. The number reported is simply the mathematical average of the 100 grains measured.

Results

The Cougar Buttes anticline

The Cougar Buttes anticline (Figures 2 and 4) was chosen for this study because it clearly is an area of recent tectonic uplift. Based upon the age of the deformed stratigraphy, this fold has been active in the late Quaternary. The Cougar Buttes anticline is topographically expressed for 2 km, and has an amplitude of 20 m at the center of the fold that decreases to 12 m along strike to the east and west. The wavelength of the fold varies from 160 to 200 m. Dips on the backlimb range from 20° up to 55°, while dips on the forelimb range from 2° to 26°, with steeper dips generally near the center of the fold. Both limbs are capped and supported by a resistant 2-3 m thick petrocalcic horizon. The Old Woman Springs and Cushenbury Springs Formations are exposed in the core of the fold. The fold core also exposes a north verging thrust fault that ranges in dip between 19° and 25°. The petrocalcic horizon forms a well-defined stratigraphic markerbed that allows direct observation of fault offset. At fairly regular intervals (approximately every 0.2 km) in the central portion of Cougar Buttes anticline, the axis of the fold has been cut by transverse ephemeral channels which have incised 15-20 m. These drainages head either on the alluvial fan itself, or immediately in the mountain front, and do not vary in drainage basin area by more than one order of magnitude. The Quaternary stratigraphy and structures are mapped in detail in Figure 4. A photo cross-section of the incision into the fold by Middle wash shows the stratigraphy, the fault plane, and the 15 m of relief that exists between the crest of the fold and the channel bottom.

Channel pattern morphology

Apart from any other measurable aspect of hydraulic geometry, the observable change in channel pattern morphology is the most distinct distinguishing feature between adjacent reaches of each channel as they traverse the Cougar Buttes anticline. A large increase in w:d values from reach A to B, a sharp decrease in reach C, and a slow increase from D to E was a general trend found for each stream and best expressed in East Middle wash (Figure 7). The overall morphology of the channel, as seen in the photos of reaches A, B and C (Figure 7) corroborates the w:d variations. Reach A is generally a small single channel approximately 0.5 to 1 m wide, incised 1 to 2 m into the fan surface. Reach B is distinctly braided, with many active channels, each about 1 m wide, and a much wider valley bottom. This reach usually contains active bars and debris flow lobes, and is the storage site for a large wedge of sediment. Once the stream enters

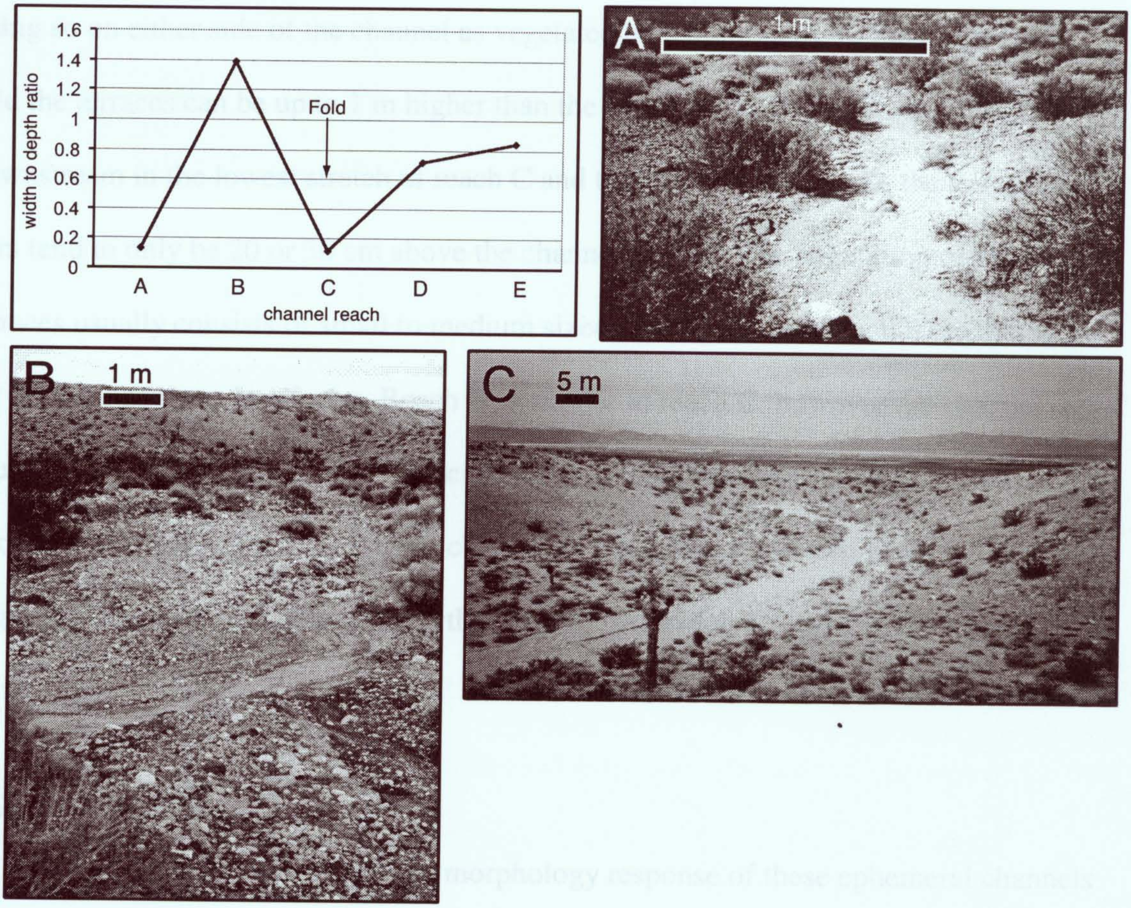

Figure 7. Plot showing the width to depth ratio of a representative portion of each channel reach for East Middle wash. Photos of each reach illustrate the disparity in gross channel pattern morphology between each reach. Notice the coarse cobbles of the debris lobes in photo B, and the vegetated terrace to the left of the channel in photo C.

the fold (reach C), it transforms again to a single channel approximately 3 to 6 m wide. Reaches C and D are storing large amounts of alluvium like reach B, however they are doing so on either side of the channel as vegetated bars or terraces. In the hinge of the fold the terraces can be up to 1 m higher than the active channel bottom, but further downstream in the lowest stretch of reach C and the entirety of reach D, the terraces and bars tend to only be 20 or 30 cm above the channel bottom. The vegetation on these terraces usually consists of small to medium sized shrubs and creosote bushes that likely act to stabilize these landforms. Reach D is similar to reach C, however the channel is usually only incised into the fan surface 2 to 5 m, rather than 10 to 20 m as in reach C. Like reach D, reach E is also a single channel approximately 2 to 4 m wide, but the vegetated bars have disappeared, and the channel is only incised 0.5 to 1 m into the fan surface.

Tectonic transition

The changing channel pattern morphology response of these ephemeral channels is not limited to the uplift of Cougar Buttes anticline. Northwest-trending faults synthetic to the Helendale fault, strike across the distal portions of the fans and may accommodate some of the shortening across the San Bernardino-Mojave block transition. Instead of creating an east-west trending fault-propagation-fold similar to the Cougar Buttes anticline, deformation appears to be taking advantage of the pre-existing northwest-trending structural grain of the Mojave block, creating uplifts with this northwest Mojave block orientation. The deformation is expressed as small northwest-trending anticlinal (or monoclinal) uplifts that have not yet exposed older units or a fault plane, and are not always recognized as structures (Powell and Matti, 1999). Based upon topography alone, these uplifts would be characterized as 0.3 to 1 km in length and stand 3 to 10 meters above the fan surface (Figure 8). Two streams, Blackhawk and Woodlane washes, interact with one such uplift 3 km northeast of the Cougar Buttes anticline (Figure 5). Blackhawk wash is merely deflected around the structure, but Woodlane wash cuts the structure. The longitudinal profile of both channels shows the disparity in gradient between the two as Woodlane crosses the axis. In addition to changes in gradient, these channels also adjust their channel pattern morphology. Photo C (Figure 8) shows a representative reach of Blackhawk wash, which is approximately 6 m wide, flat-bottomed, lacking any vegetated bars, and incised only 10's of cm into the fan surface. In comparison, photo D (Figure 8) shows that Woodlane wash changes from a wide, flat-bottomed channel 0.5 km upstream of the fold, similar to Blackhawk wash, to a braided channel with active and vegetated bars immediately upstream and into the axis of the fold (corresponding to reaches B and C of Cougar Buttes anticline). The response of Woodlane wash suggests that the main adjustment made by these ephemeral streams to an uplift, whether it be these small northwest-trending uplifts or Cougar Buttes anticline, is to change channel pattern morphology to a braided pattern, temporarily storing sediment in the reach immediately upstream of the fold and in the fold axis itself.

Transverse drainage development

In addition to capturing the response of these ephemeral channels to changes in tectonically altered gradients, the Cougar Buttes anticline also provides an ideal field location to explore the development of transverse drainages. A space-for-time

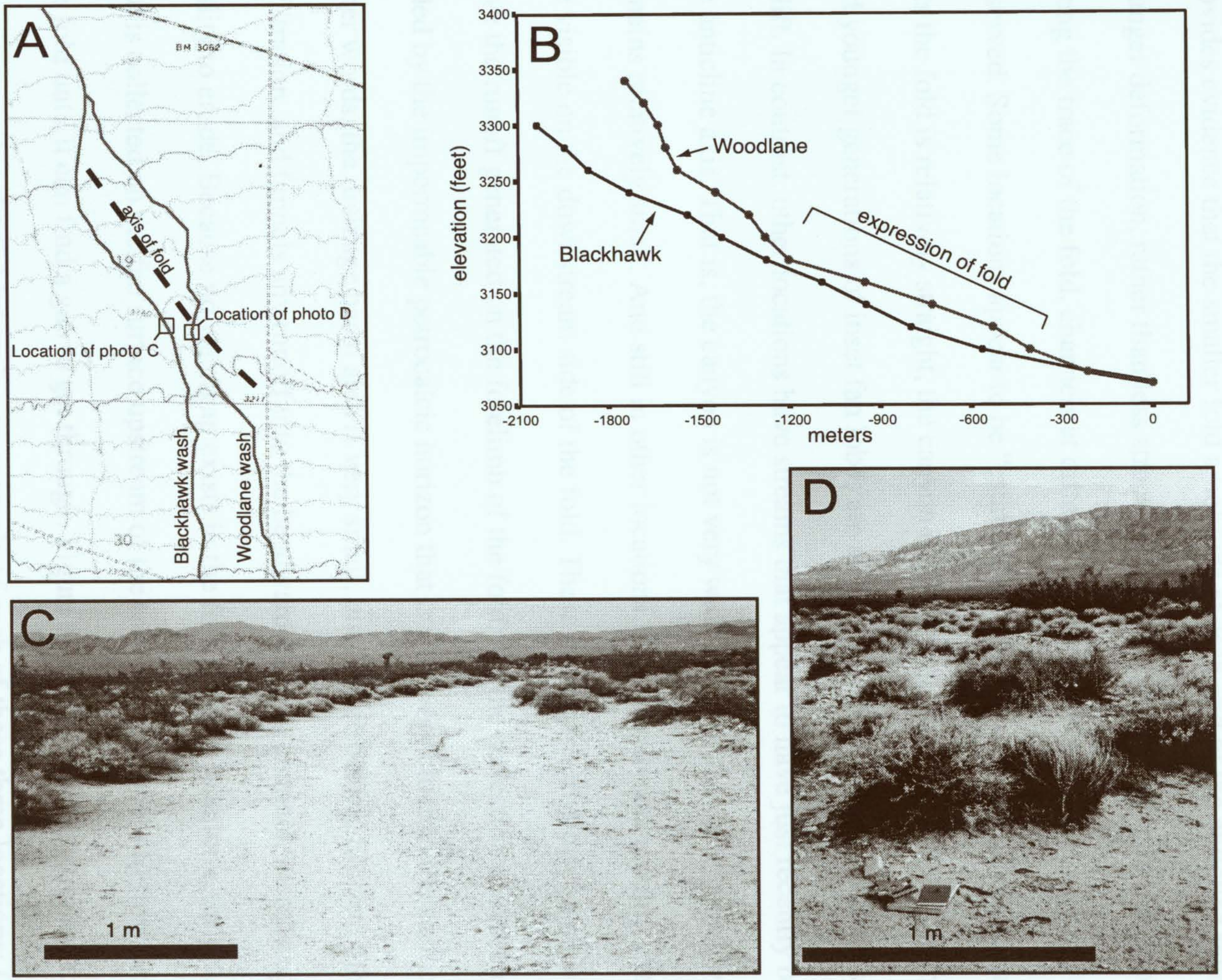

Figure 8. (A) Topographic map showing portions of Blackhawk and Woodland washes as they encounter a northwest-trending uplift (dashed). (B) Longitudinal profiles of Blackhawk (lower curve) and Woodlane (upper curve) washes for the corresponding map area. (C) Photo of an average reach of Blackhawk wash. (D) Photo of a reach of Woodlane wash as it crosses the northwest-trending structure.

substitution can be performed along strike of Cougar Buttes anticline, because structural and stratigraphic offset in the fold's center is greater than at its tips. The geomorphology provides evidence that the smaller fold amplitude at each end of the anticline represents younger deformation, rather than less structural offset, as a result of fault tip propagation. Along the trace of the fold, channels at different stages of breeching the anticline can be observed. Some locations appear to be "established", that is, the path of the stream that cuts the fold is relatively straight, the canyon is 10's of meters wide and deeply incised, and younger generations of inset fan lobes are able to use these gaps to get across the uplift. In contrast, other locations have streams that appear to have just recently breeched the anticline axis. That is, the canyon is not very wide or deep, and the channel width remains relatively small. And still in other locations, small headward-eroding channels are visible on the downstream side of the fold. These headward-eroding channels only have the runoff generated on the forelimb of the fold, but the collection of discharge is aided by the impermeable petrocalcic horizon that is at or very close to the surface. In other words, the drainage basin area is very small, but the petrocalcic horizon limits infiltration, and funnels any runoff into the headward-eroding channel, increasing its ability to erode. Because no watergap exists in the fold in these locations, the drainage that is collected on the fan surface upstream of the fold is often forced to flow parallel to the fold until it can find a gap to get through. Figure 9 shows three topographic maps that were surveyed in the field showing an example of each of these three locations; (A) illustrates a headward-eroding channel, (B) illustrates a stream that has recently breeched the anticline, and (C) illustrates a channel that is "established". Numerous factors such as the aridity of the climate, the amplitude of Cougar Buttes anticline, and the presence of

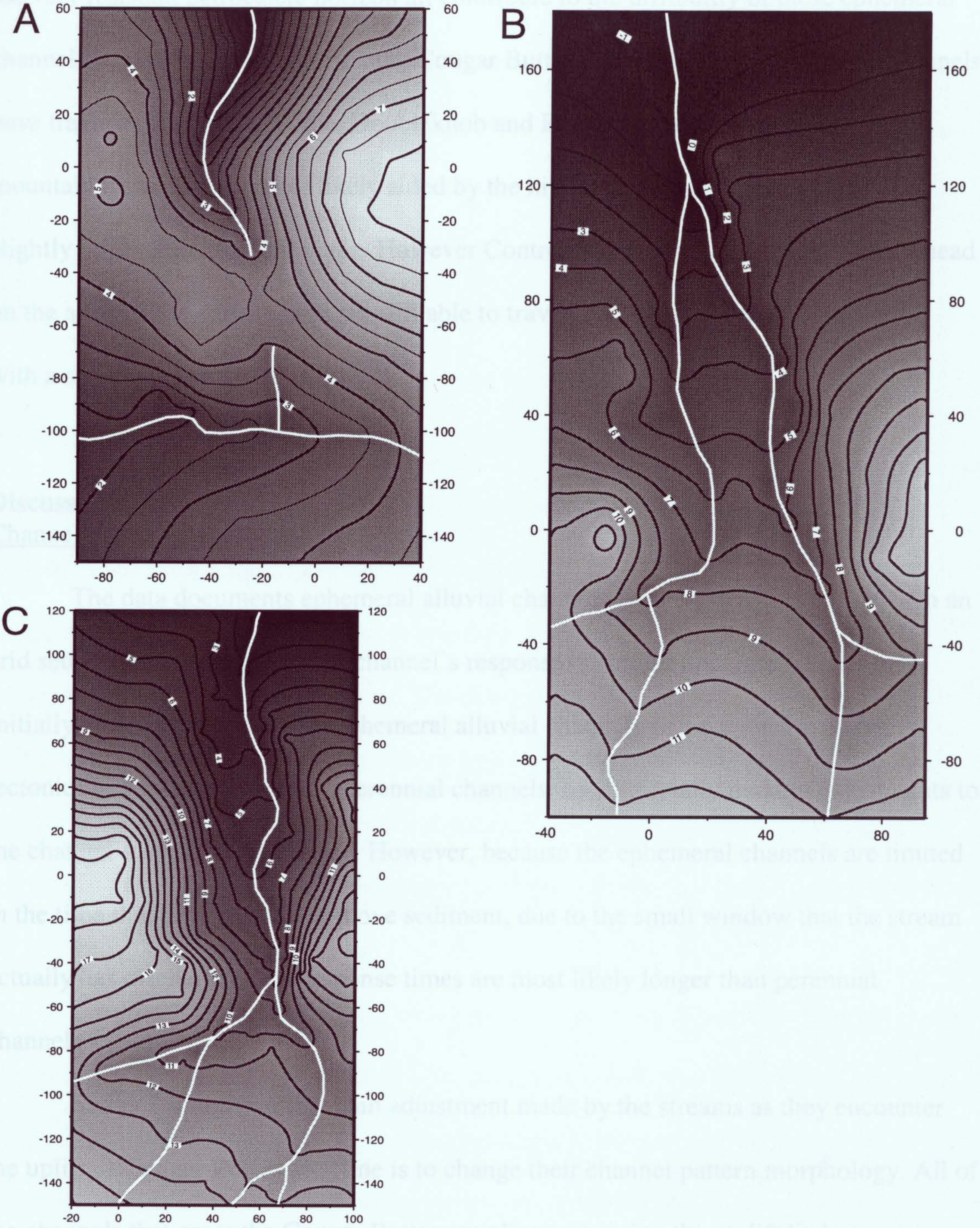

Figure 9. (A) Topographic map showing the initial stage of headward erosion into the anticline axis just west of Slick wash. (B) Topographic map showing an area just west of Doubleknob wash, which has recently breached the anticline axis. (C) Topographic map of Doubleknob wash, an "established" channel. Scale is in meters. See Figure 5 for locations.

the very resistant petrocalcic horizon all contribute to the difficultly of these ephemeral channels actually making it across the Cougar Buttes anticline. But clearly these channels *have* traversed the fold. Middle, Doubleknob and Blackhawk washes head in the mountain front, and are most likely aided by the higher discharge produced from the slightly larger drainage basin area. However Control, Slick and East Middle washes head on the alluvial fan surface, and are still able to traverse Cougar Buttes anticline, even with a smaller drainage basin area.

Discussion

Channel pattern morphology

The data documents ephemeral alluvial channel response to active tectonics in an arid setting. In some aspects, the channel's response is similar to perennial channels. Initially one might believe that ephemeral alluvial channels will respond to active tectonics in a manner similar to perennial channels, by continually making adjustments to the channel's hydraulic geometry. However, because the ephemeral channels are limited in the time that they are able to move sediment, due to the small window that the stream actually has discharge, their response times are most likely longer than perennial channels.

Earlier I stated that the main adjustment made by the streams as they encounter the uplift of Cougar Buttes anticline is to change their channel pattern morphology. All of the channels that cross the Cougar Buttes anticline respond to this uplift by becoming braided and storing sediment upstream of the fold in reach B (sometimes reaching up to 500 meters upstream of the fold axis). Also, they incise and preserve a terrace in reach C, downstream of the fold hinge. This series of adjustments in the channel pattern morphology are summarized in a cartoon block diagram (Figure 10). Whereas perennial channels aggrade downstream of the uplift, these ephemeral channels widen and return to the grade of the fan; a behavior perhaps influenced by the downstream loss of discharge. Although each stream makes the same adjustments in their channel patterns, some channels have a greater magnitude of change. Among the channels, some are choked with coarse sediment in reach B, while others have fewer and smaller bars and debris flow lobes in this reach. This distinction is most likely related to the size of the drainage basin above the fold, and thus, the amount of sediment supplied to each stream. Streams that head in the mountain front have a greater magnitude of change in channel pattern morphology, and often have coarser debris flow lobes in reach B, when compared to streams that head on the alluvial fans. The changes that are observed are much more subtle for streams that head on the alluvial fans. When making observations of stream reaches to identify areas of tectonic deformation, one must be aware of drainage basin size above the deformation, and the source (and size) of sediment that is being supplied to the stream.

The most consistent response observed amongst these ephemeral channels is a change to a braided, aggrading pattern upstream of an uplift. Yet, the physical rationale for this response is unknown. Perhaps the aggradation is a response to the change in gradient associated with the fold. Alternatively, it could be a response to the physical barrier of the fold and bottleneck produced by the narrow width of the gap cut in the fold. In this specific location, it is difficult to quantify how much of the channel pattern change is a response to the tectonic change in channel gradient versus how much is a response to

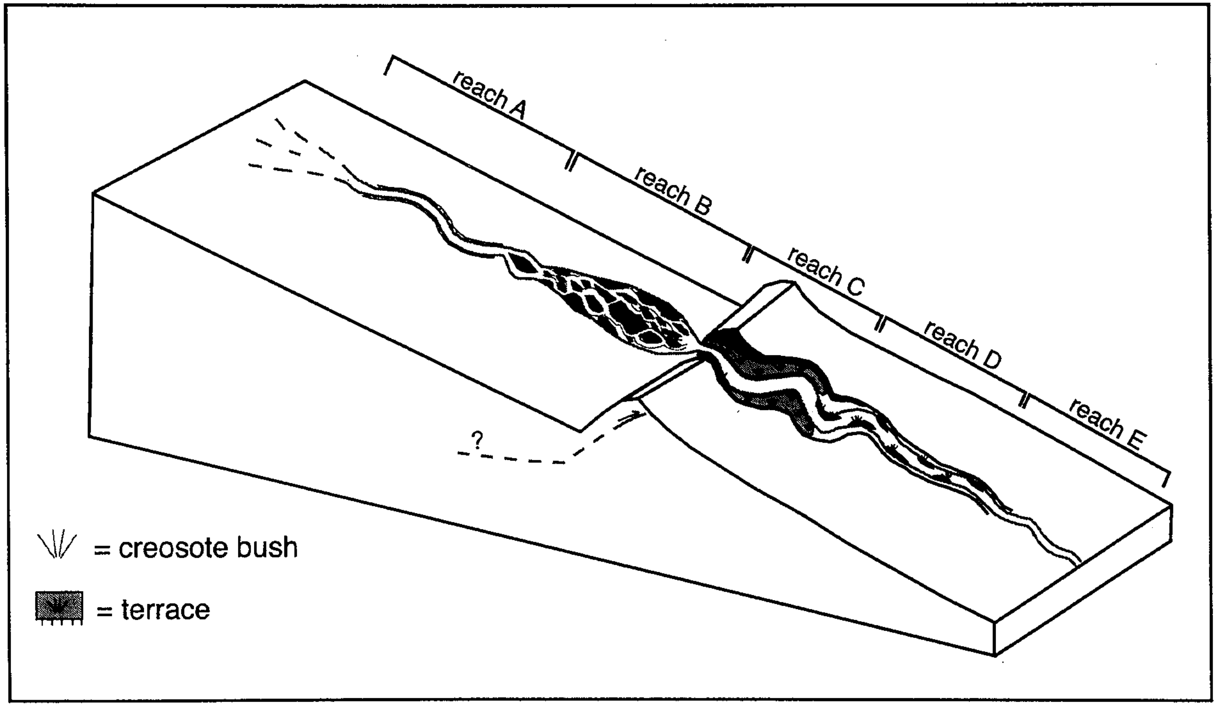

Figure 10. Cartoon block diagram illustrating the gross changes in channel pattern morphology for ephemeral alluvial channels responding to an active tectonic uplift.

the topographic barrier physically trapping the wedge of sediment, although the two are more or less related.

Besides the streams that cross the Cougar Buttes anticline and Woodlane wash as it crosses a northwest-trending anticlinal uplift, another stream clearly undergoes similar changes in channel pattern in response to crossing an uplift. Reaches D, E and F of Doubleknob wash show changes in channel pattern morphology as this stream encounters another northwest-trending uplift just north of the Cougar Buttes anticline (Figure 5, dashed line). As the channel encounters this structure, the channel responds by slightly aggrading in reach D, the reach immediately upstream of the structure. In the axis of this structure (reach E), the channel incises into the fan surface, and preserves a vegetated terrace. Finally, after the stream passes any influence of uplift, reach F returns to a wide single channel only incised 0.5 m into the fan surface (Figure 6). Again, I see the same series of changes in channel pattern morphology in reaches D, E and F of Doubleknob wash as I see in streams transverse to the Cougar Buttes anticline, as well as in Woodlane wash. Thus, it appears that the changes in channel pattern morphology illustrated in Figure 10 are common to any of these ephemeral channels that encounter an uplift.

Transverse drainage development

The existence of transverse drainages demonstrates that ephemeral channels in an arid setting, and with small drainage basin areas are able to traverse the topographic barrier and resistant petrocalcic horizon of the Cougar Buttes anticline. However, it is still unclear what mechanisms the channels use to traverse the fold. One model to explain the development of the transverse drainages involves a progression between the three "stages" of development illustrated in Figure 9. Initially a headward-eroding channel forms on the forelimb of the anticline (Figure 9 A). Given enough time, it breeches the axis of the anticline, gains the drainage basin area that previously was deflected by the topographic barrier, and rapidly incises (Figure 9 B). At its final stage of development, the channel has deeply incised and created an "established" path through the axis of the anticline (Figure 9 C). Alternatively, these three stages of development may not be linked at all. In some locations, these streams could have been flowing along their present course long before the Cougar Buttes anticline began to uplift. As the anticline developed, these channels merely incised at a rate to keep up with the uplift of the fold. These streams are antecedent (Figure 9 C) and are the primary means of breeching the anticline. Later, headward-eroding channels develop, and once they breech the anticline, they become the subsequent streams (Figure 9 A and B) representing the secondary means of breeching the anticline.

It is difficult to prove which model is correct, but at the Cougar Buttes anticline the development of transverse drainages most likely involves a combination of the two models. The streams that head in the mountain front are probably antecedent because they have slightly more discharge, and have more power to keep up with the rising fold. The streams that head on the alluvial fan are probably subsequent, and breech the anticline in locations born from headward-eroding channels. This distinction can be quantified along strike of the Cougar Buttes anticline because the spacing of drainages appears to be a diagnostic characteristic between antecedent and subsequent streams. The streams that head in the mountain front, which are believed to be antecedent, have an average spacing of 0.6 km, with values ranging between 0.2 and 1.2 km. Alternatively, the subsequent streams that head on the alluvial fans have an average spacing of 0.2 km, with values ranging between 0.1 and 0.4 km. The greater spacing of the antecedent streams represents the larger drainage area of the mountain front basins, and the smaller spacing of the subsequent streams represents the spacing on the forelimb of the fold of the headward-eroding channels. In other words, a distance of approximately 0.2 km could be the threshold needed before the headward-eroding channel is able to collect enough discharge to be able to breech the anticline.

Tectonic Significance

The shortening associated with the uplift of the San Bernardino Mountains is accommodated in the complicated zone of faults and folds between the Big Bear and Mojave blocks (Figure 1). As shortening continues, the deformation is progressively taking advantage of pre-existing northwest-trending Mojave block structures. Although the Cougar Buttes anticline generally trends east-west, the more distal structures all trend northwest. This suggests that the transition between the Big Bear block of the San Bernardinos, and the Mojave block is apportioned over a span of at least 4 km, which is the distance between the Cougar Buttes anticline and the furthest distal northwest-trending monocline.

This field study provides an opportunity to gain insights on the rates of deformation along the north flank of the San Bernardino Mountains, as well as the potential magnitude of earthquakes resulting from rupture on blind thrust faults such as the Cougar Buttes anticline. I am able to do this because the response of these ephemeral channels can be used as a tool to locate zones of tectonic deformation in arid or semi-arid landscapes. Along the north flank of the San Bernardinos, the stream response and geomorphology compels the consideration of a wider zone of shortening than is observed in the topographic expression of the Cougar Buttes anticline. Besides locating areas of tectonic deformation, the streams also are able to show that the length of any individual structure is greater than what would be interpreted from topographic maps or aerial photos. For example, any topographic expression on a 20' contour map of Cougar Buttes anticline stops just west of Slick wash (topographic contours of Figure 5). However, the behavior of Control wash, and the convexity in the interfluve longitudinal profile shows that indeed, the anticline extends at least that far west (Figure 5). Based upon the expression on the topographic map, Cougar Buttes anticline extends only 2 km, but if the streams are faithful recorders of the active structure, in fact the anticline extends at least 3 km. The magnitude of an earthquake is highly correlated to the surface length of the rupture that generates it (Wells and Coppersmith, 1994). Applying this relationship to the Cougar Buttes anticline would predict an earthquake of maximum magnitude 5.4 for a fault 2 km in length, the topographic extent of the fold, but an earthquake of maximum magnitude 5.7 for a fault 3 km length, the minimum length of the fold.

This study was strategically designed to document the response of ephemeral channels to tectonic uplift in an area where the uplift is obvious in the topography. Once this response has been documented, this tool can be applied in other locations where the effect of deformation is not so clear in the topography. In this respect, it is useful to investigate that portion of the piedmont that is west of the Helendale fault. On the alluvial fans composed of granitic grus, I suspect that fault-propagation-folds exist, but topographic anticlines are absent because of the lack of a resistant petrocalcic horizon as well as more effective erosion and modification of fan surfaces. The differences in parent material of the fan, and the soil that develops, creates a huge disparity with respect to the limestone dominated fans in the manifestation of topography, and does not allow any topographic expression of the Pitzer Buttes anticline (details found in Eppes et al., in prep.). A detailed geologic map of the fans near Pitzer Buttes (Figure 11) reveals warped Tertiary and Quaternary beds I term the Pitzer Buttes anticline. Changes in channel pattern morphology as Pitzer Buttes wash encounters the Pitzer Buttes anticline are similar to changes along the channels transverse to the Cougar Buttes anticline. The stream begins as a single channel 2 m wide, only slightly incised into the fan surface, then the valley widens to accommodate many individual active channels, and finally the stream returns to a single channel that is storing sediment as small vegetated bars. This response corresponds to reaches A, B and C of streams that cross the Cougar Buttes anticline, with the only major difference being the lack of a vegetated terrace in reach C. Although similar changes in channel pattern morphology are present, these changes are muted and more difficult to distinguish, because the entire stream system is constantly inundated with the easily erodable fine grussy sediment from the fan surface.

Coarse debris lobes are present in reach B, immediately upstream of the fold, however they are stranded 2 m above the current channel elevation. I believe that these debris lobes were deposited immediately after the fold was uplifted, in response to the topographic barrier of the fold, as well as the change in gradient as the stream encountered the fold. However, because these granitic fans and their soils offer no resistance to erosion, Pitzer Buttes wash has since incised through the fan material, and

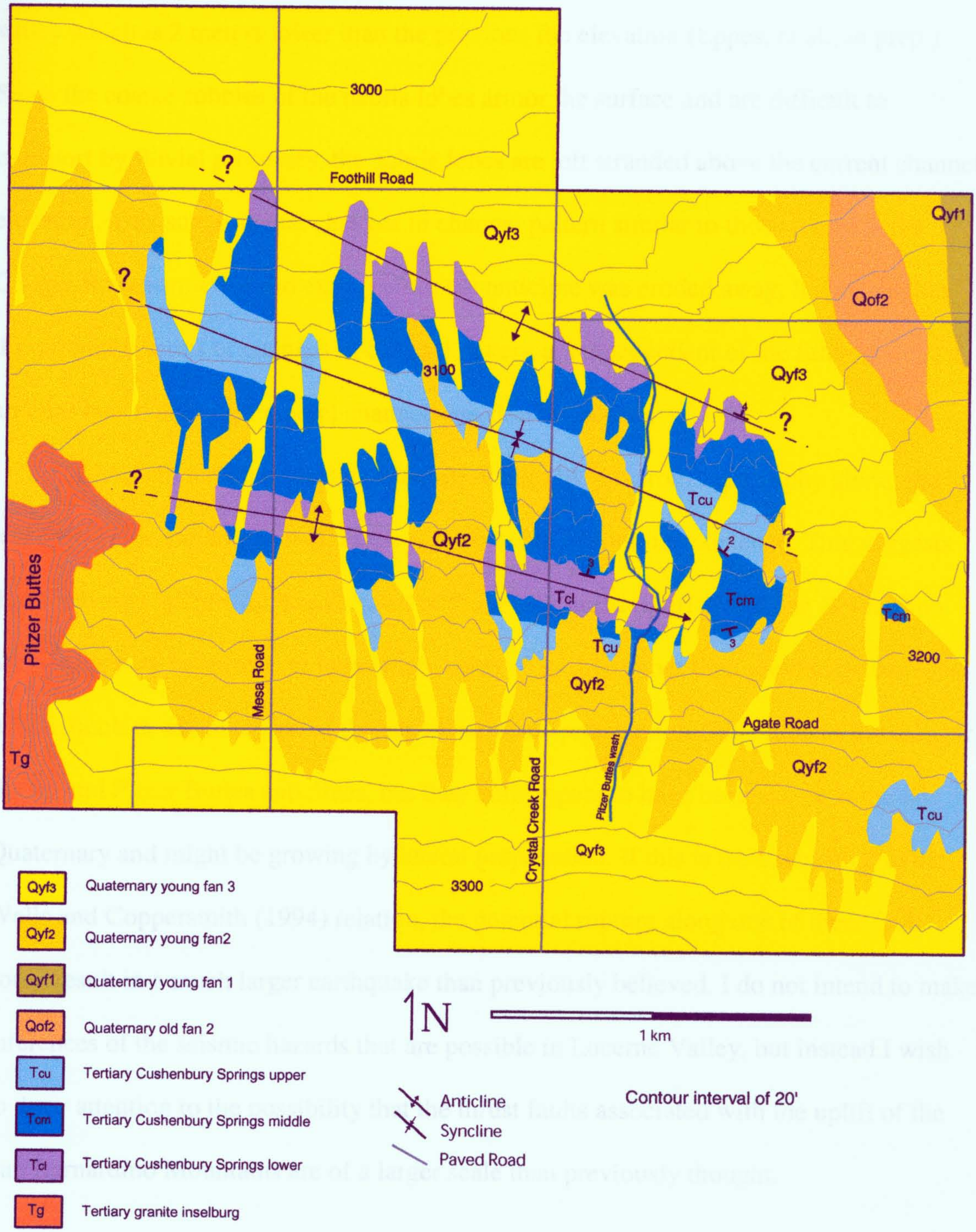

Figure 11. Geologic map of Pitzer Buttes anticline. Surficial geology mapped by Powell and Matti, in prep.

into the easily erodable Cushenbury Springs in the fold's core, creating an anticlinal valley which is 2 meters lower than the previous fan elevation (Eppes, et al., in prep.). Since the coarse cobbles of the debris lobes armor the surface and are difficult to transport by fluvial processes, the debris lobes are left stranded above the current channel elevation. This suggests that changes in channel pattern similar to those found at the Cougar Buttes anticline did exist, before the anticline was eroded away. It appears that this common series of changes in channel pattern are independent of the lithology of the alluvial fans that the ephemeral channels are flowing across.

Although the Pitzer Buttes anticline is not obvious from topography alone, the response of the streams as well as the map patterns attest to its existence. This suggests that fault-propagation-folds associated with the continued uplift of the San Bernardino Mountains may be located in many more areas of the piedmont than previously believed. It is difficult to say much about the activity of fault-propagation-folds such as the Cougar Buttes and Pitzer Buttes anticlines, but they both appear to have been active in the late Quaternary and might be growing by lateral propagation. If this is true, returning to the Wells and Coppersmith (1994) relation, the potential rupture along one of these faults could result in a much larger earthquake than previously believed. I do not intend to make inferences of the seismic hazards that are possible in Lucerne Valley, but instead I wish to draw attention to the possibility that the thrust faults associated with the uplift of the San Bernardino Mountains are of a larger scale than previously thought.

Conclusions

The shortening associated with the uplift of the San Bernardino Mountains is being accommodated as a series of faults and folds in a complex zone between the Big Bear and Mojave blocks. The Cougar Buttes anticline is an area where the shortening is expressed topographically as an anticlinal fold. A series of ephemeral drainages traverse the Cougar Buttes anticline; some of these streams might be antecedent, whereas others are clearly subsequent. Despite the fact that active structures along the north flank have variable topographic expression controlled by the presence or absence of a resistant petrocalcic horizon, there are measurable changes in channel metrics with respect to an unequivocal active anticline, with or without topographic expression. This research is a first step in remediating the dearth of knowledge on how ephemeral alluvial channels respond to active tectonics.

The major conclusions to be drawn from this study are:

(1) Ephemeral alluvial channels *do* respond to changes in slope associated with active tectonics. The response is expressed as changes in channel pattern morphology from reach to reach as the stream crosses the tectonic uplift.

(2) One means for streams to breech an anticline begins from a small headward-eroding channel on the forelimb of the fold. Once this drainage has breeched the anticline, it gains the drainage basin area upstream of the fold and is able to quickly incise. The transverse drainages of Cougar Buttes anticline suggest that although some streams might be antecedent, others are surely subsequent, and were born from these headward-eroding drainages on the forelimb of the anticline.

(3) The response of these ephemeral channels have necessitated the consideration of a much larger zone that is accommodating the shortening associated with the uplift of the San Bernardino Mountains. A rupture along the true length of one anticlinal fault segment could potentially cause a much larger magnitude earthquake than would be expected from the topographic expression of that anticline alone.

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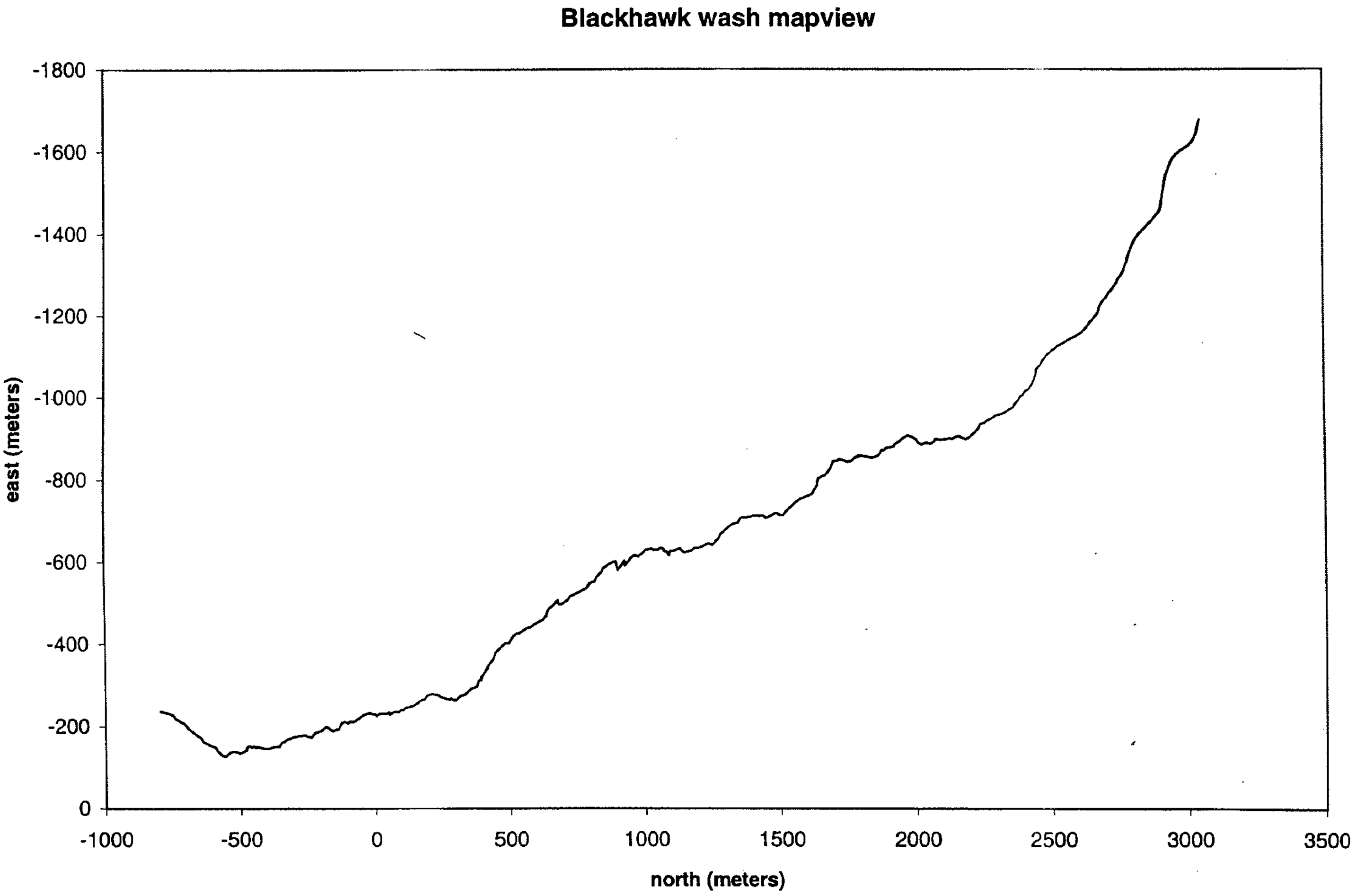
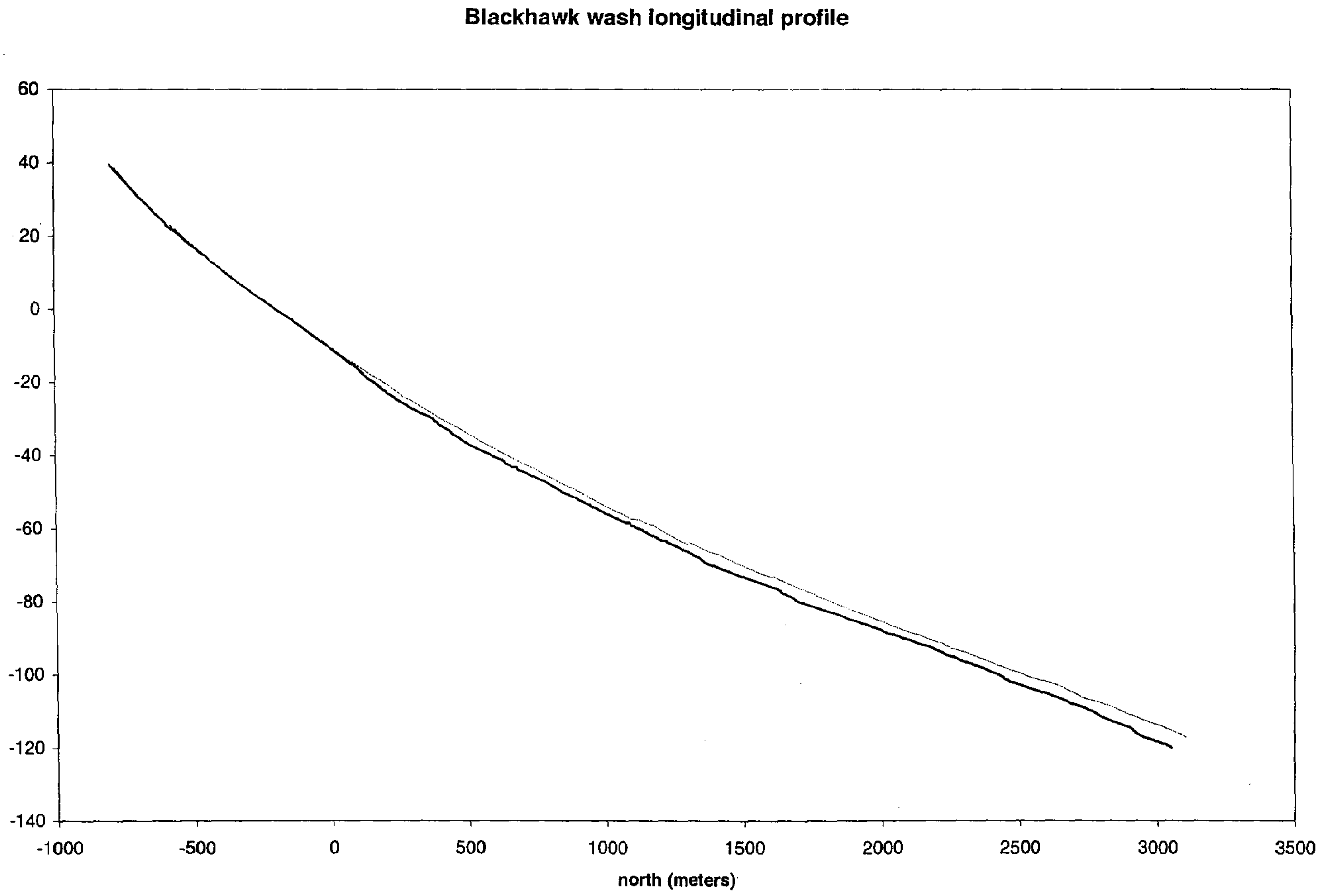
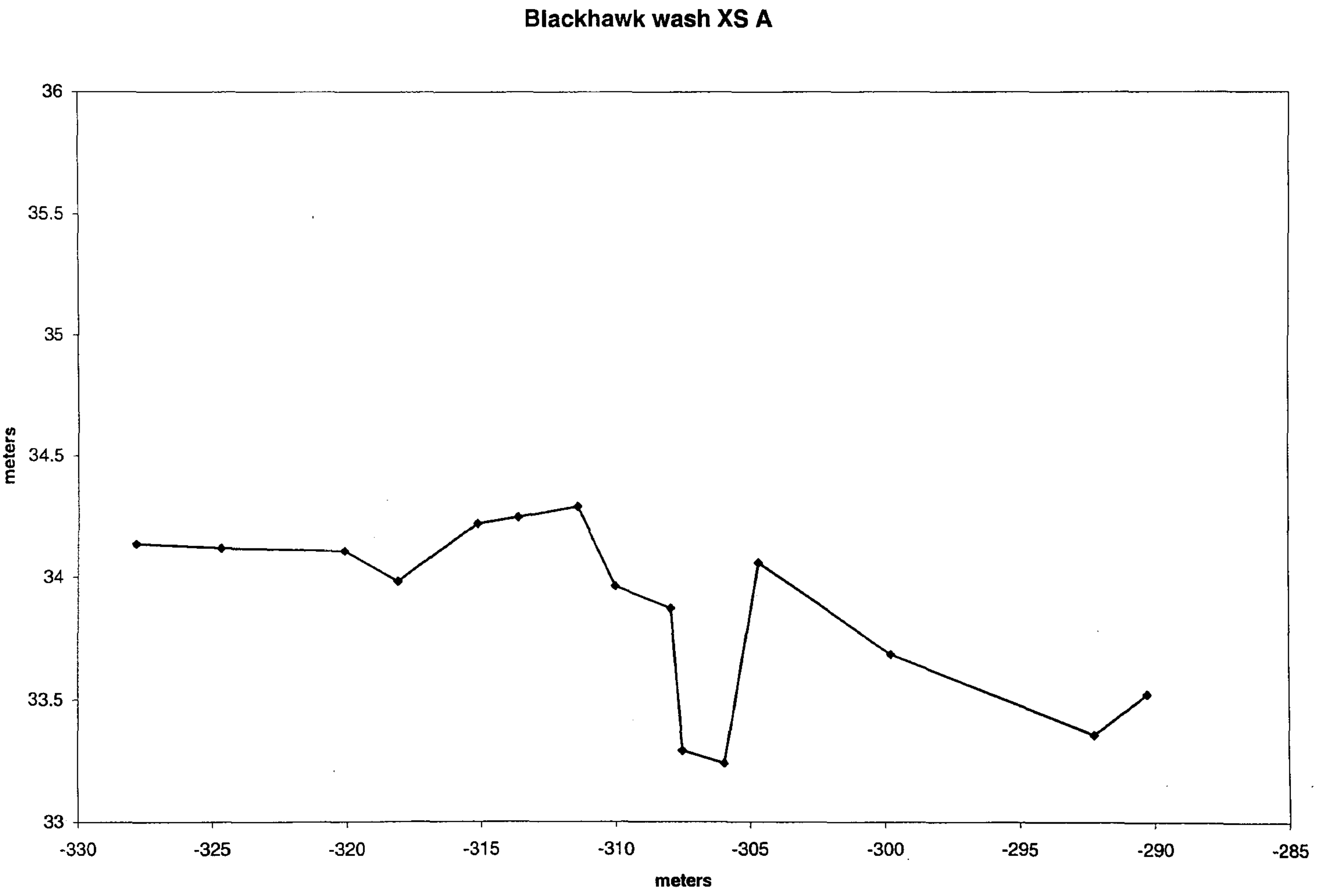
Appendix A.

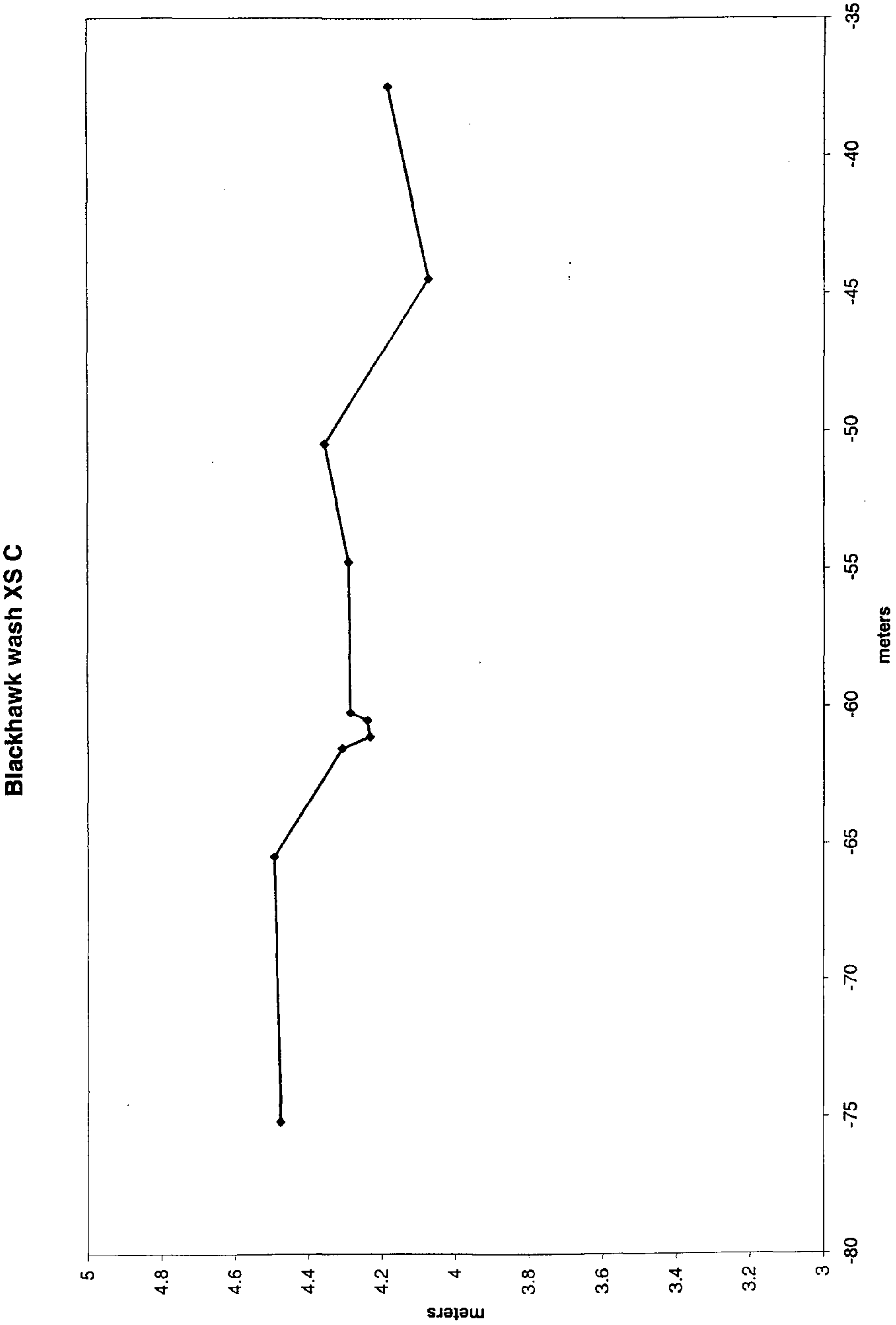
This appendix contains data surveyed for 8 ephemeral streams. Each stream has a map view, a longitudinal profile, cross sections for each reach (A-E), and a plot of the gradient for the surveyed stretch of the stream. The streams are ordered from east to west:
Blackhawk wash
Doubleknob wash
East Middle wash
Middle wash
Slick wash
Control wash
Pitzer Buttes wash
Granite wash


Blackhawk wash mapview
east (meters)
-1800
-1600
-1400
-1200
-1000
-800
-600
-400
-200
0
north (meters)
-1000
-500
0
500
1000
1500
2000
2500
3000
3500

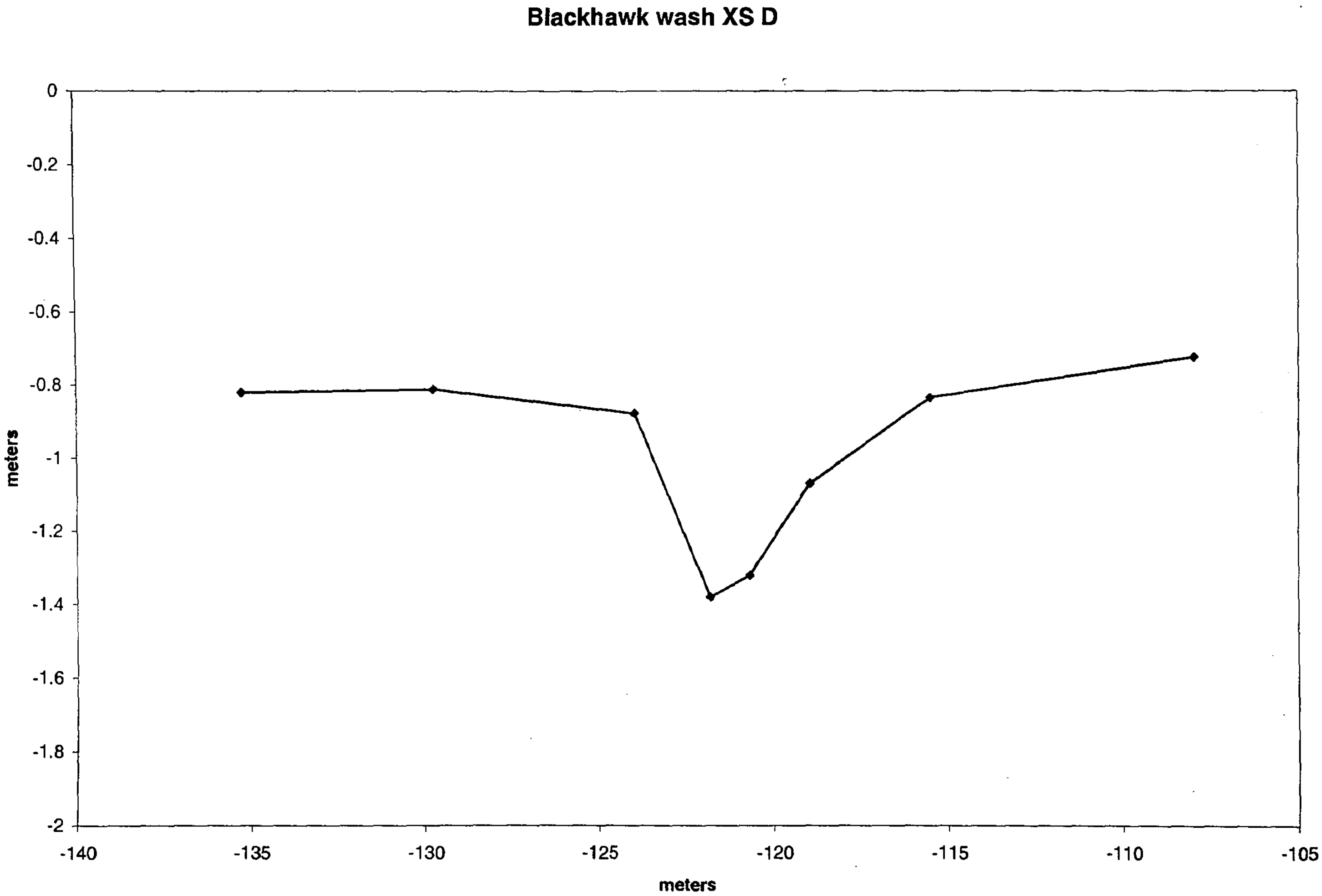

Blackhawk wash longitudinal profile
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-1000
-500
0
500
1000
1500
2000
2500
3000
3500
north (meters)

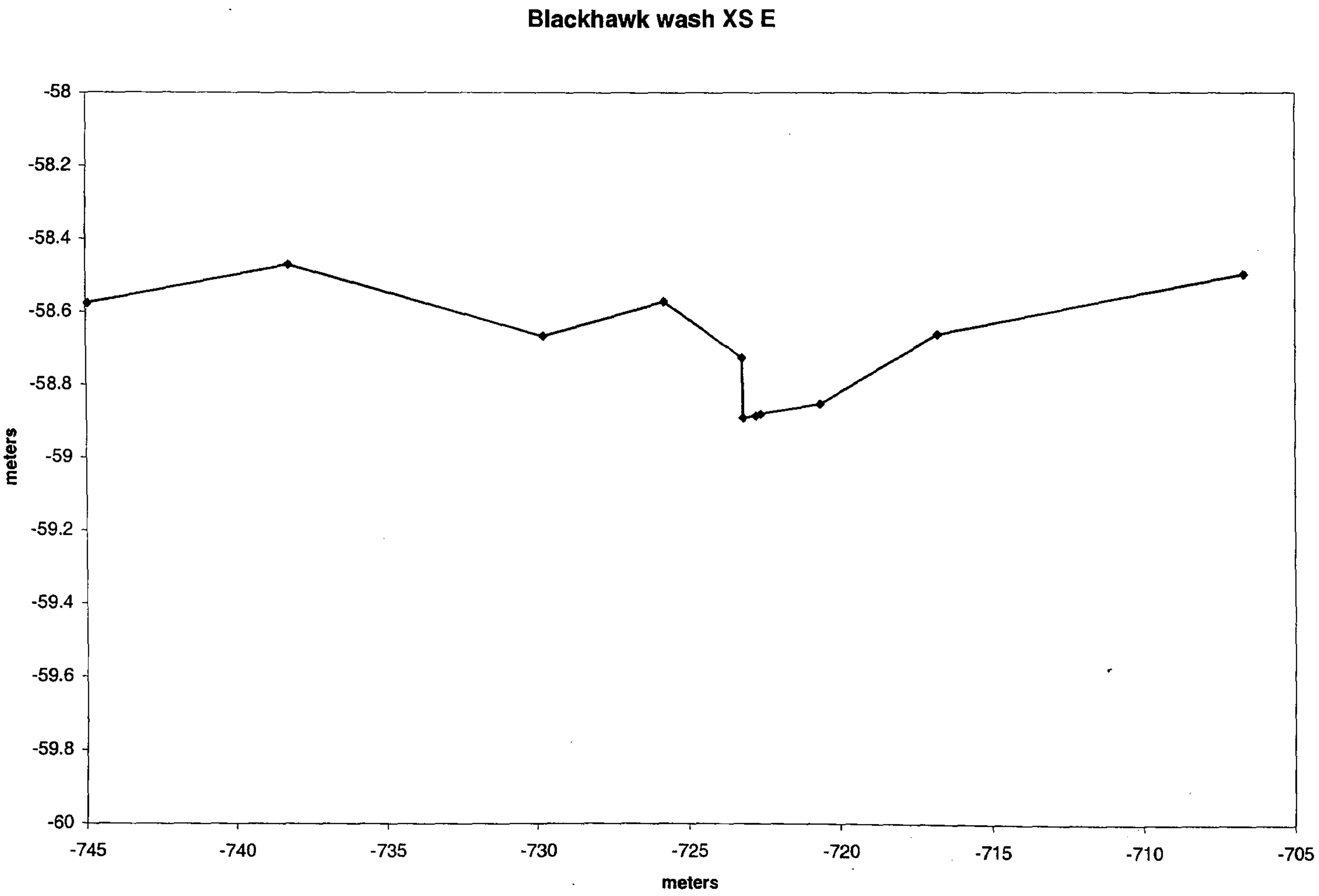


Blackhawk wash XS A

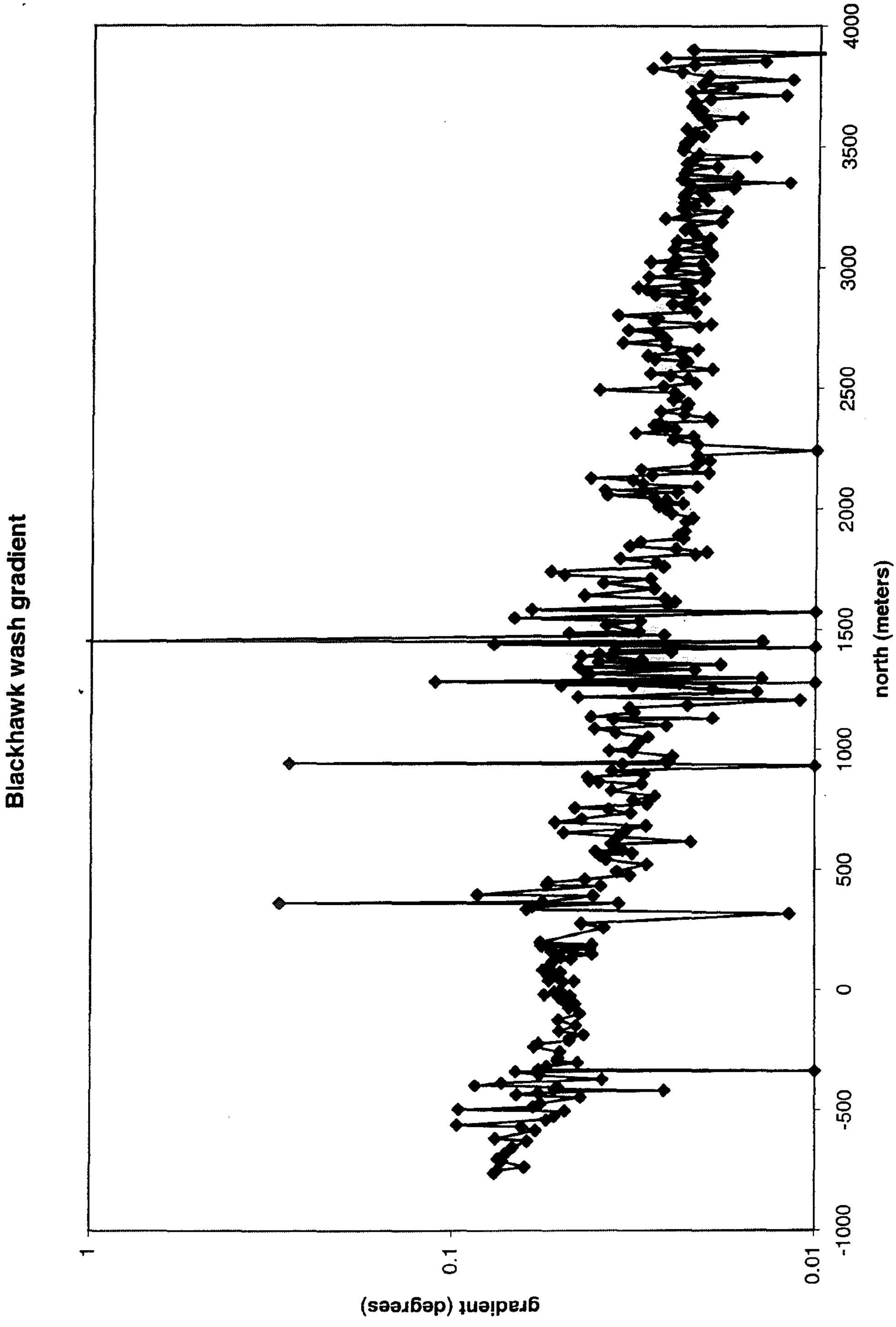


Blackhawk wash XS C

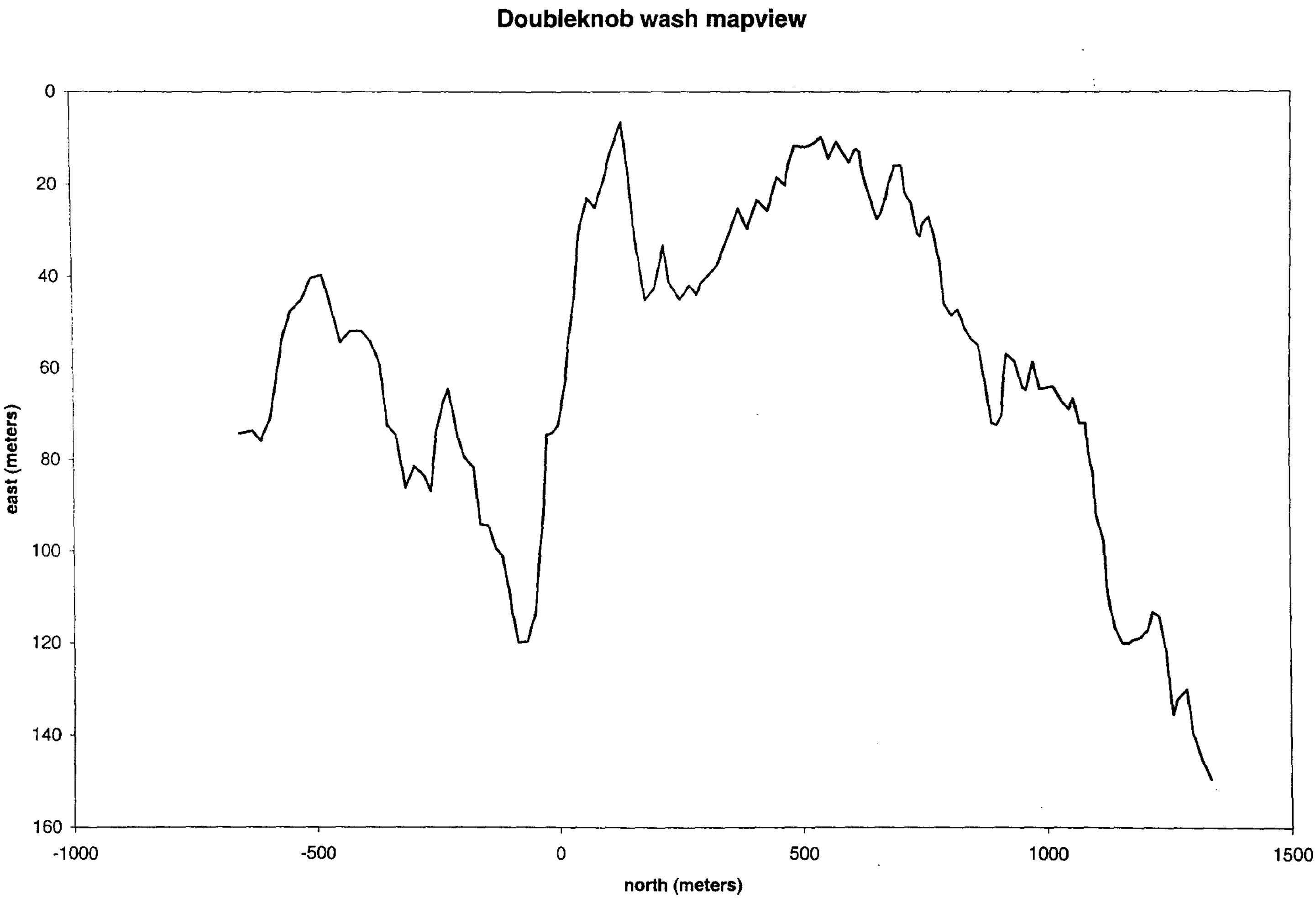

Blackhawk wash XS D
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
meters
-140
-135
-130
-125
-120
-115
-110
-105
meters



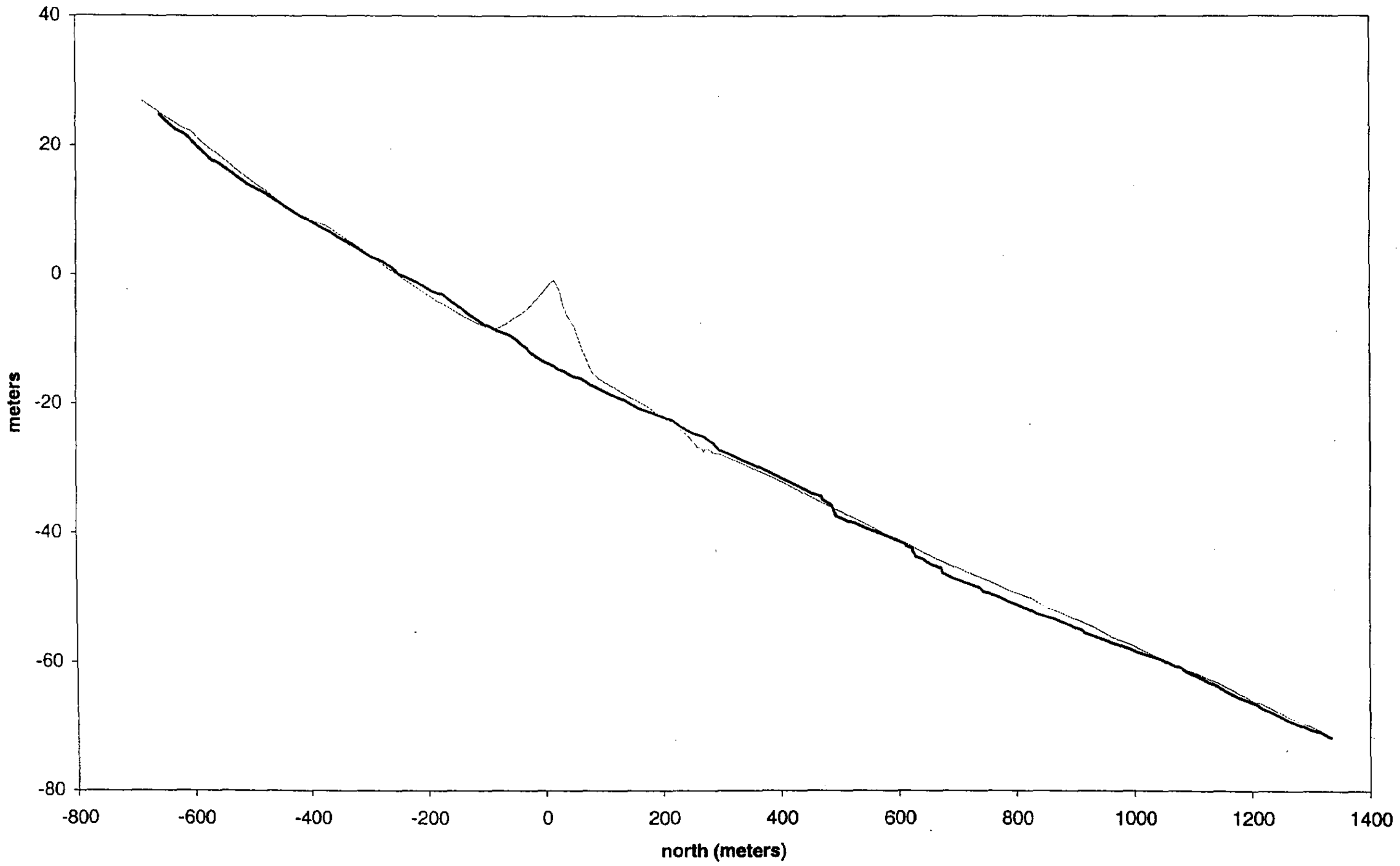
Blackhawk wash XS E
meters
-58
-58.2
-58.4
-58.6
-58.8
-59
-59.2
-59.4
-59.6
-59.8
-60
-745
-740
-735
-730
-725
-720
-715
-710
-705
meters

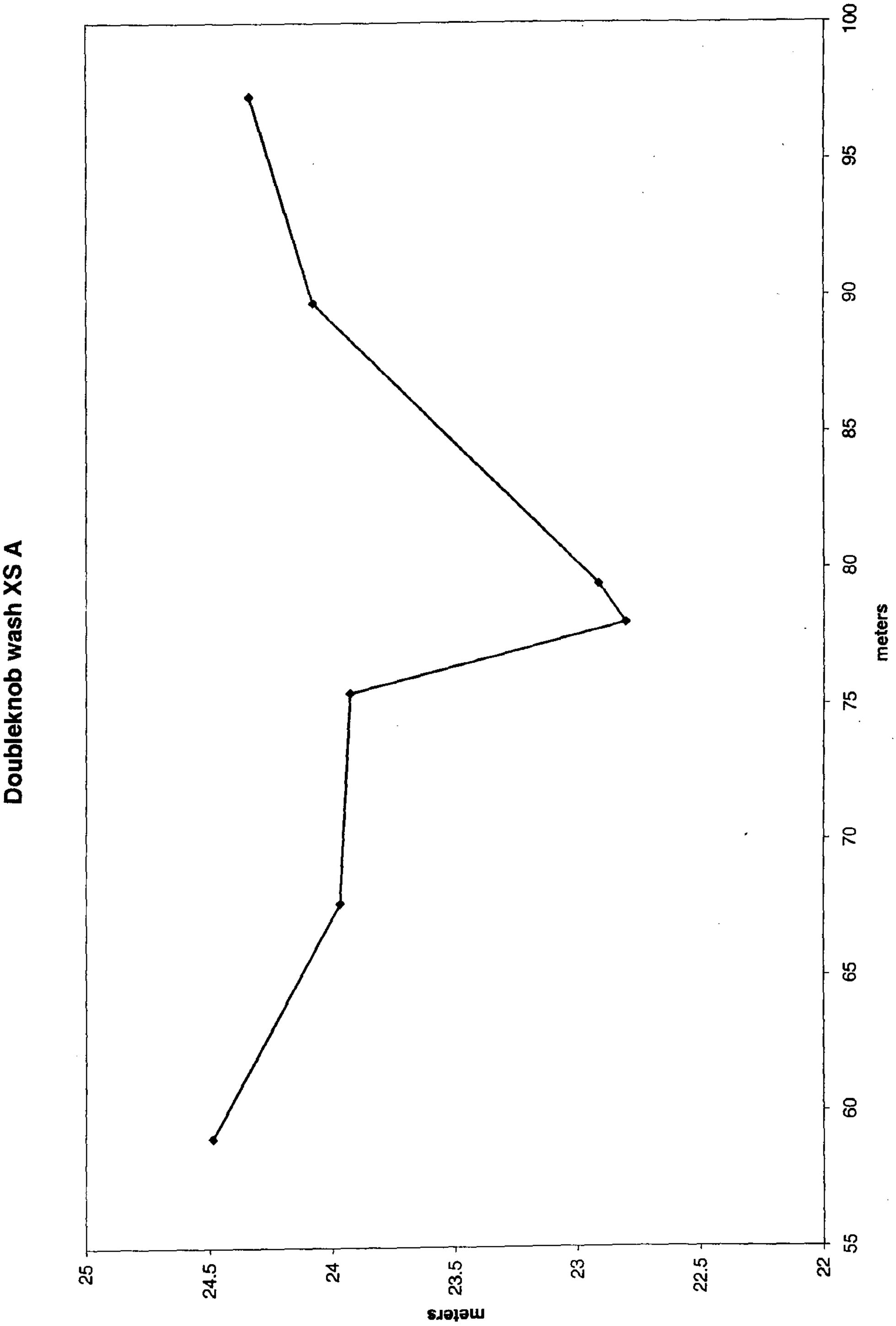


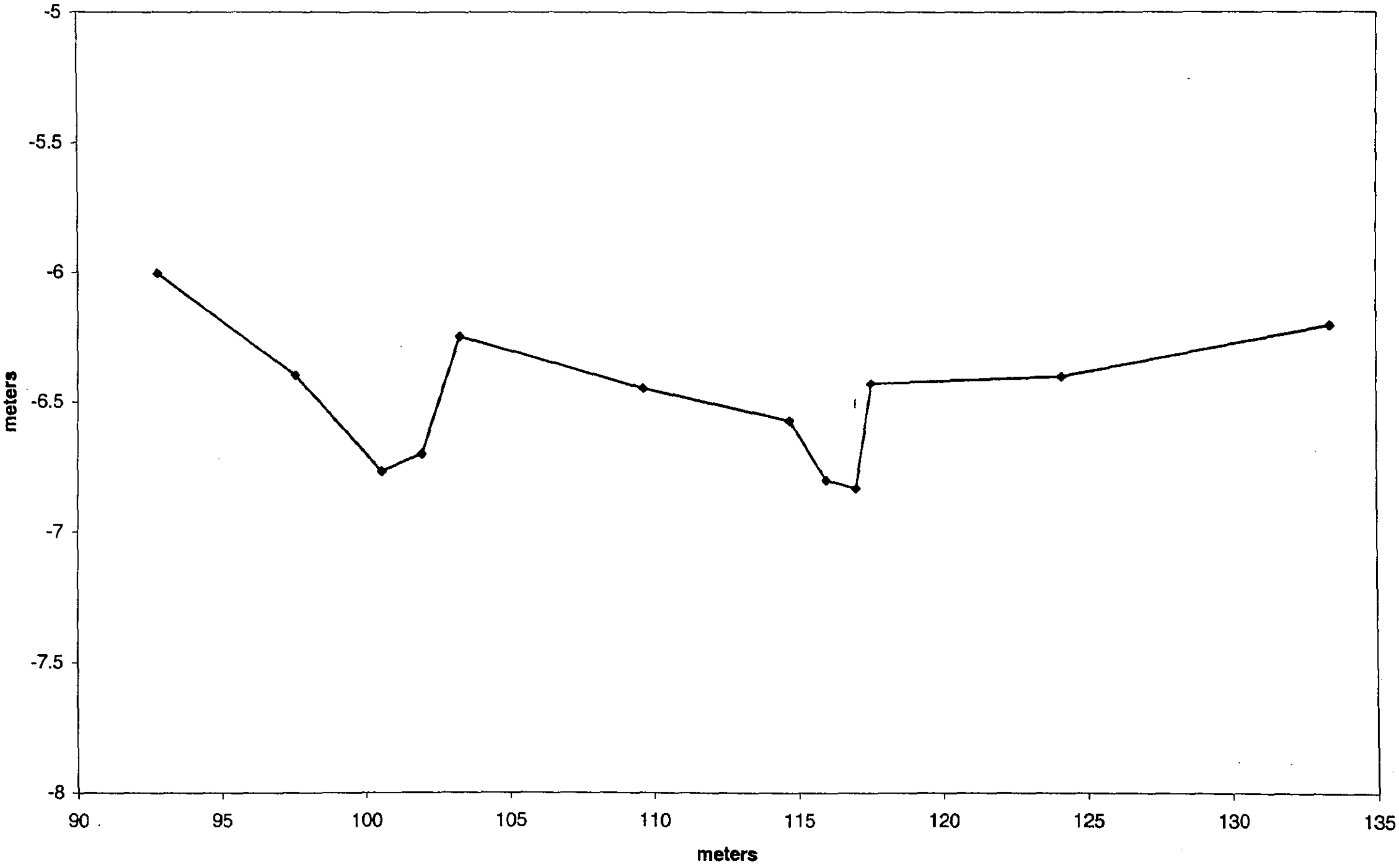
Blackhawk wash gradient
gradient (degrees)
1
0.1
0.01
north (meters)
-1000
-500
0
500
1000
1500
2000
2500
3000
3500
4000


Doubleknob wash mapview
0
20
40
60
80
100
120
140
160
east (meters)
-1000
-500
0
500
1000
1500
north (meters)

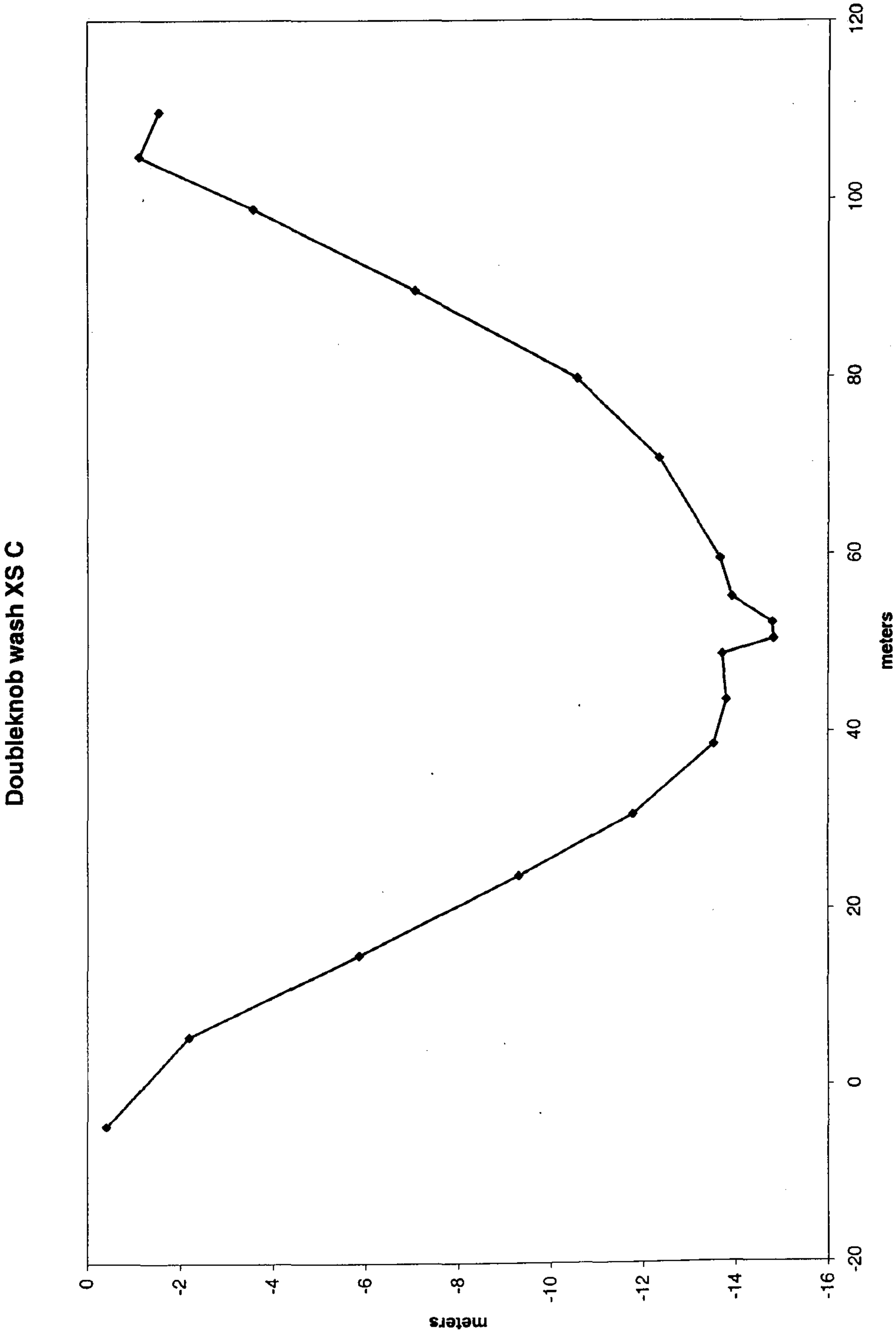
Doubleknob wash longitudinal profile




Doubleknob wash XS A
meters
25
24.5
24
23.5
23
22.5
22
meters
55
60
65
70
75
80
85
90
95
100

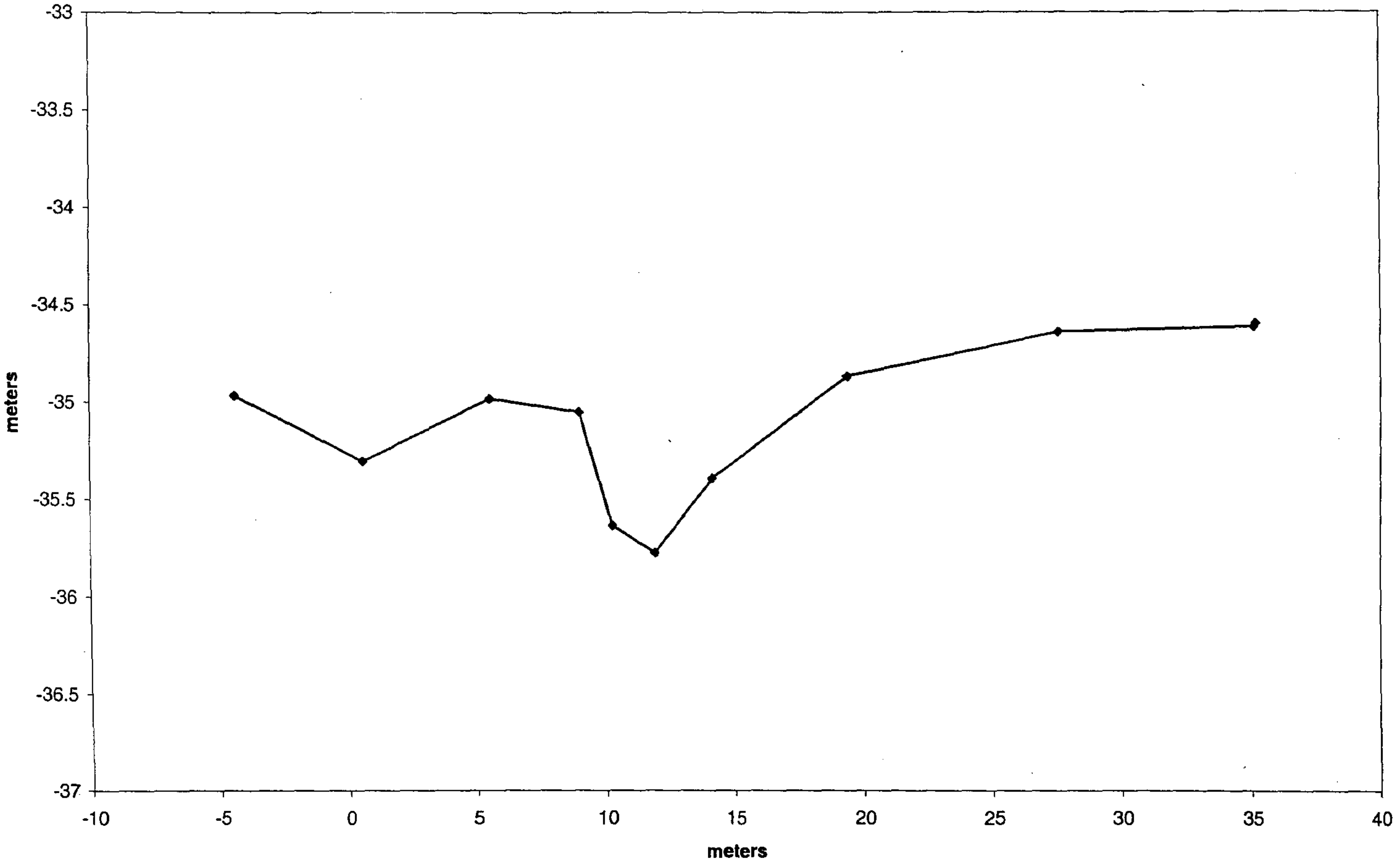


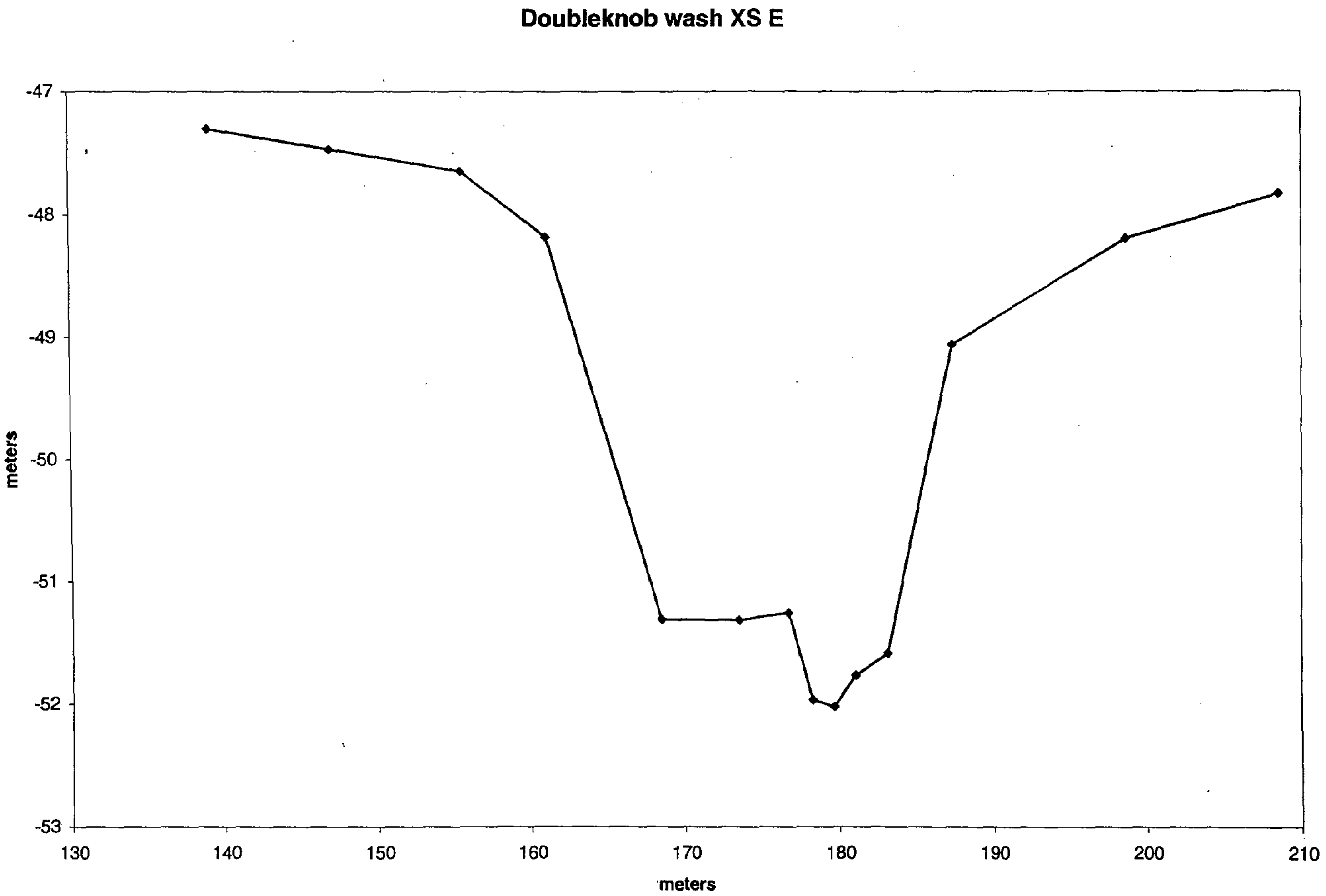
Doubleknob wash XS B

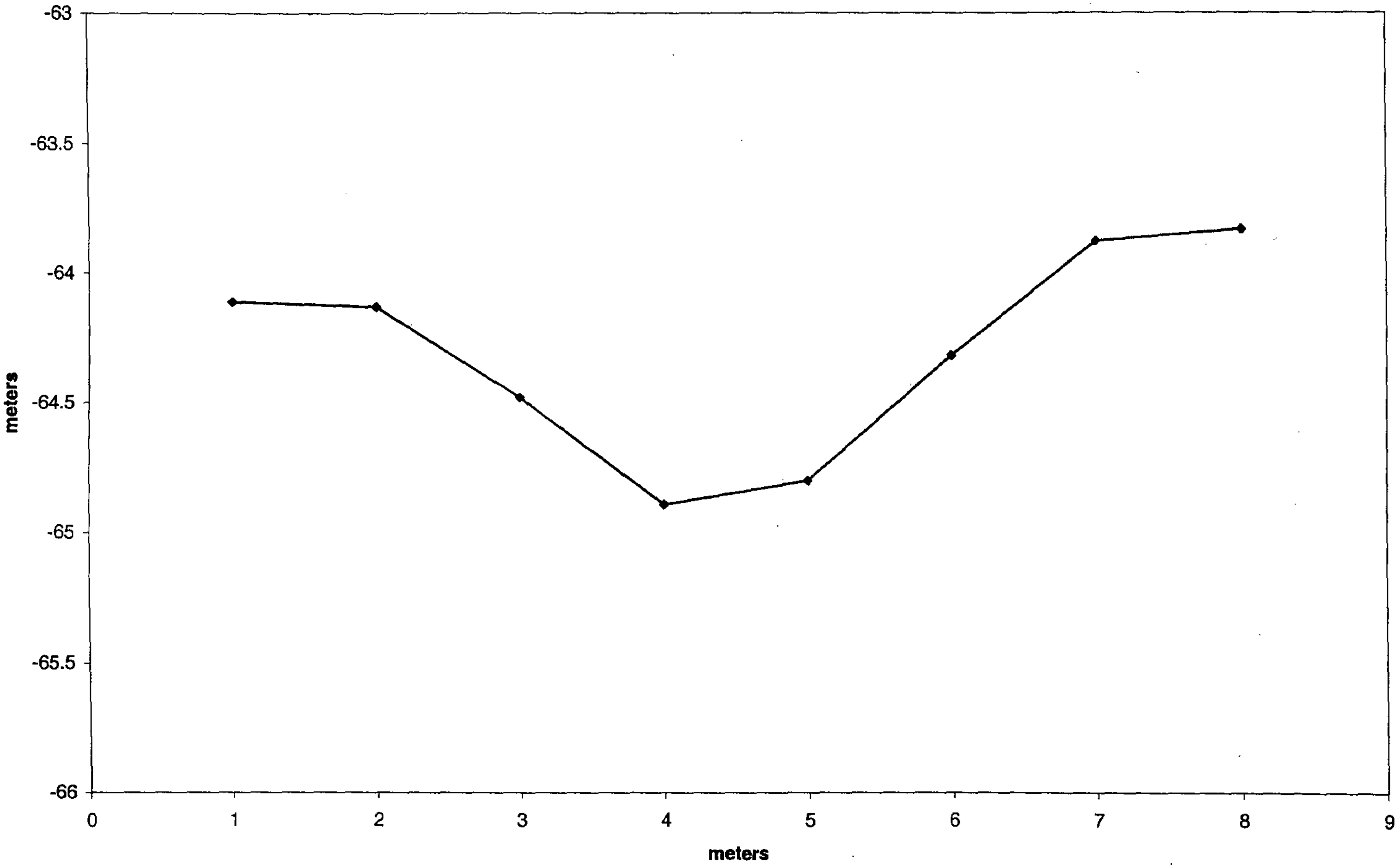


Doubleknob wash XS C

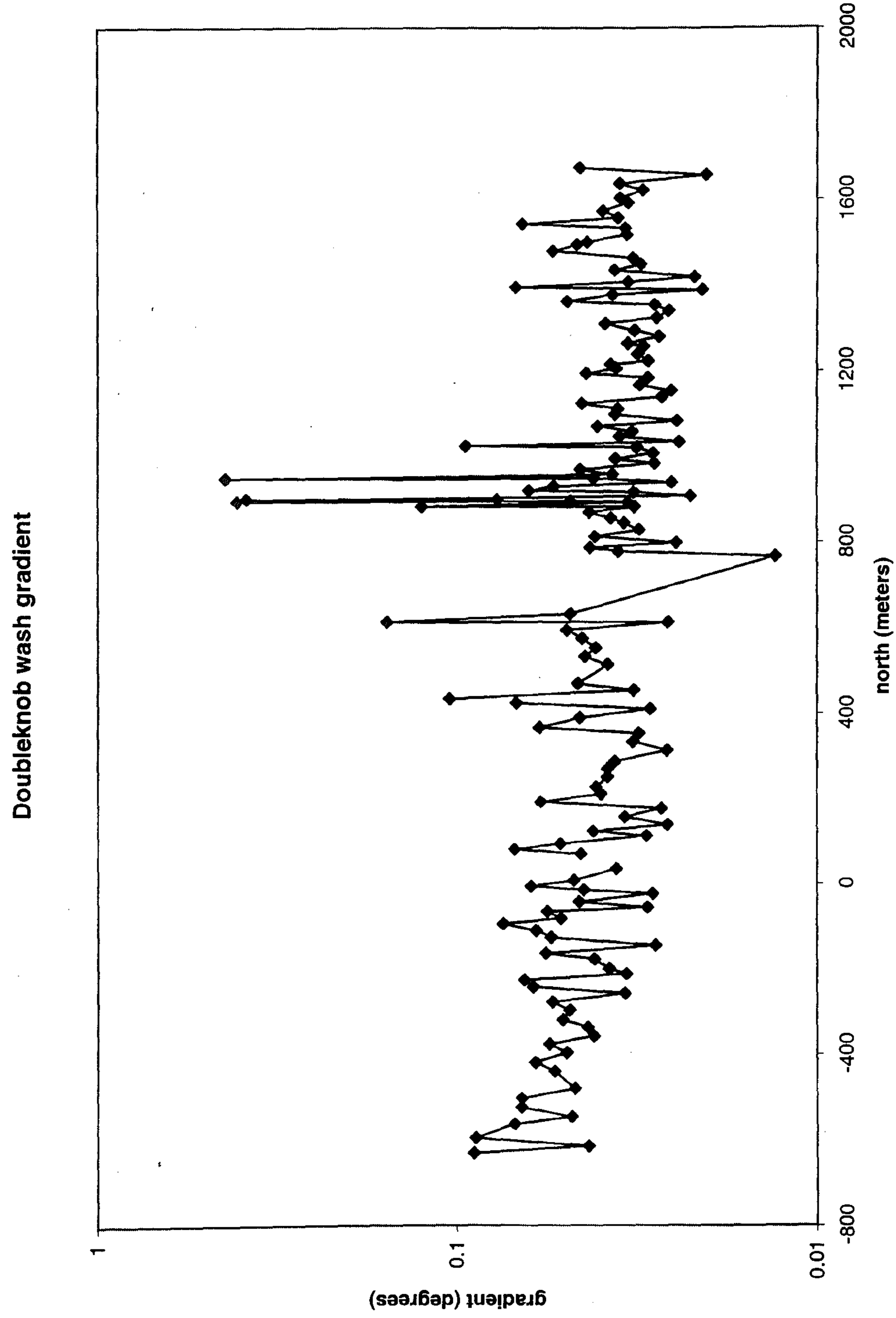
Doubleknob wash XS D

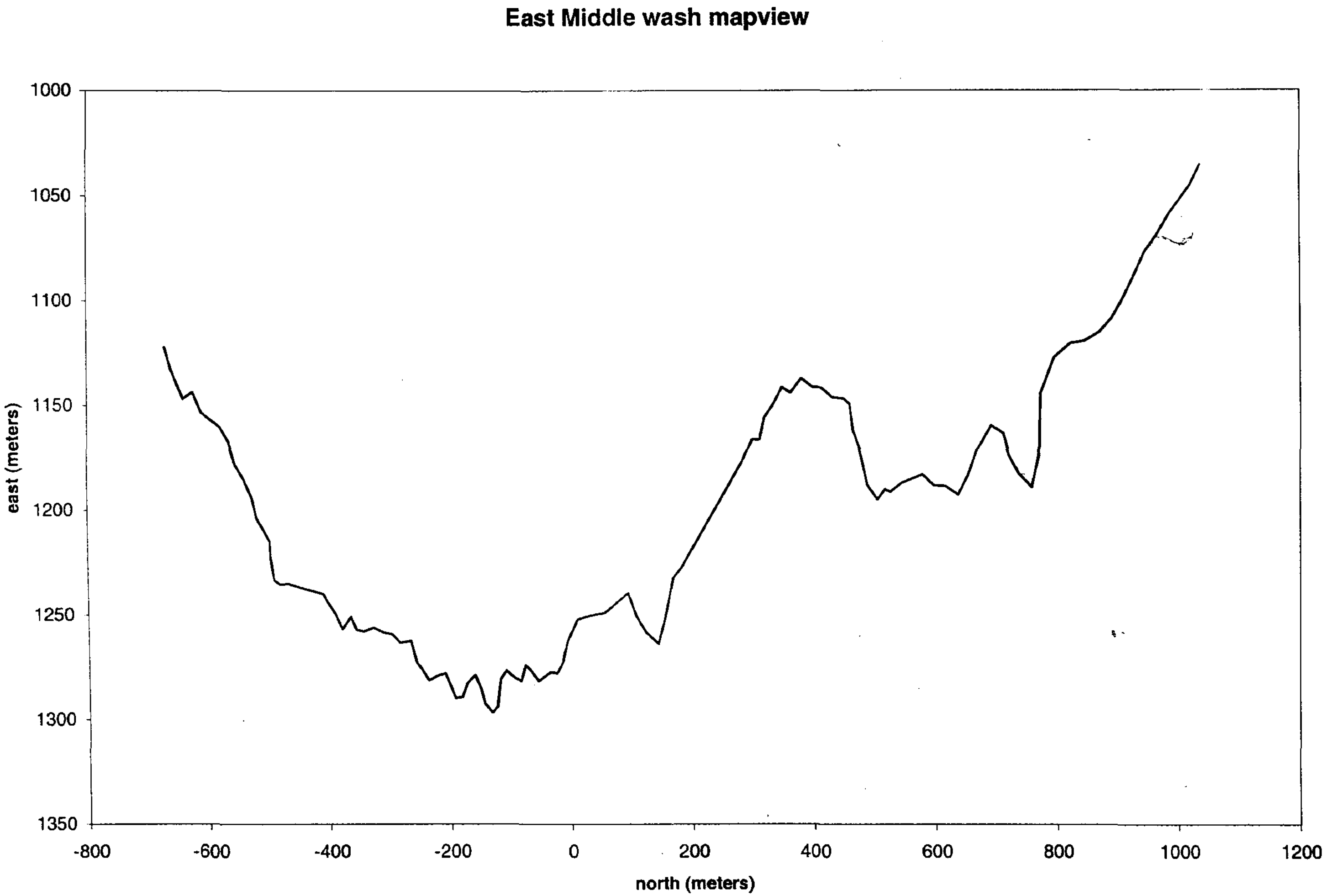



Doubleknob wash XS E
-47
-48
-49
-50
-51
-52
-53
meters
130
140
150
160
170
180
190
200
210
meters

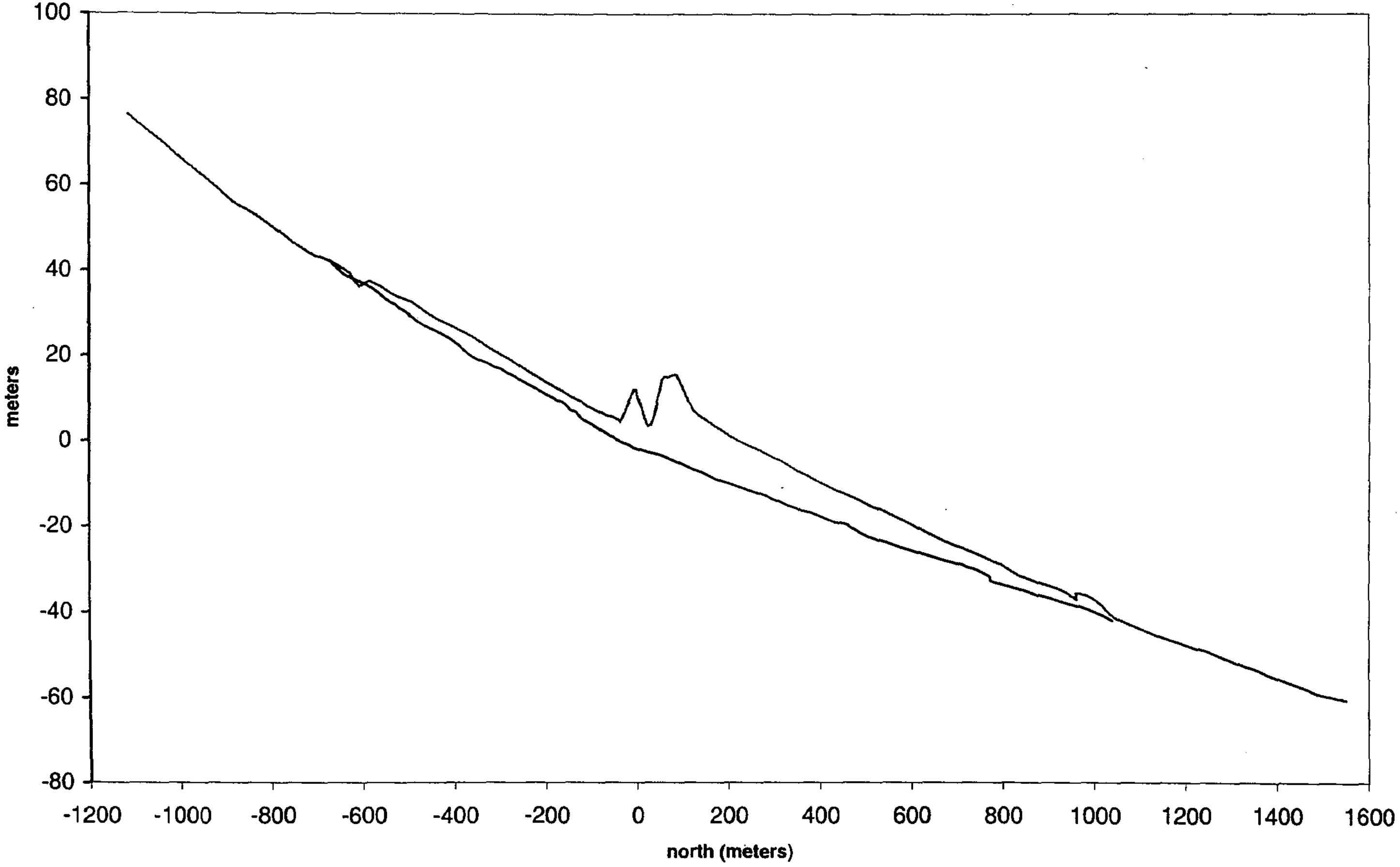


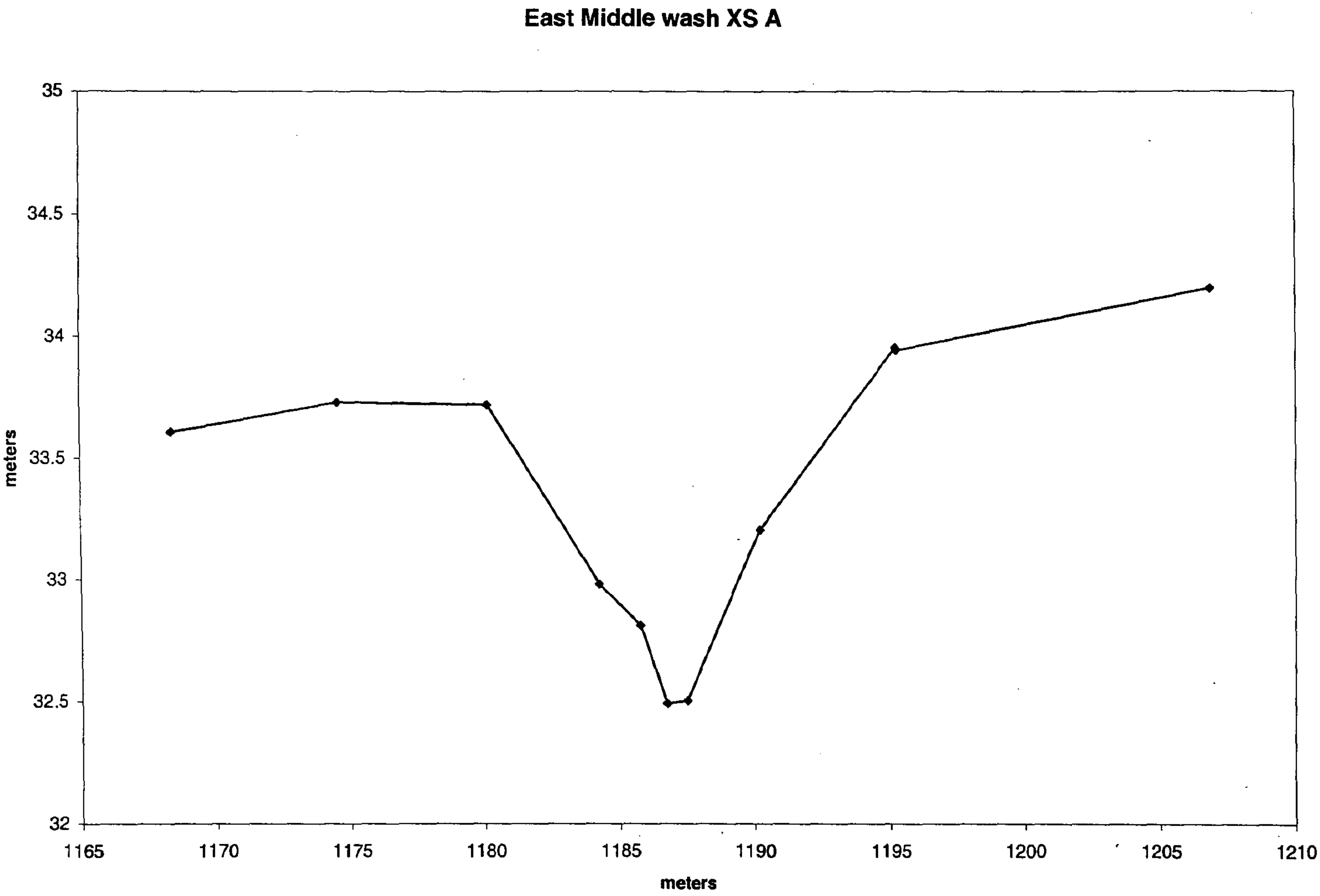
Doubleknob wash XS F

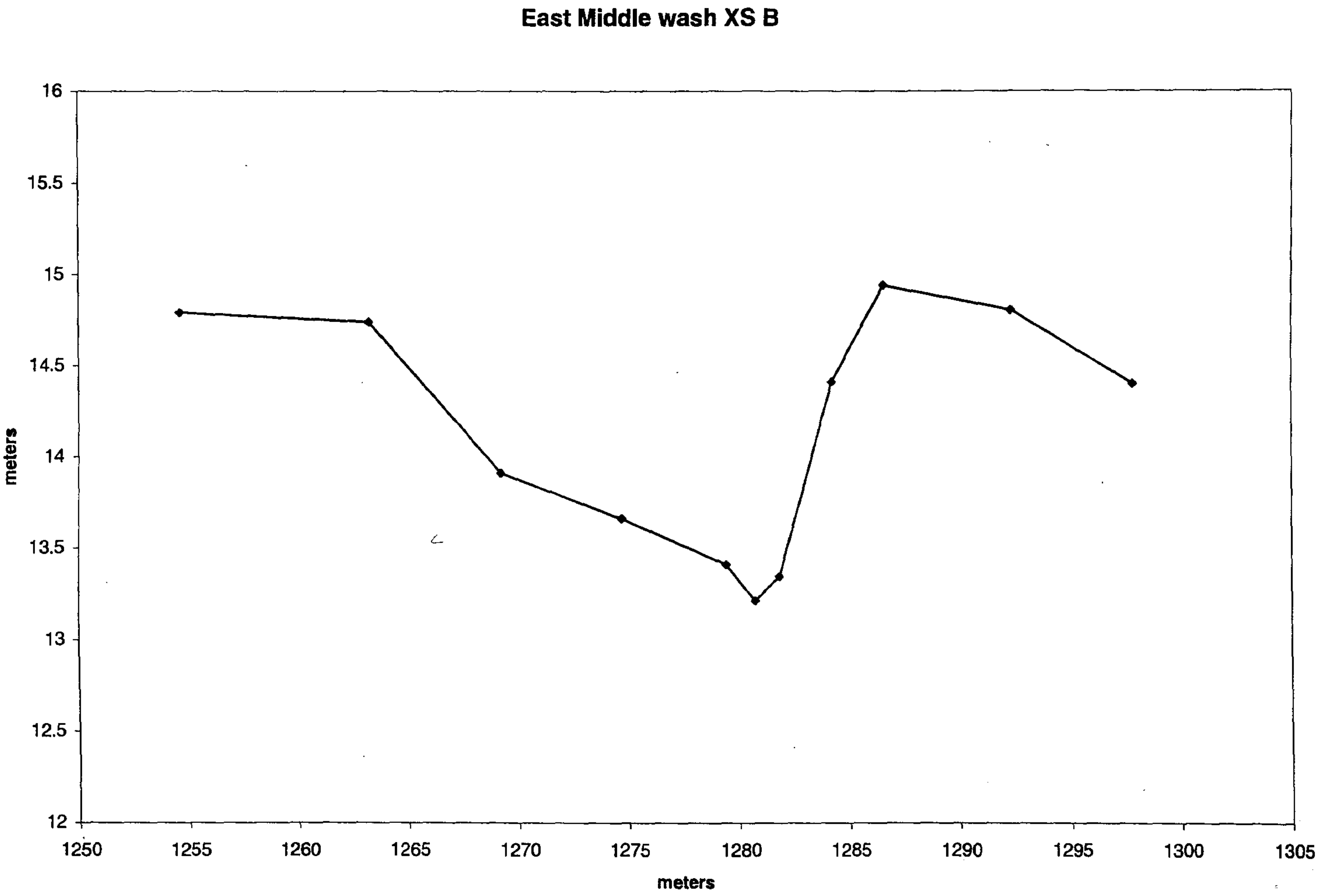

Doubleknob wash gradient
gradient (degrees)
1
0.1
0.01
north (meters)
-800
-400
0
400
800
1200
1600
2000

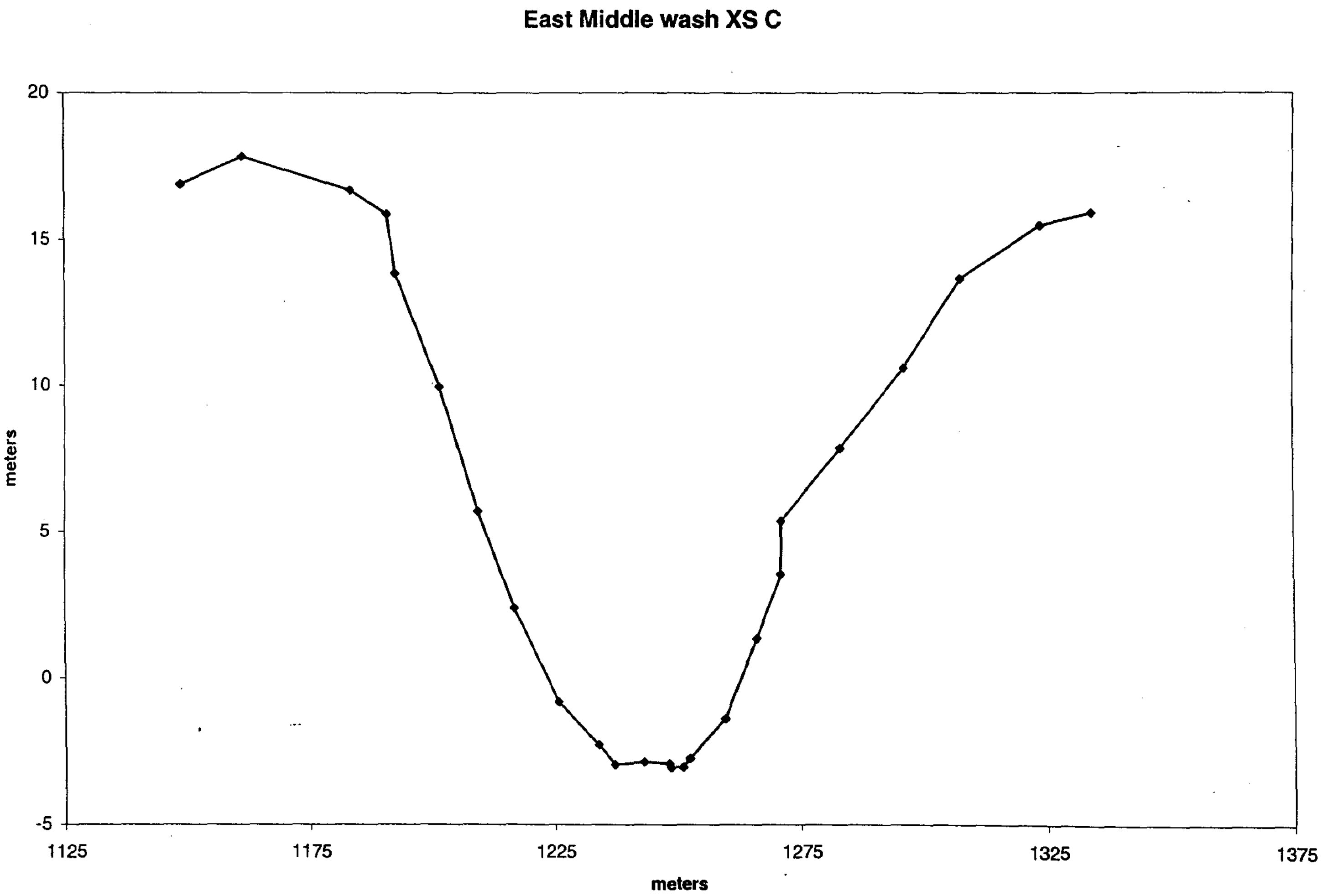

East Middle wash mapview
east (meters)
1000
1050
1100
1150
1200
1250
1300
1350
north (meters)
-800
-600
-400
-200
0
200
400
600
800
1000
1200

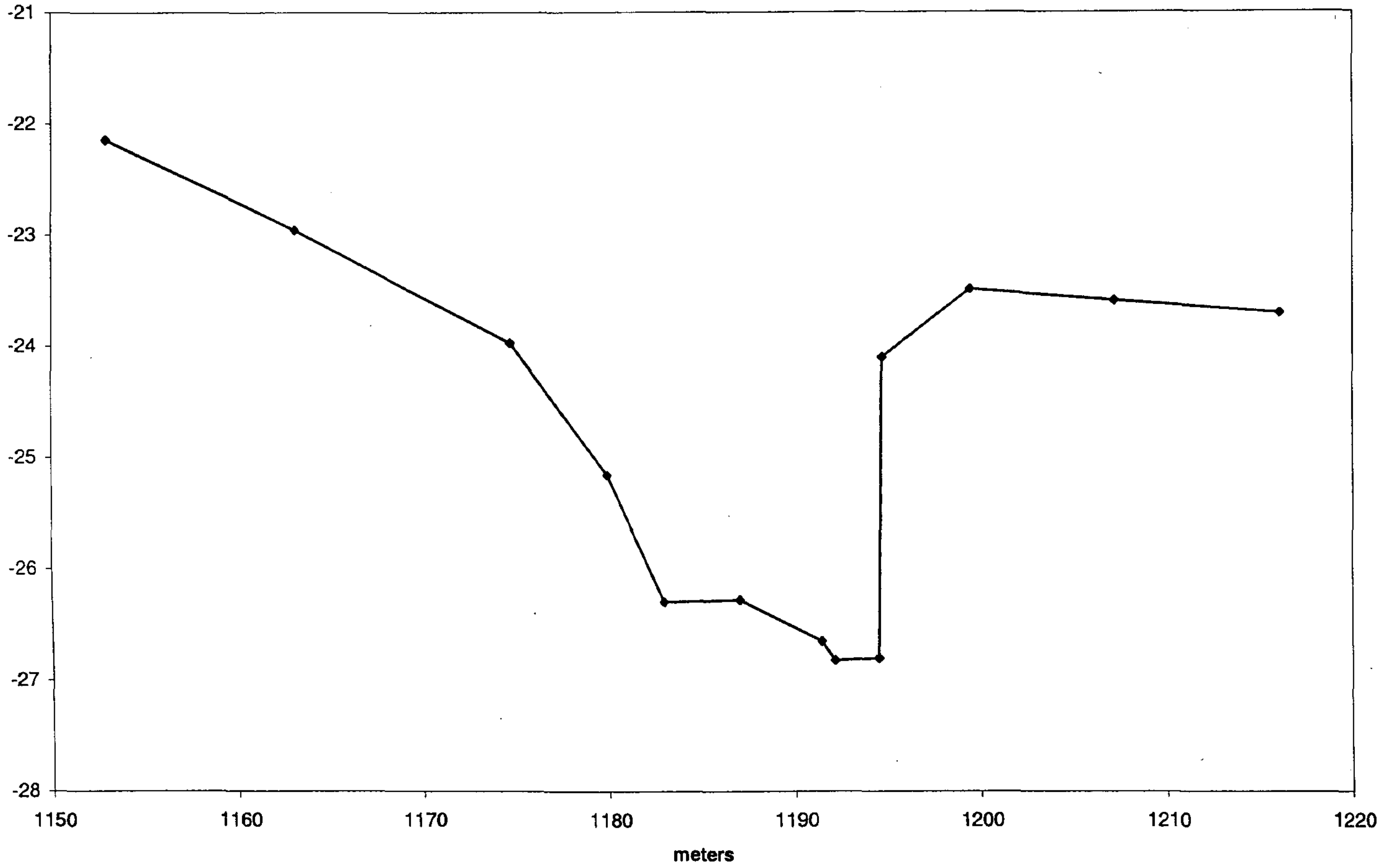
East Middle wash longitudinal profile



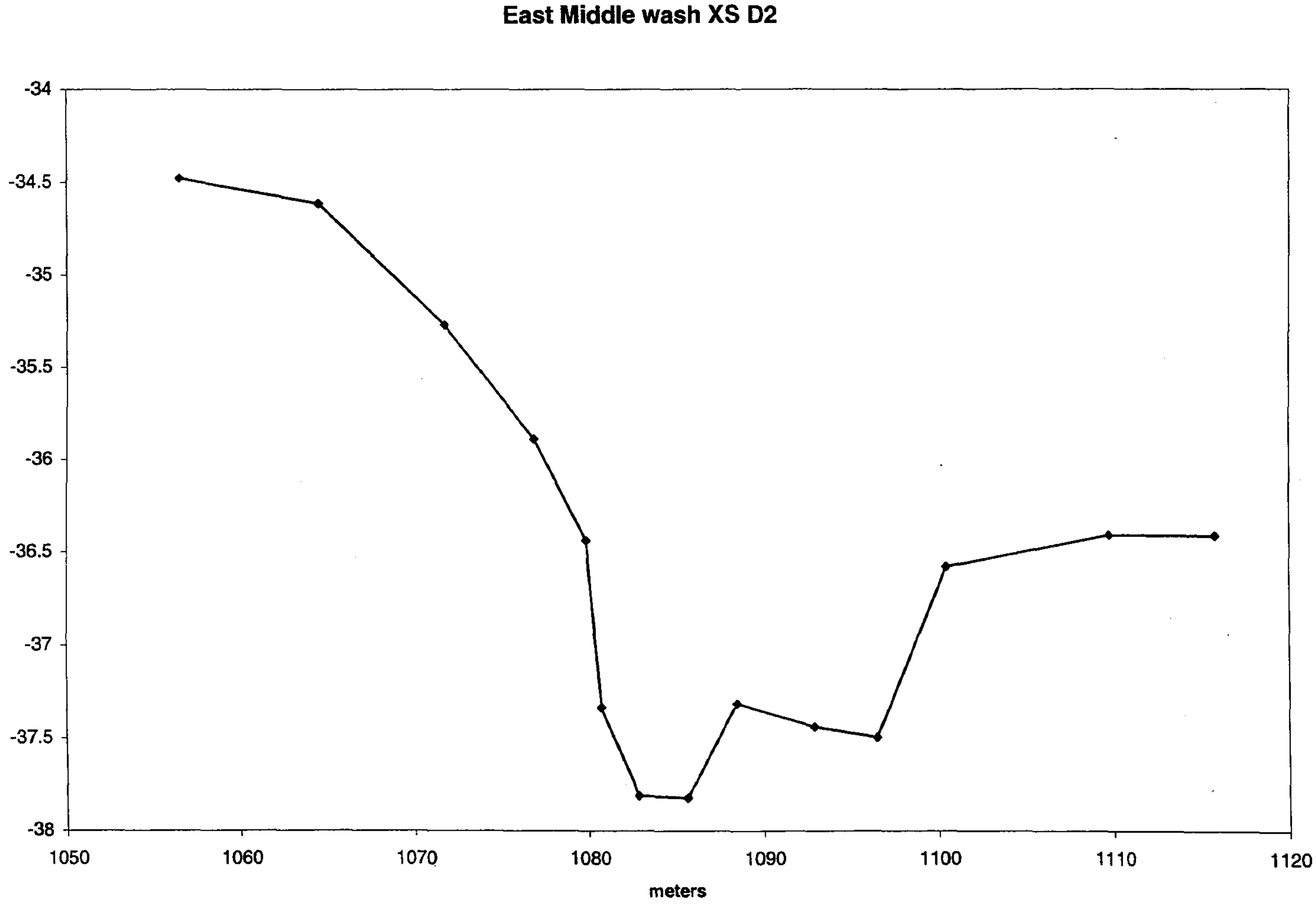

East Middle wash XS A
35
34.5
34
33.5
33
32.5
32
meters
1165
1170
1175
1180
1185
1190
1195
1200
1205
1210
meters

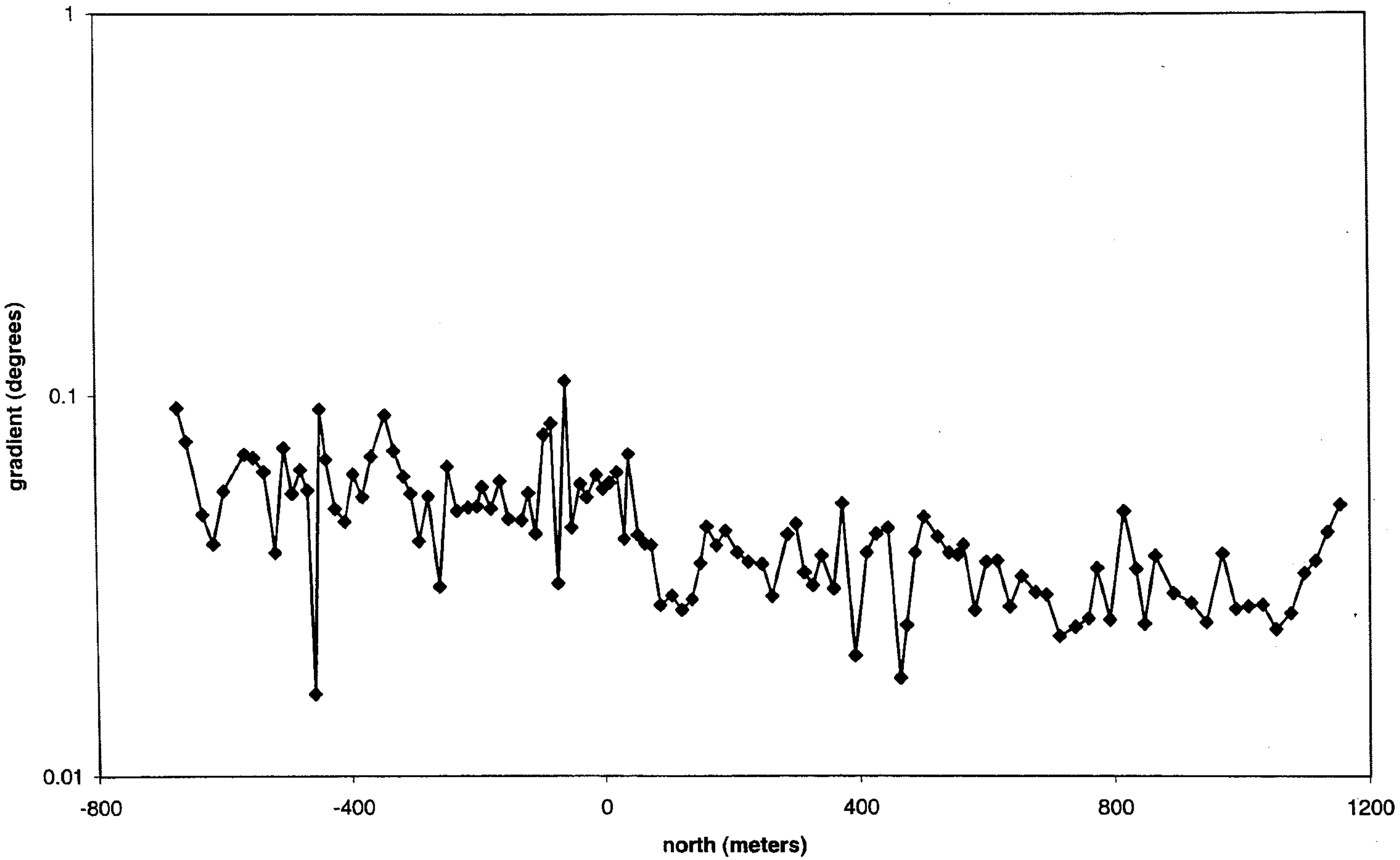

East Middle wash XS B
meters
16
15.5
15
14.5
14
13.5
13
12.5
12
1250
1255
1260
1265
1270
1275
1280
1285
1290
1295
1300
1305
meters

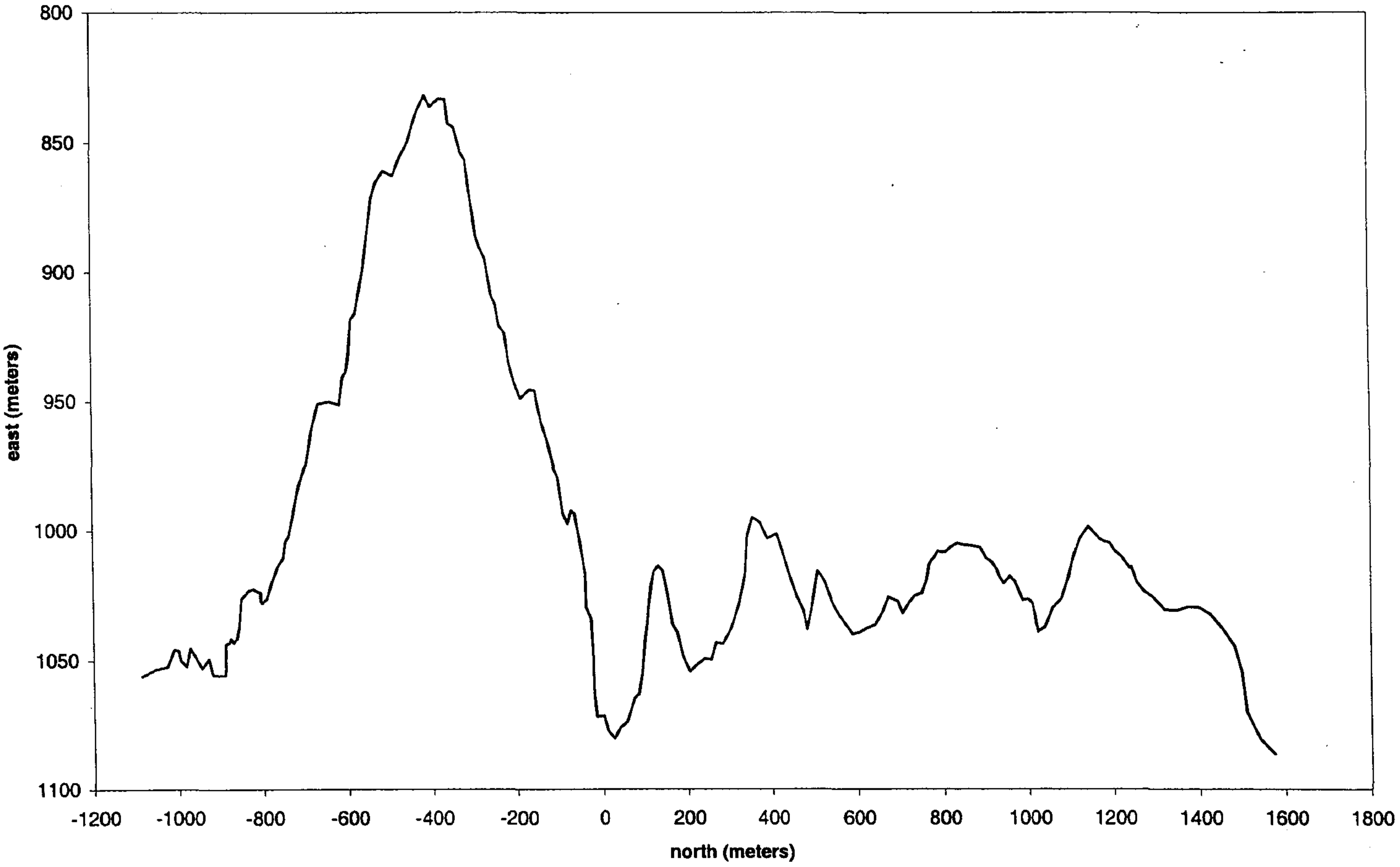

East Middle wash XS C
meters
20
15
10
5
0
-5
1125
1175
1225
1275
1325
1375
meters



East Middle wash XS D

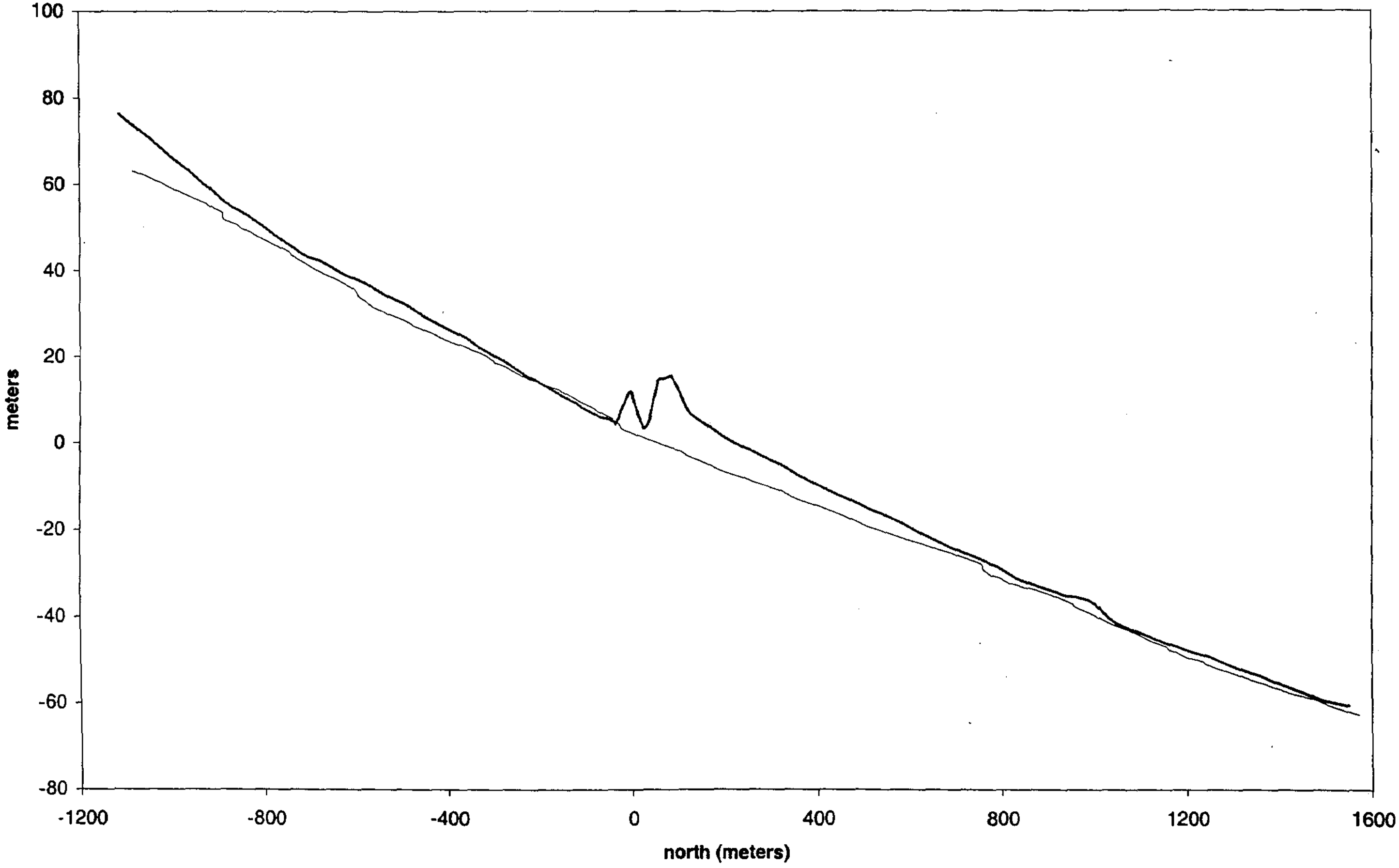

East Middle wash XS D2
meters
-34
-34.5
-35
-35.5
-36
-36.5
-37
-37.5
-38
1050
1060
1070
1080
1090
1100
1110
1120
meters


East Middle wash gradient

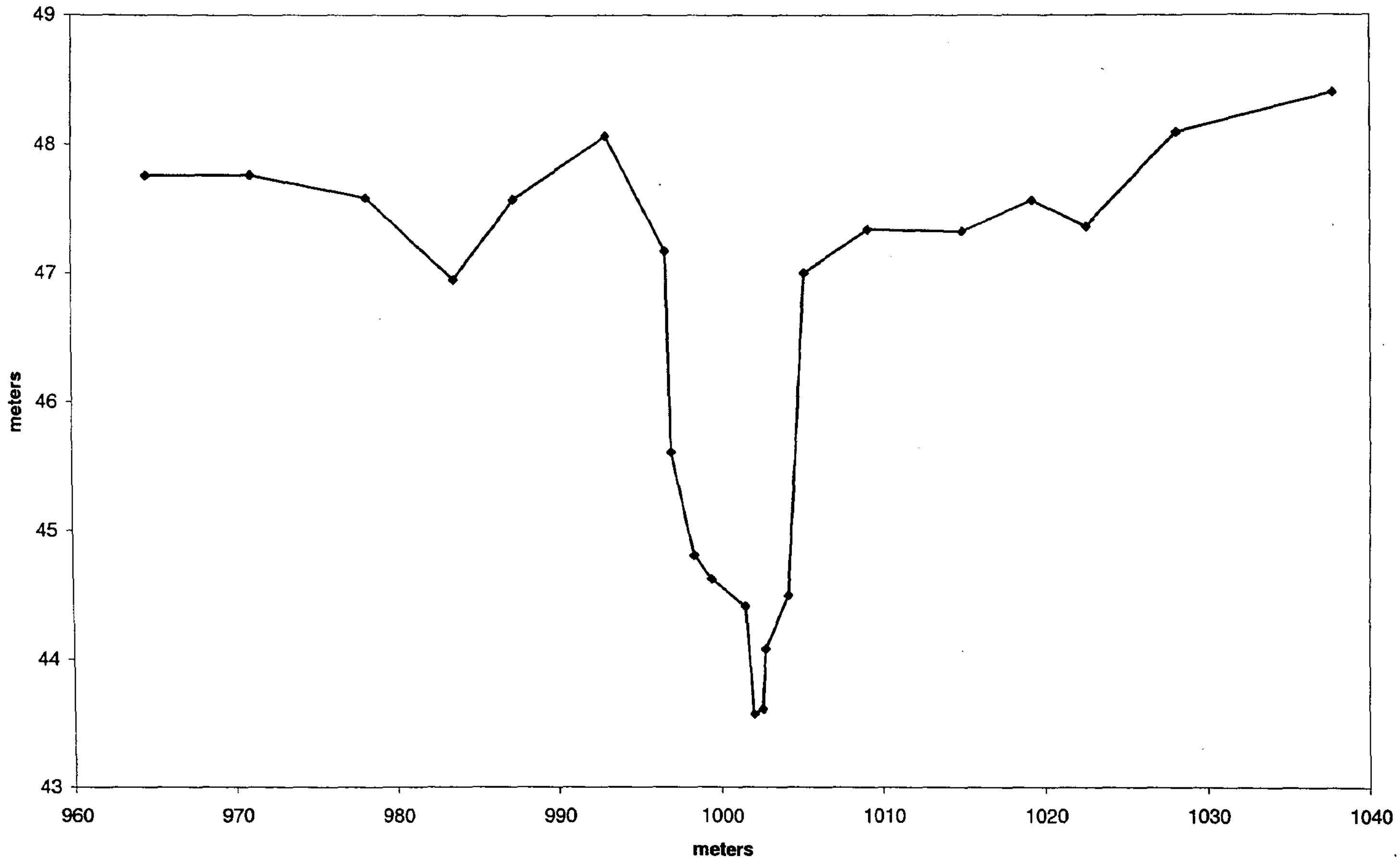


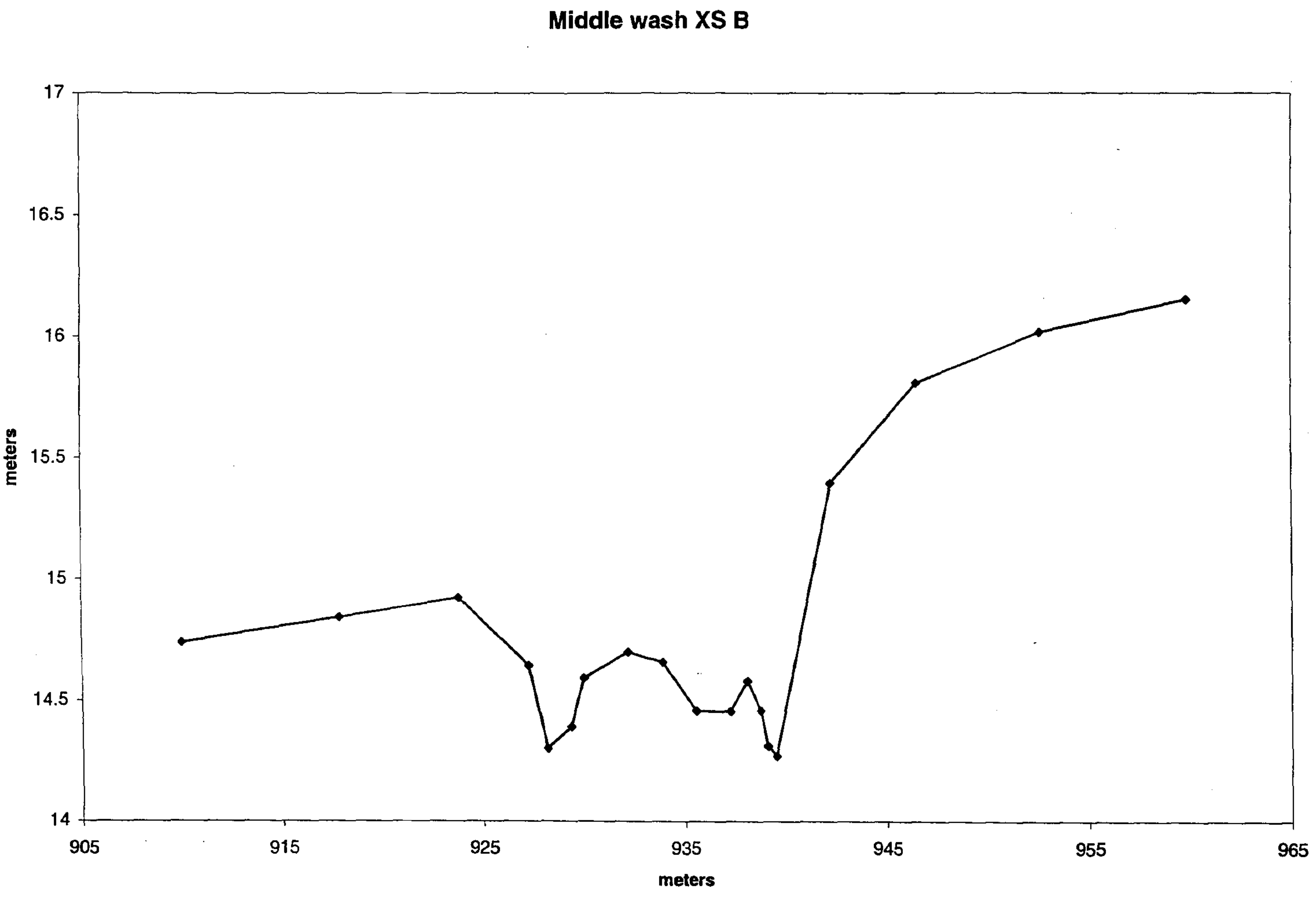
Middle wash mapview

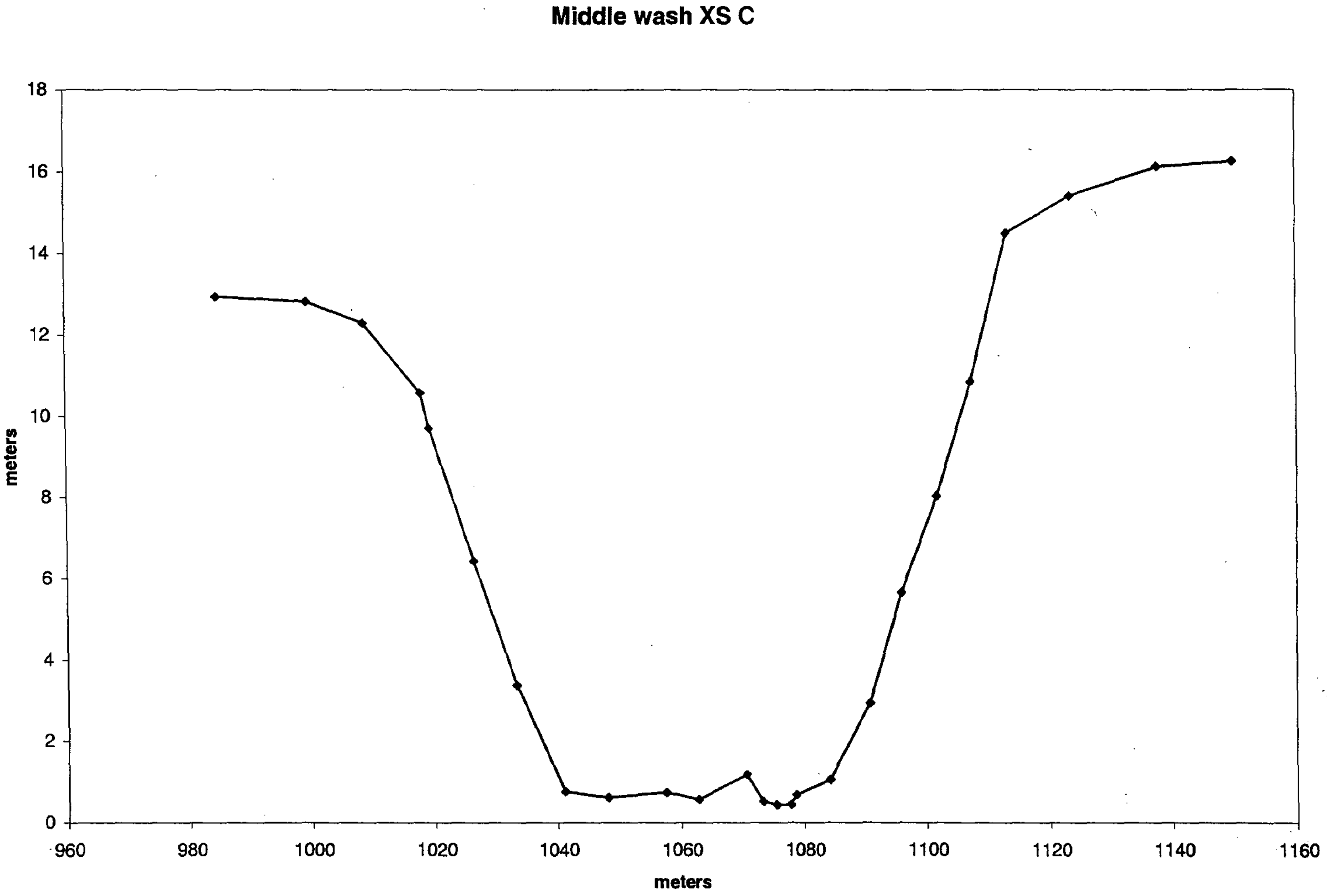
Middle wash longitudinal profile



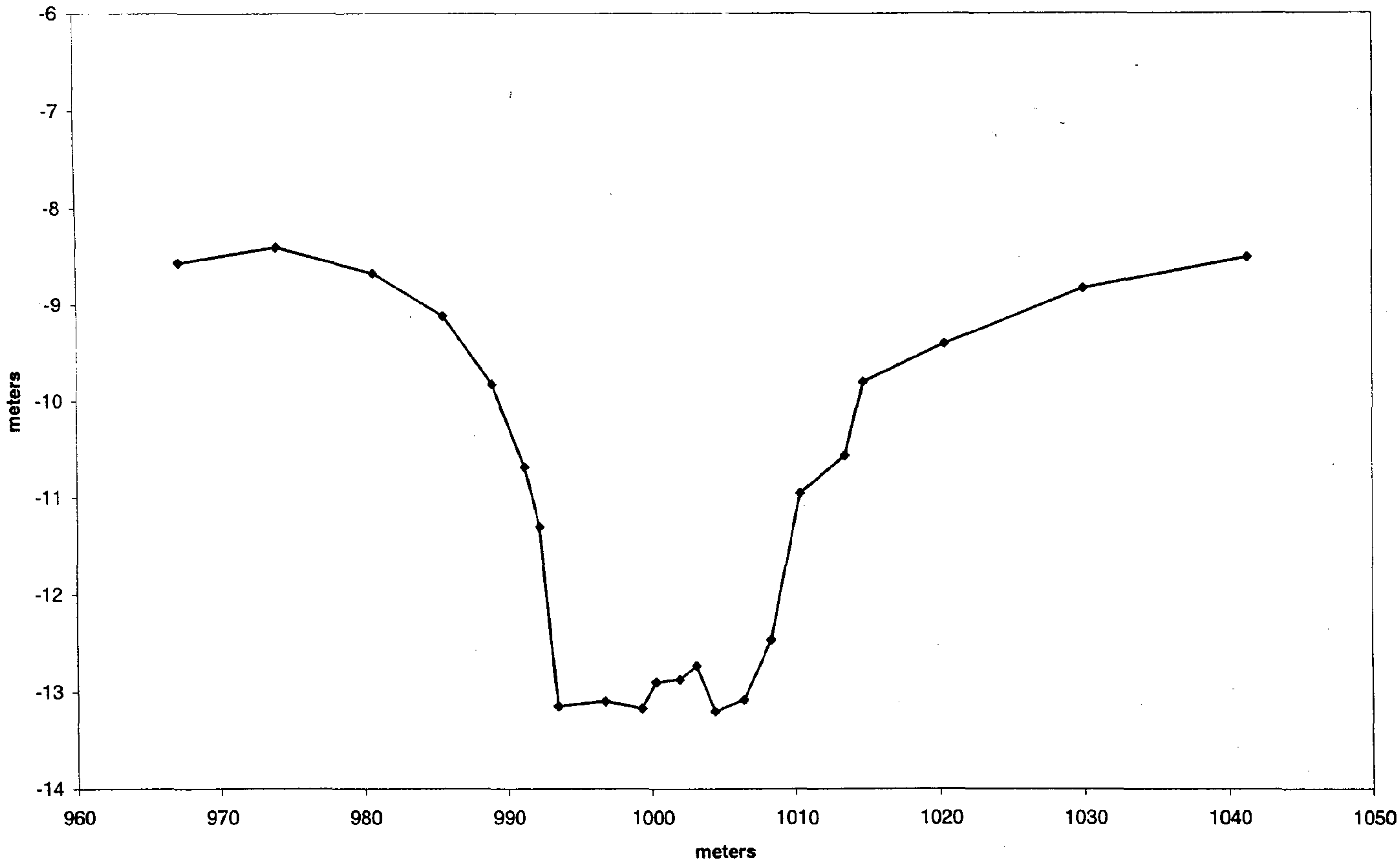
Middle wash XS A

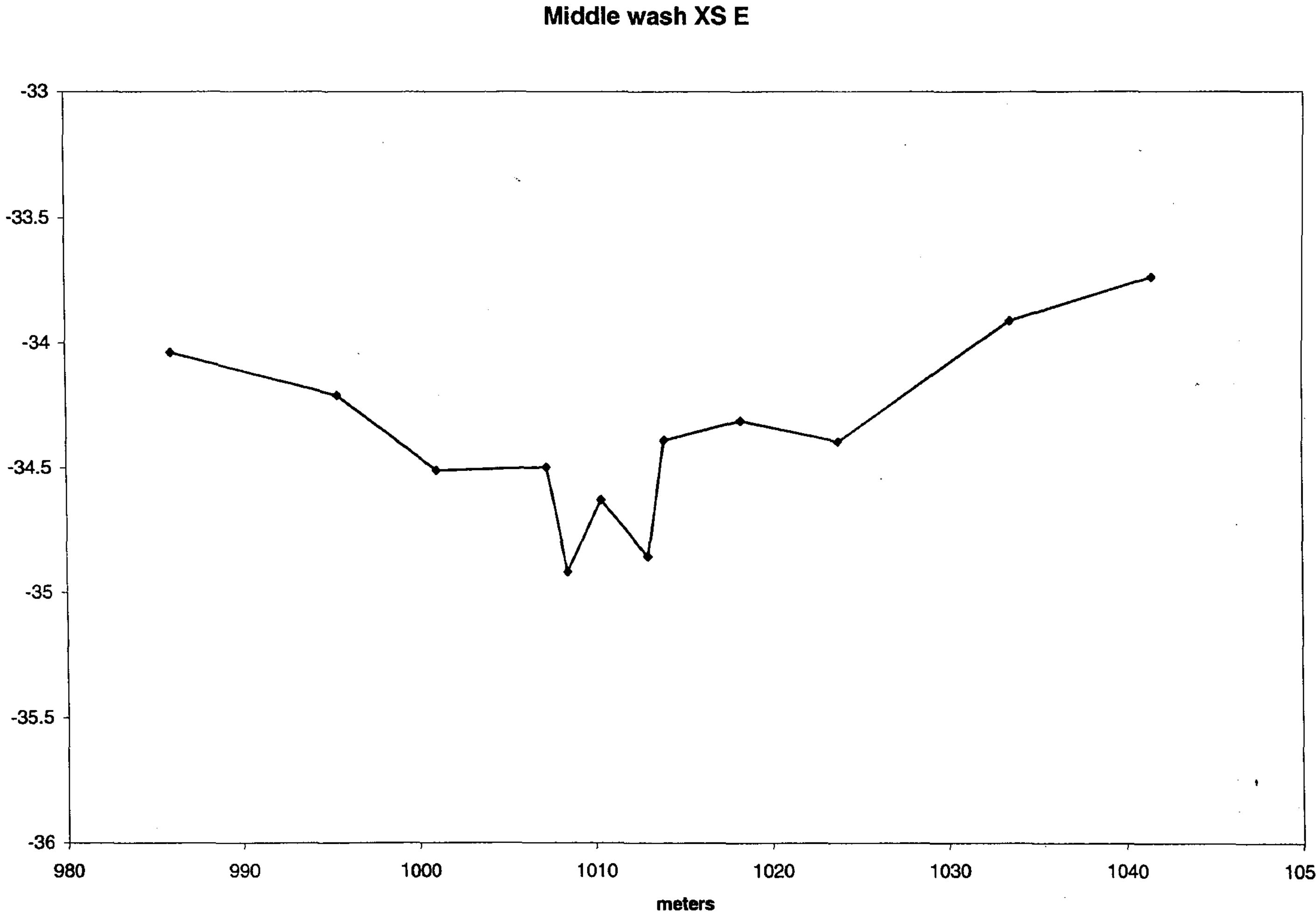


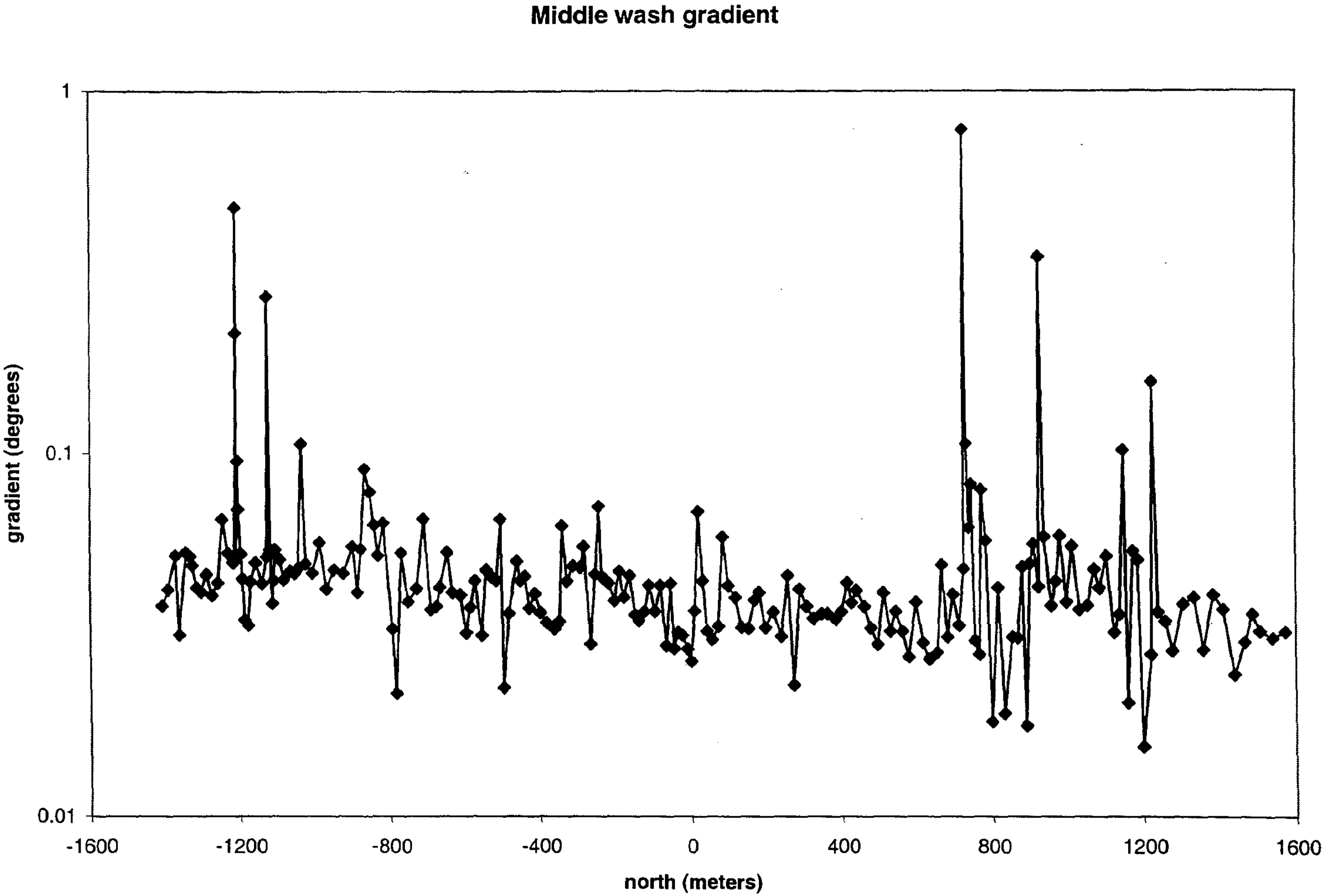

Middle wash XS B
17
16.5
16
15.5
15
14.5
14
meters
905
915
925
935
945
955
965
meters

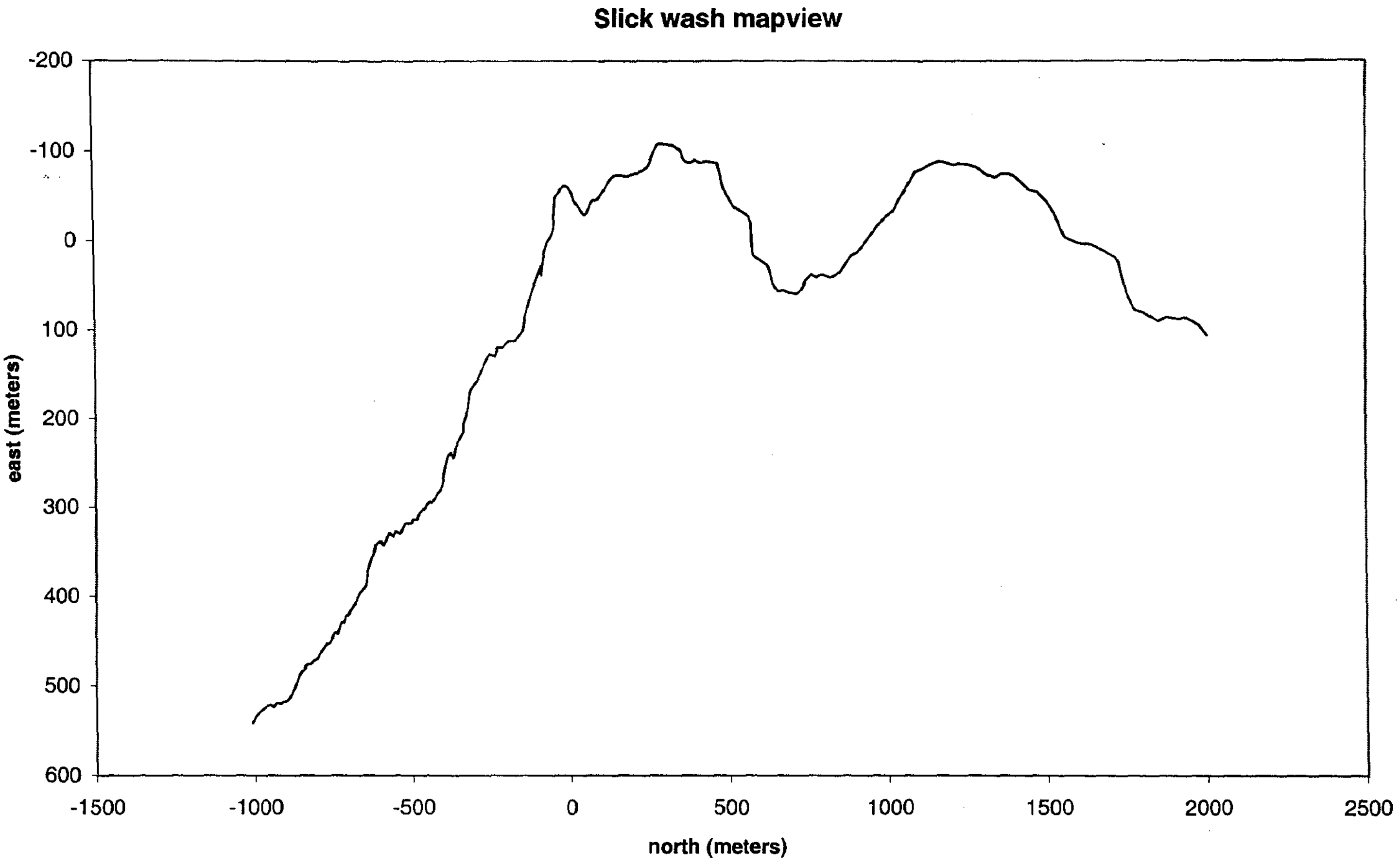

Middle wash XS C
meters
18
16
14
12
10
8
6
4
2
0
960
980
1000
1020
1040
1060
1080
1100
1120
1140
1160
meters

Middle wash XS D



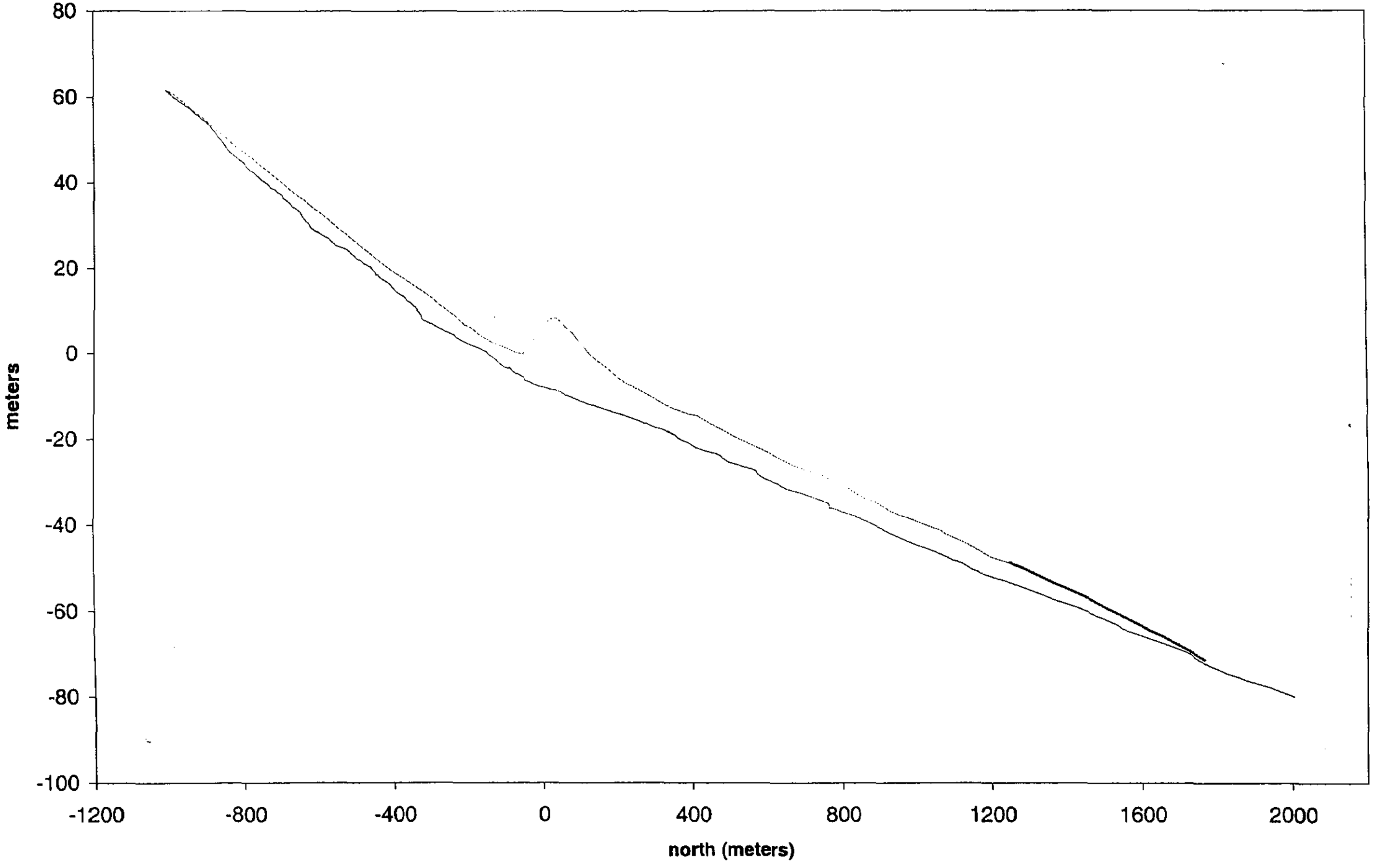

Middle wash XS E
-33
-33.5
-34
-34.5
-35
-35.5
-36
meters
980
990
1000
1010
1020
1030
1040
1050
meters

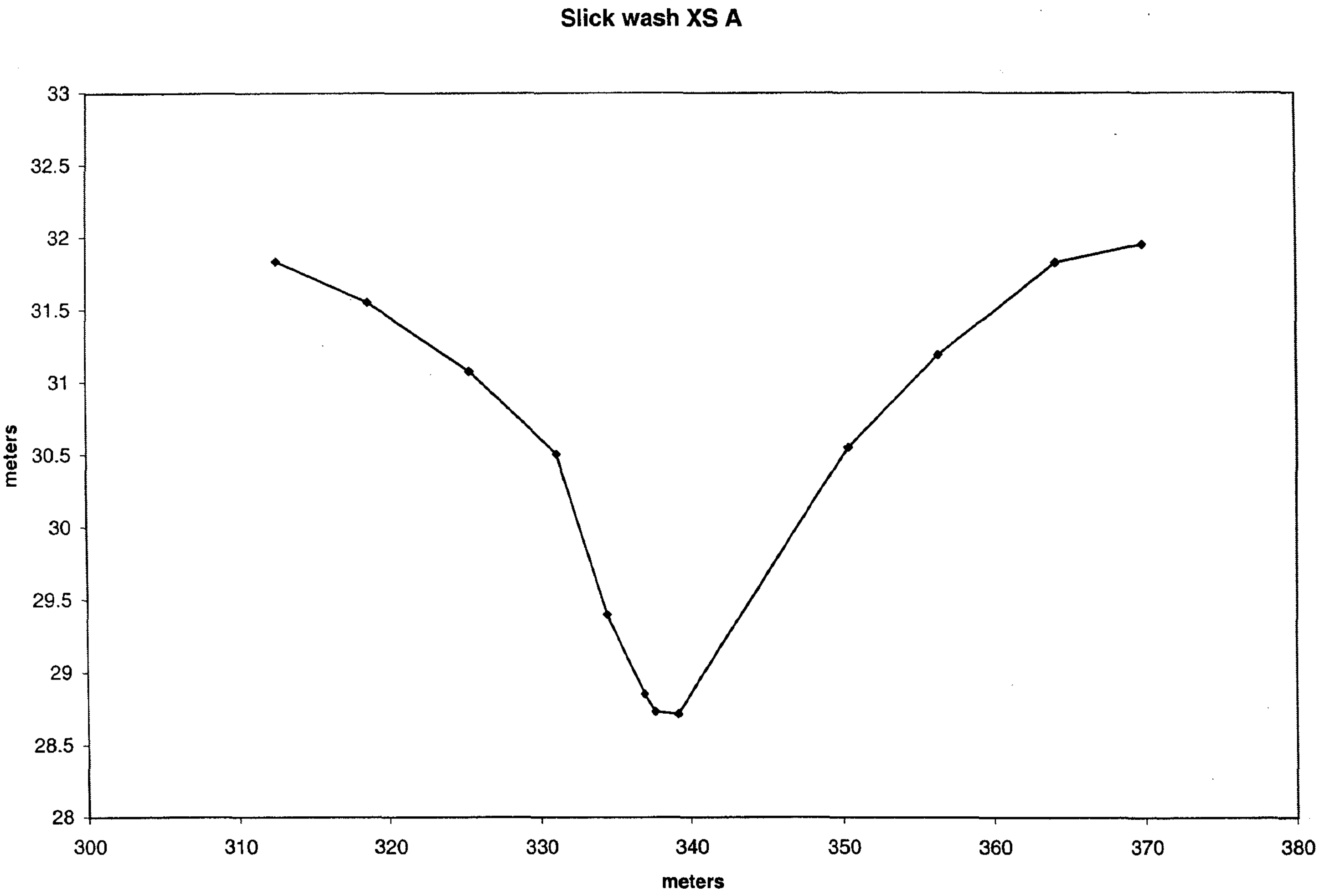

Middle wash gradient
gradient (degrees)
1
0.1
0.01
-1600
-1200
-800
-400
0
400
800
1200
1600
north (meters)

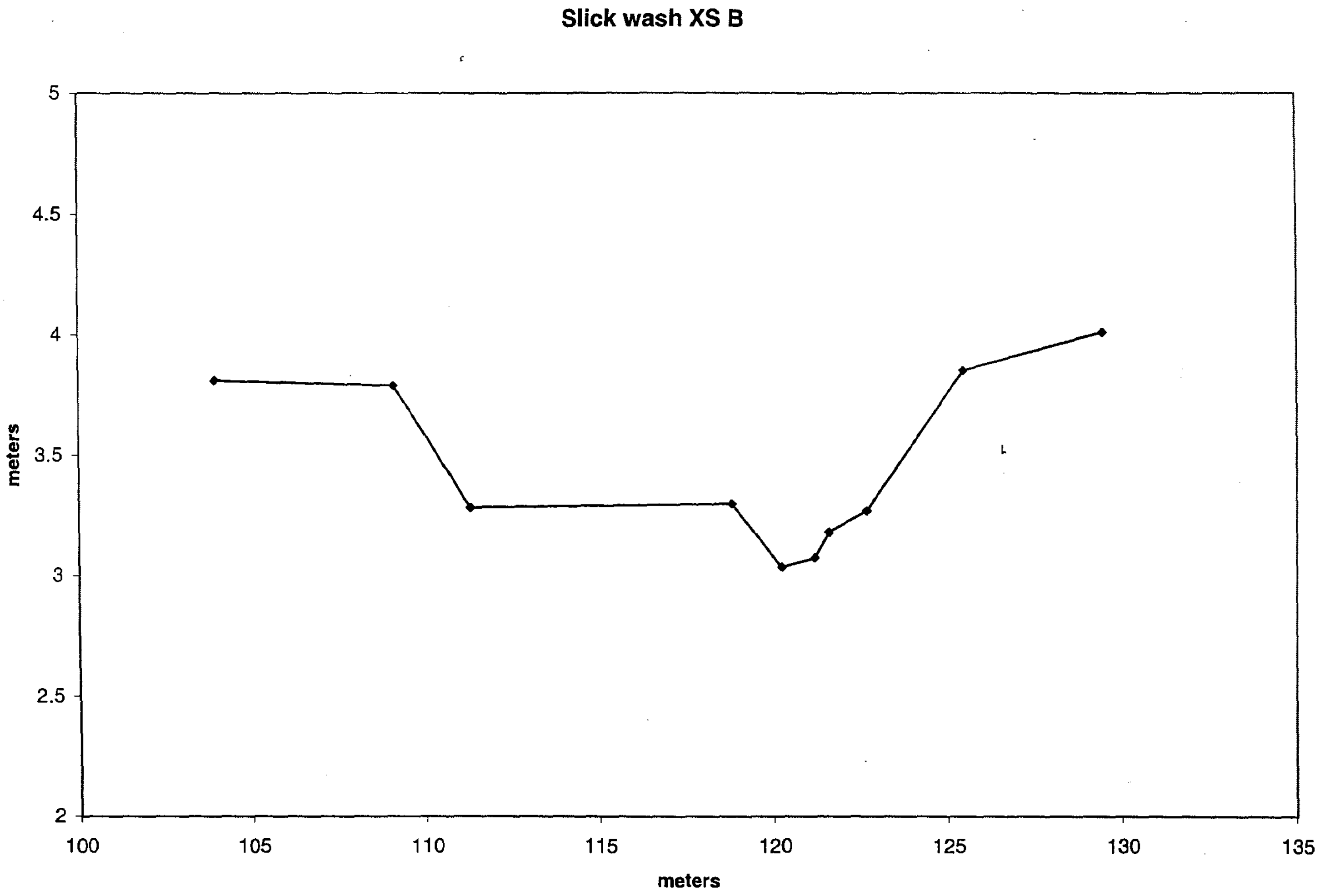


Slick wash mapview
-200
-100
0
100
200
300
400
500
600
east (meters)
-1500
-1000
-500
0
500
1000
1500
2000
2500
north (meters)

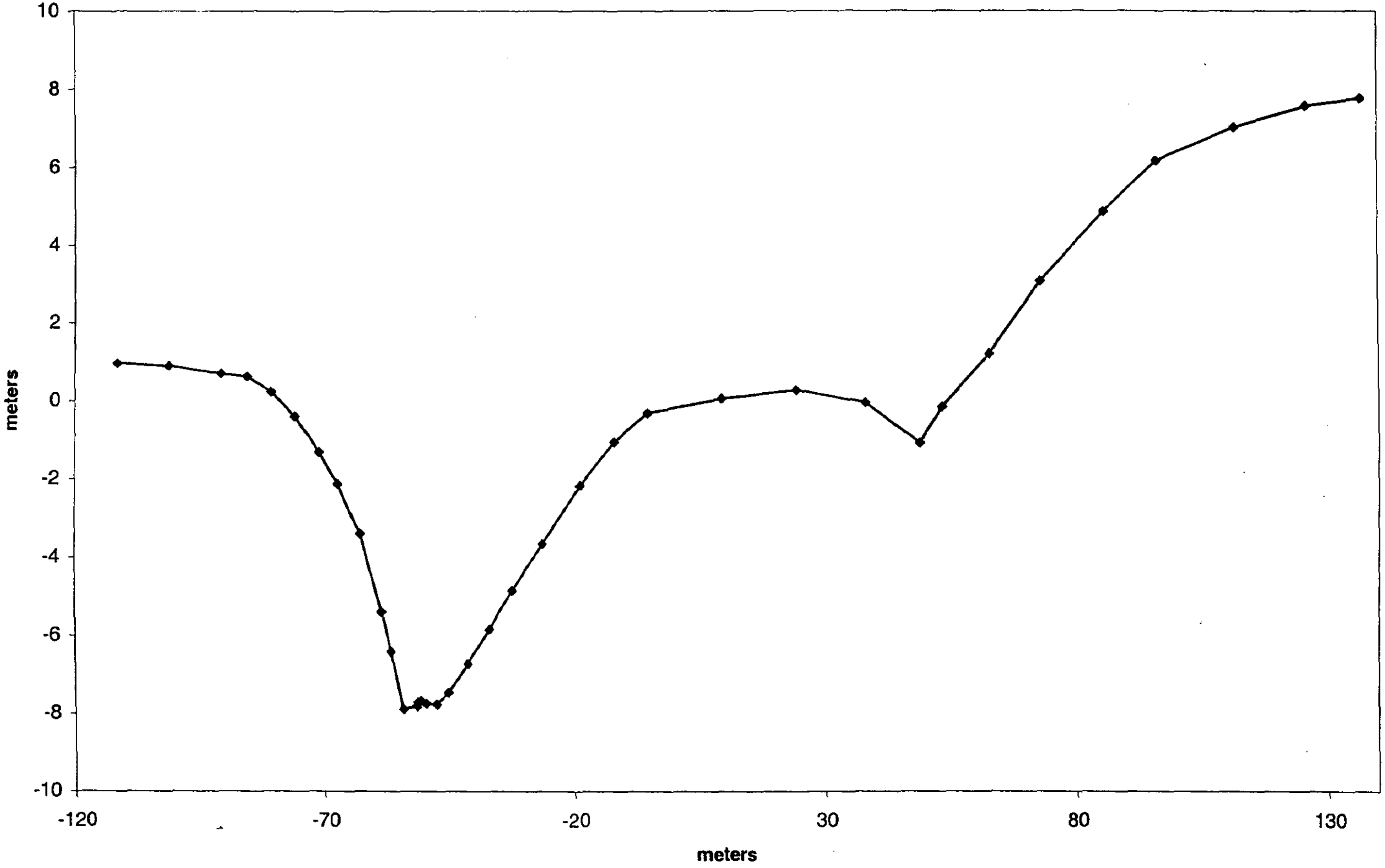
Slick wash longitudinal profile

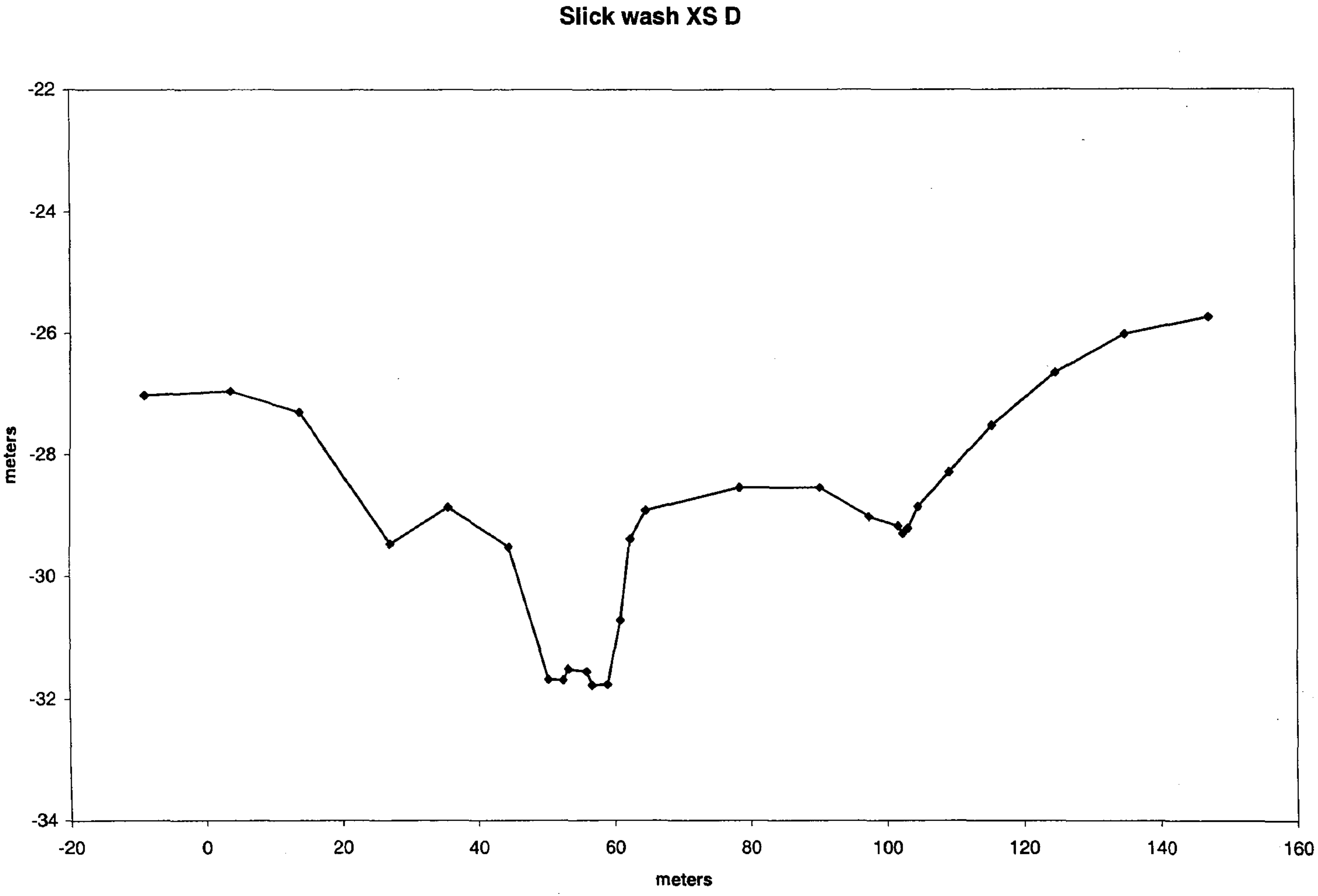


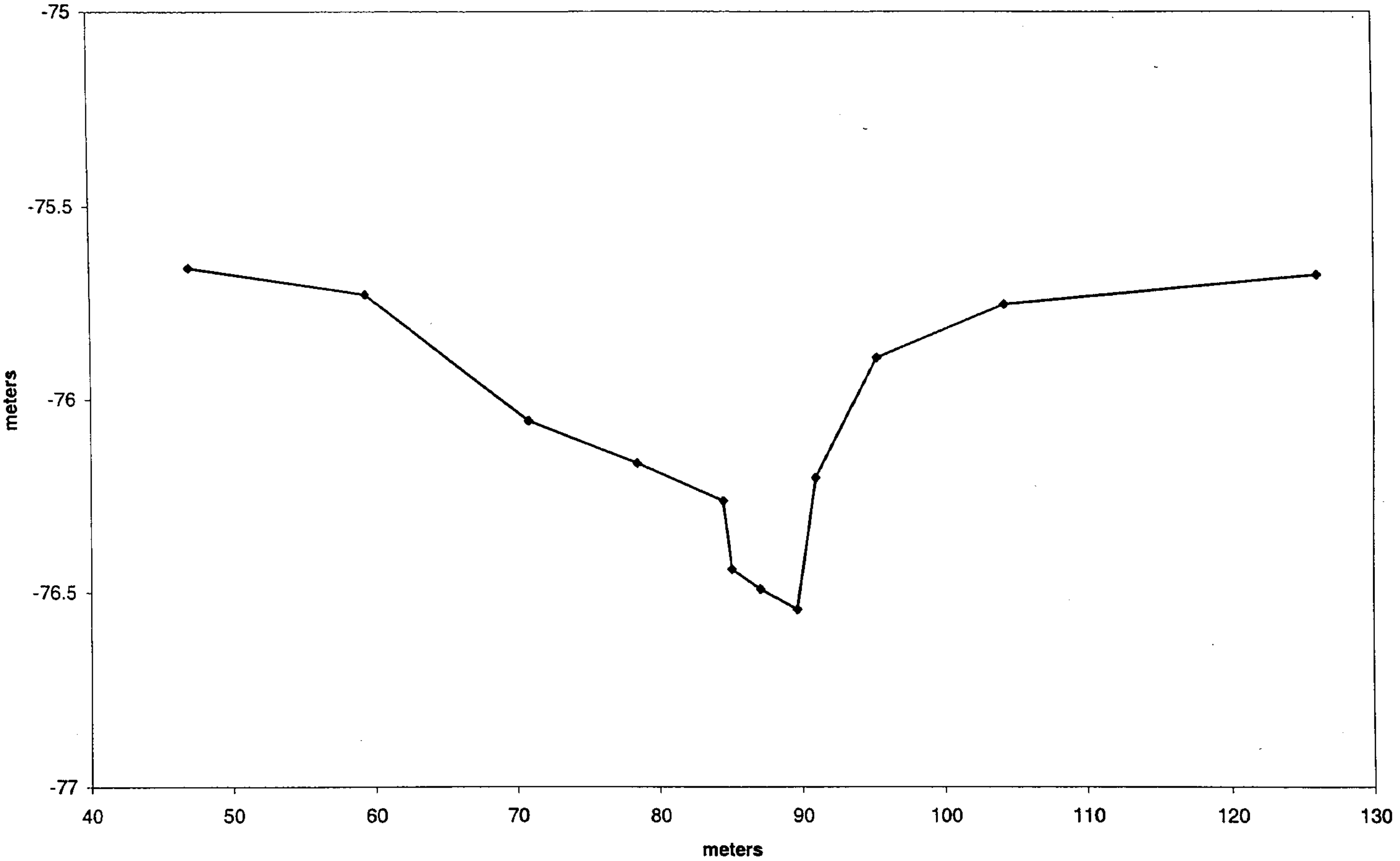

Slick wash XS A
33
32.5
32
31.5
31
30.5
30
29.5
29
28.5
28
meters
300
310
320
330
340
350
360
370
380
meters


Slick wash XS B
meters
5
4.5
4
3.5
3
2.5
2
100
105
110
115
120
125
130
135
meters

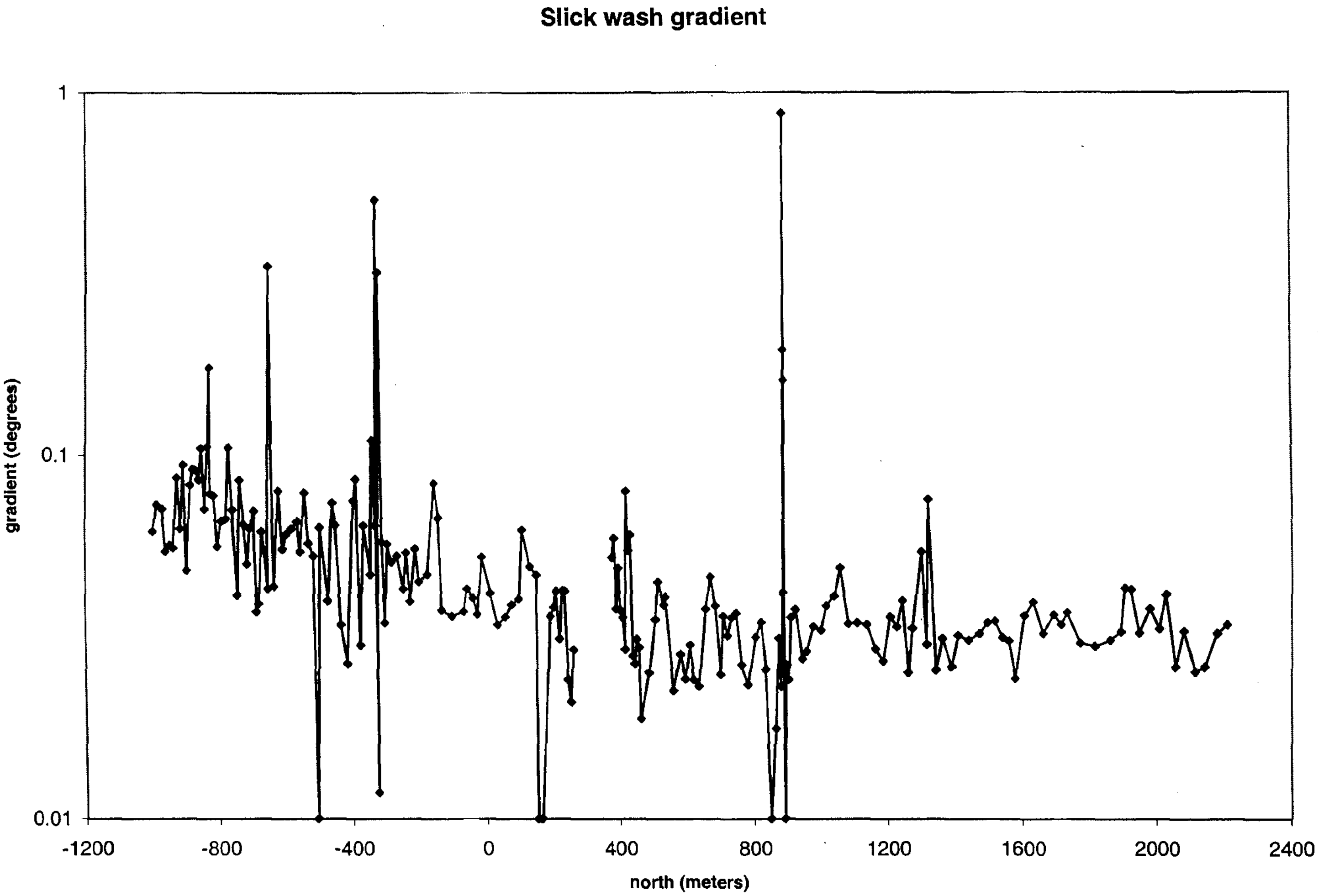
Slick wash XS C

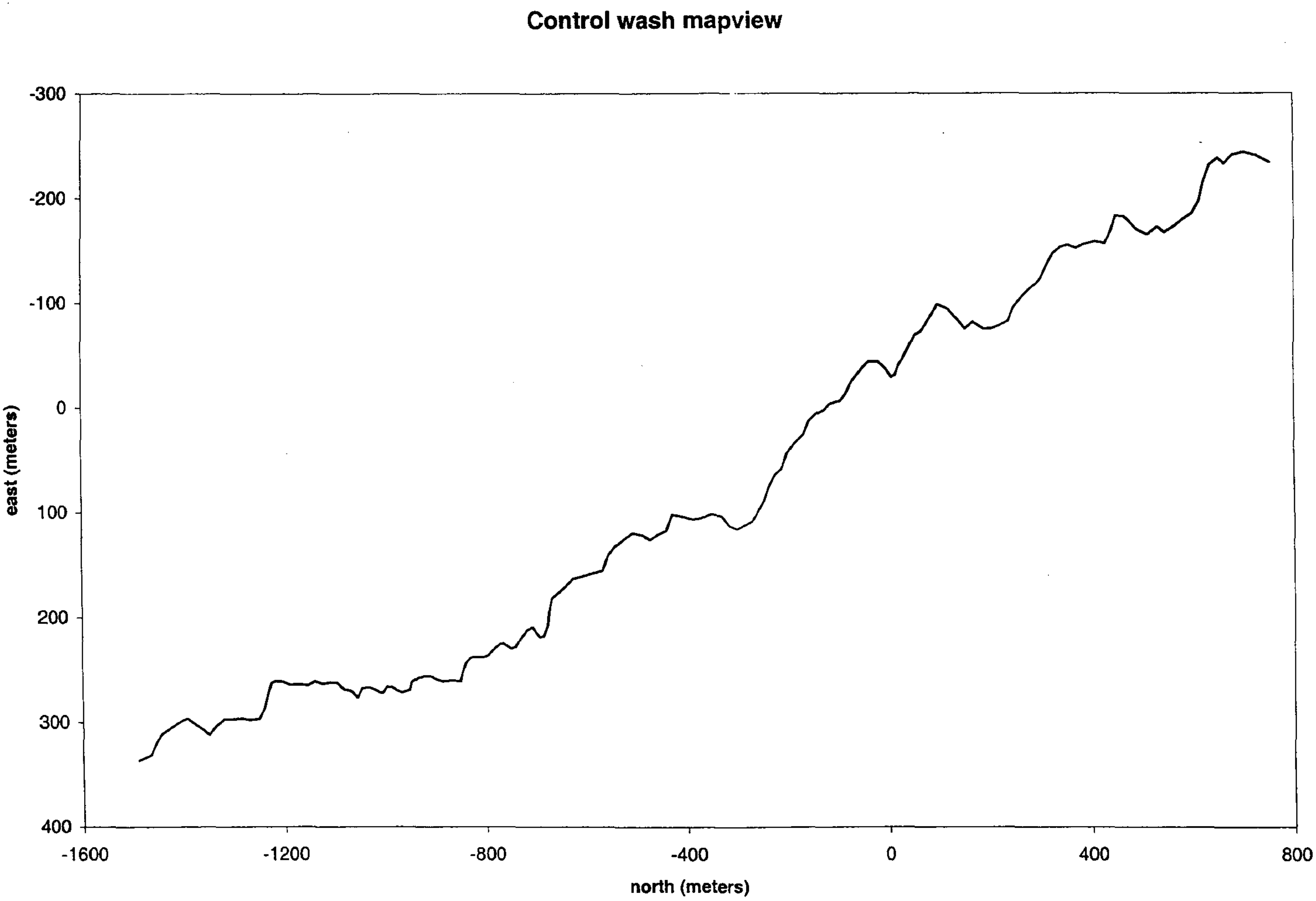


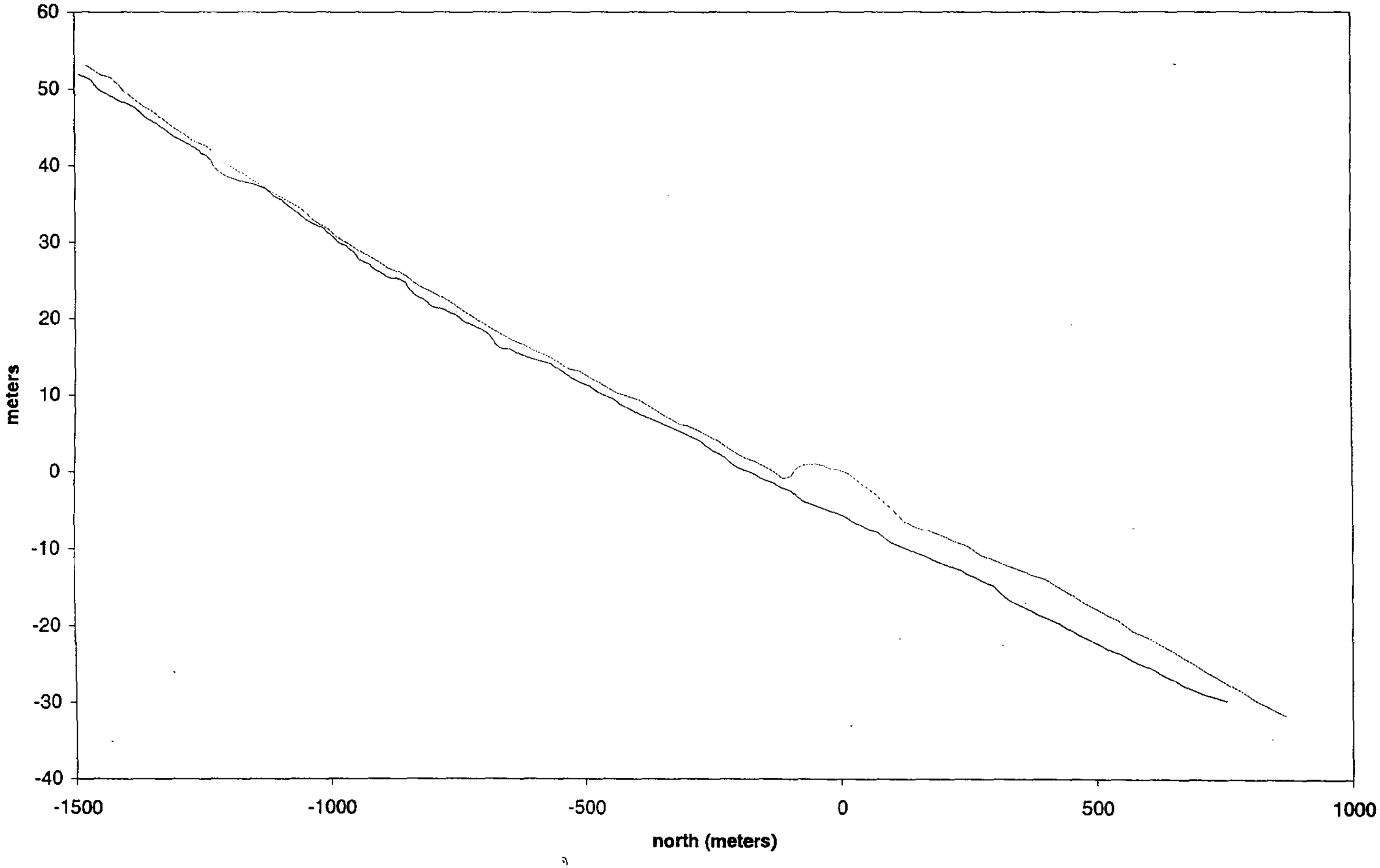

Slick wash XS D
-22
-24
-26
-28
-30
-32
-34
meters
-20
0
20
40
60
80
100
120
140
160
meters



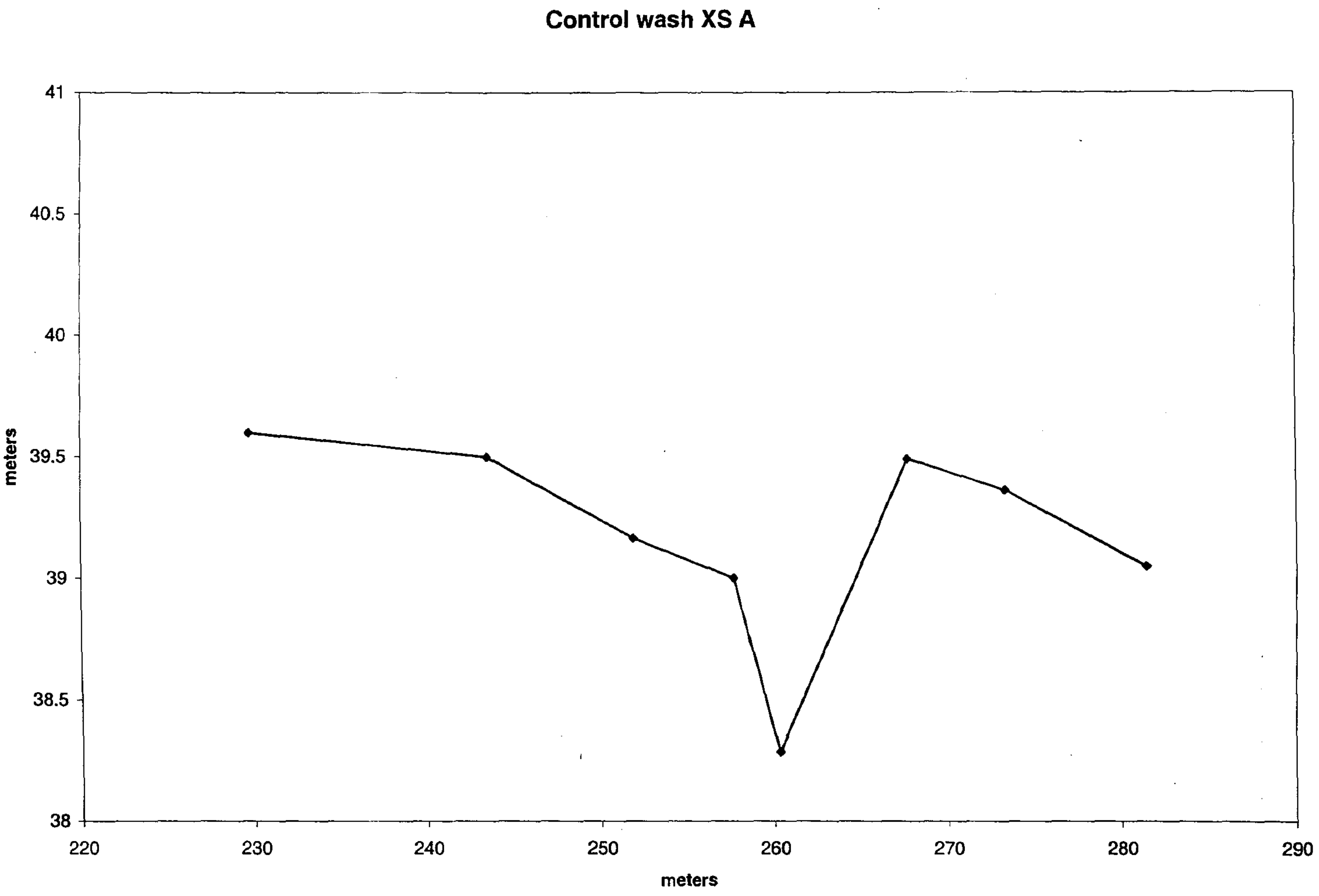
Slick wash XS E

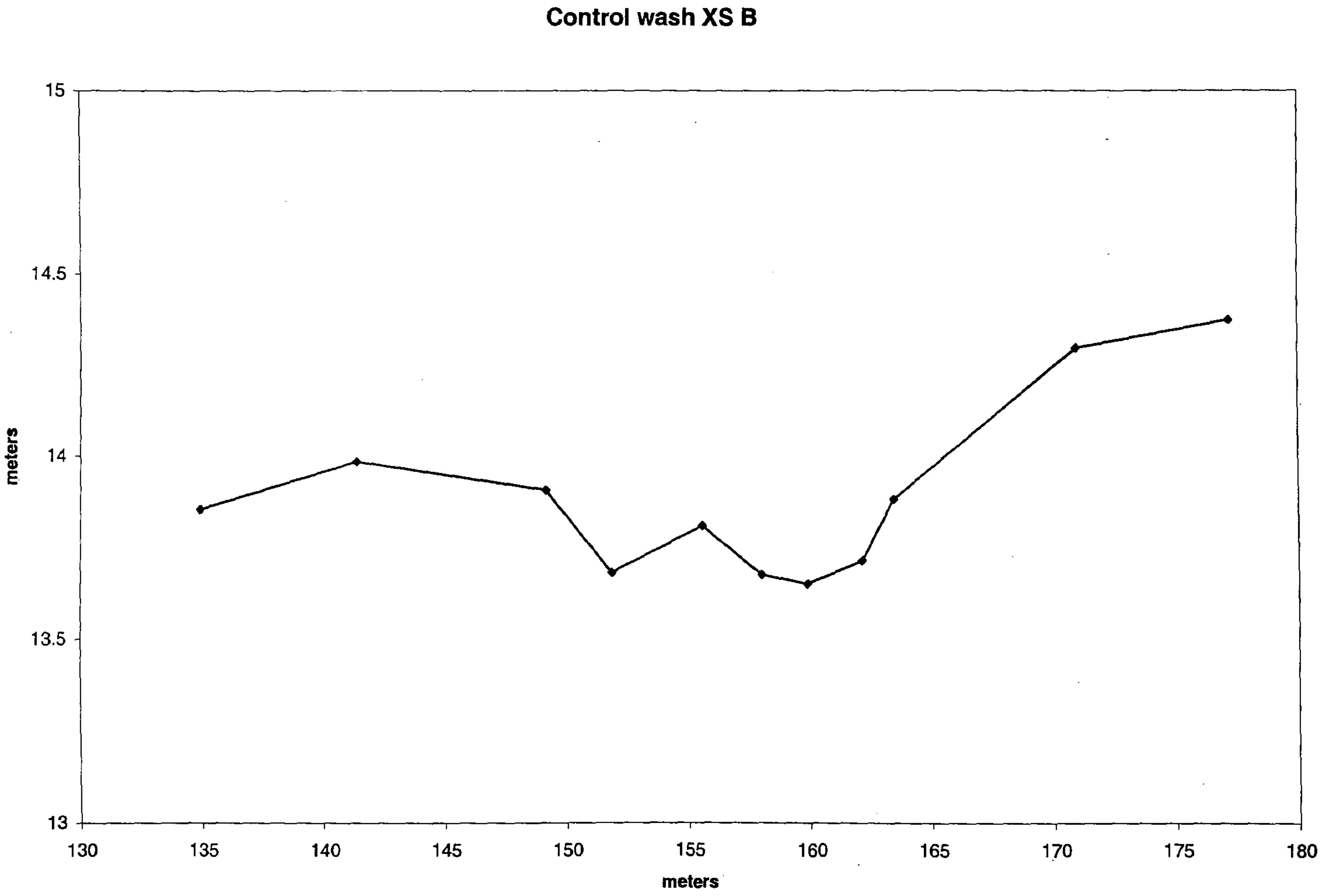

Slick wash gradient
gradient (degrees)
1
0.1
0.01
-1200
-800
-400
0
400
800
1200
1600
2000
2400
north (meters)

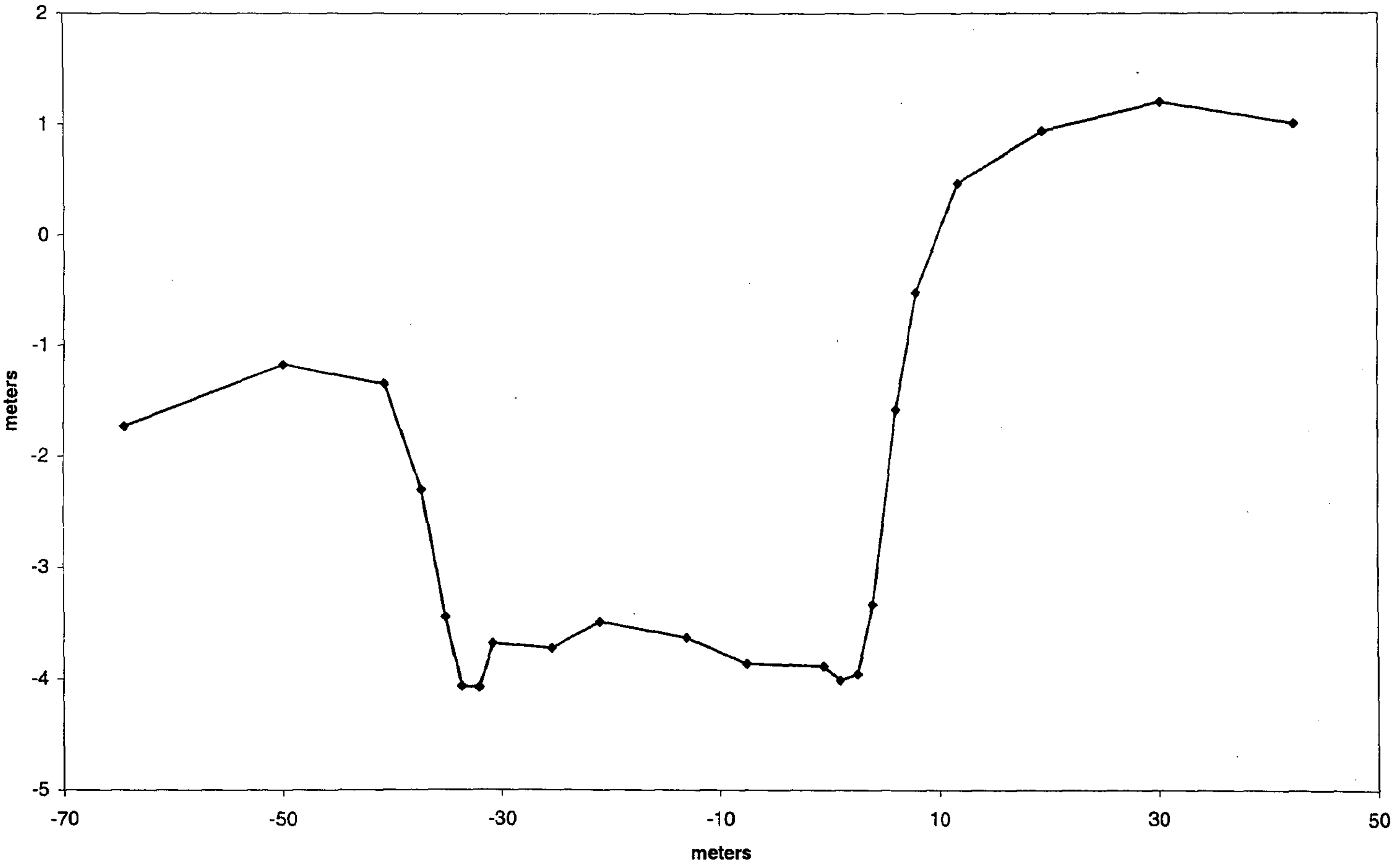

Control wash mapview



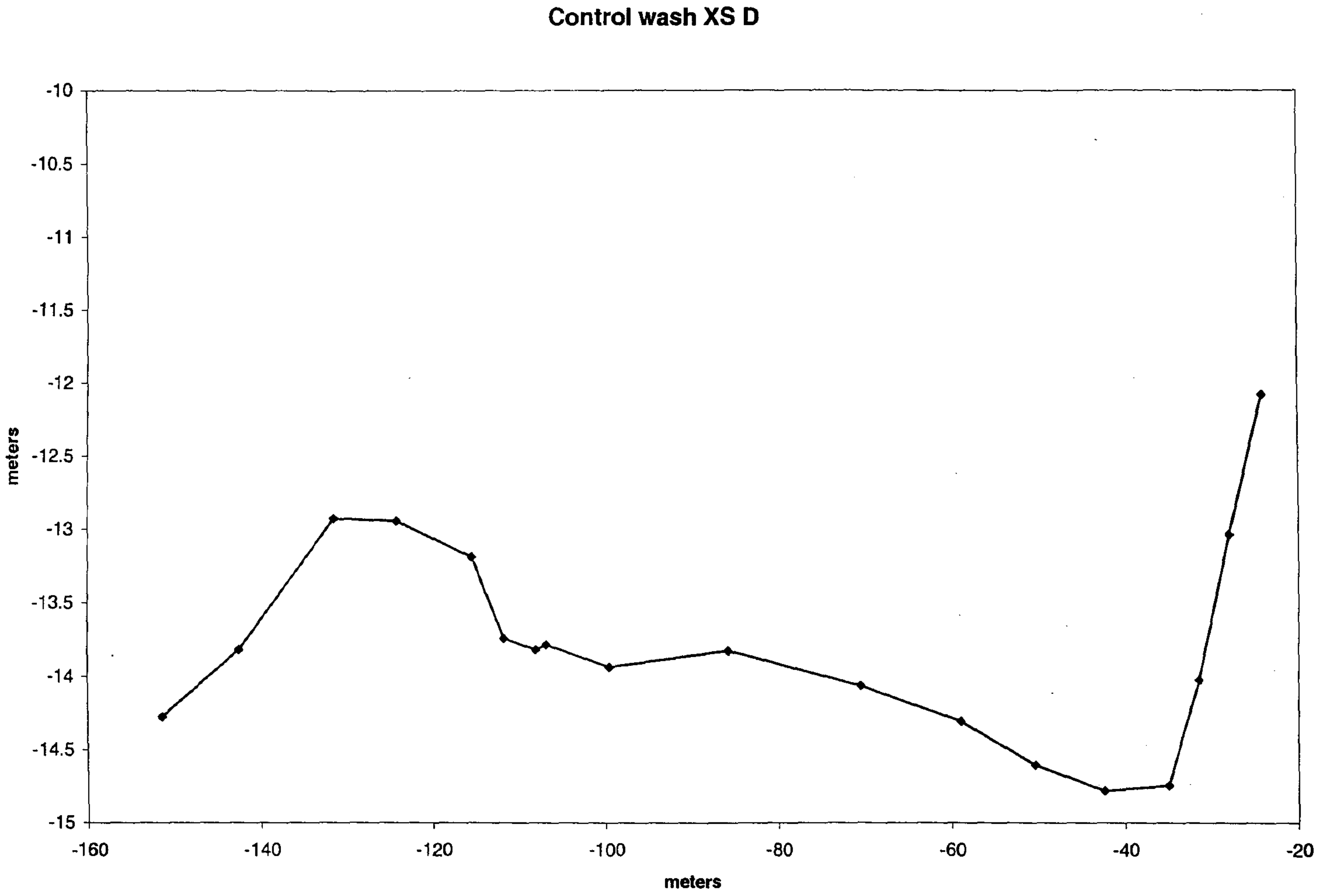
Control wash longitudinal profile

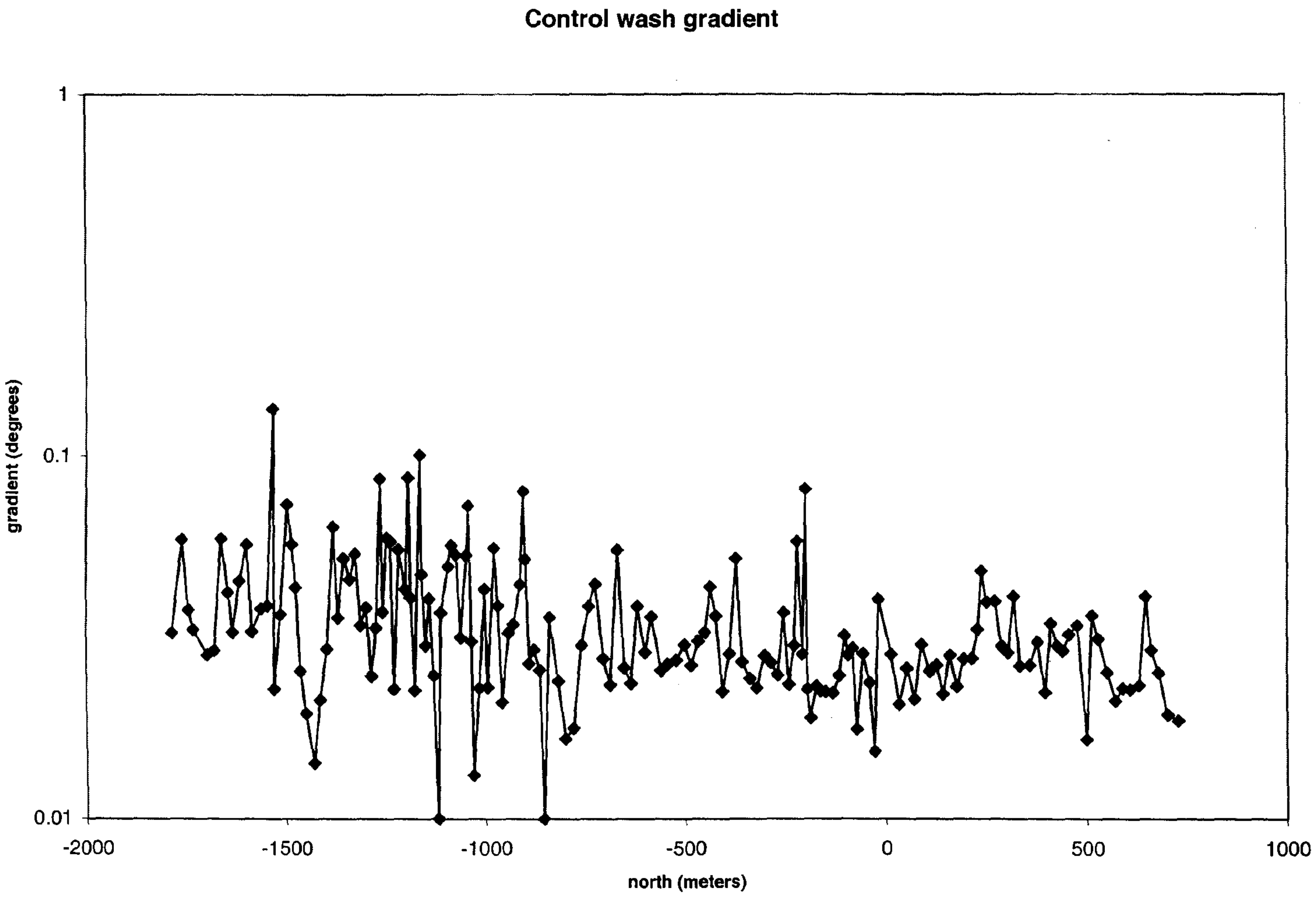

Control wash XS A
41
40.5
40
39.5
39
38.5
38
meters
220
230
240
250
260
270
280
290
meters

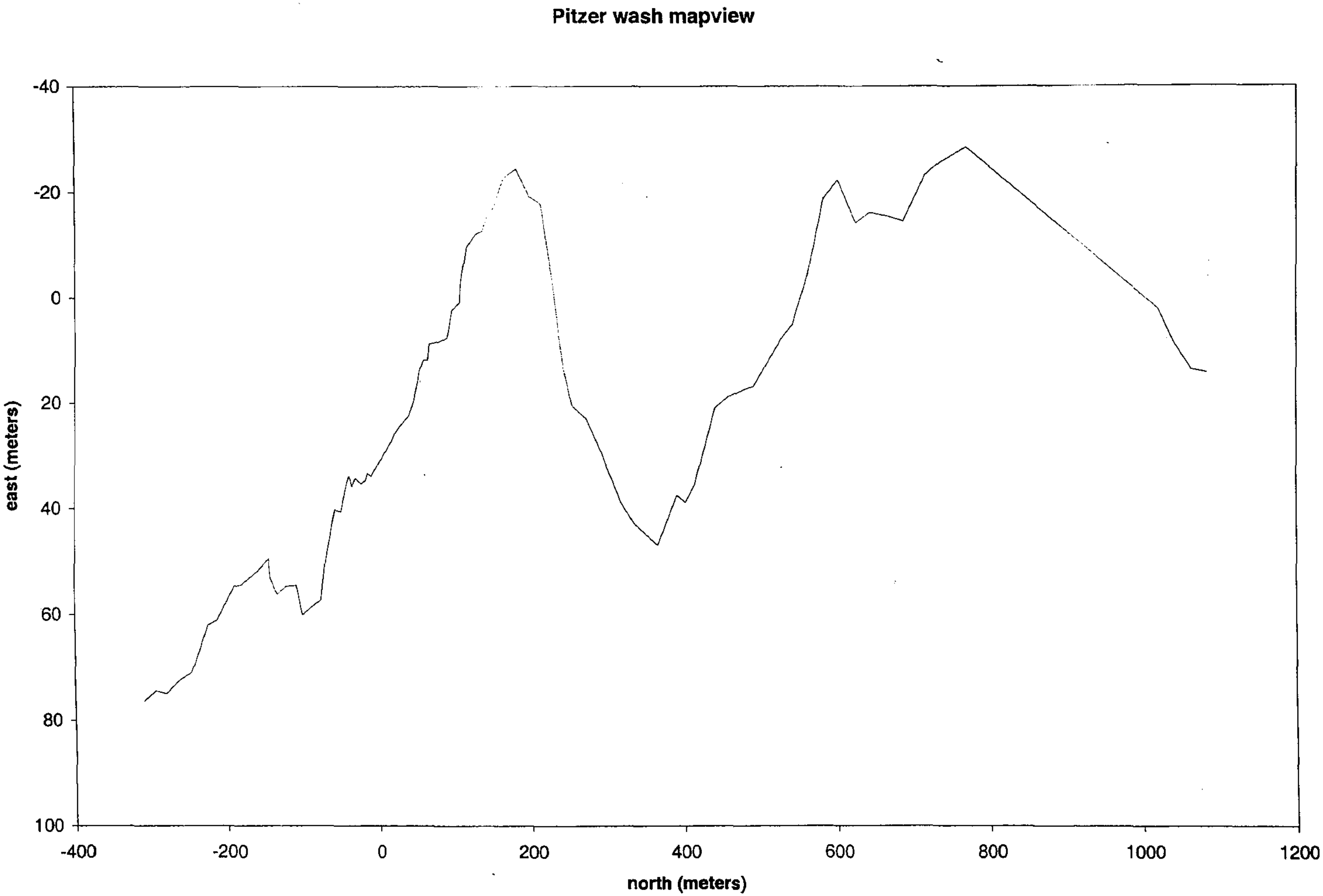

Control wash XS B
meters
15
14.5
14
13.5
13
130
135
140
145
150
155
160
165
170
175
180
meters

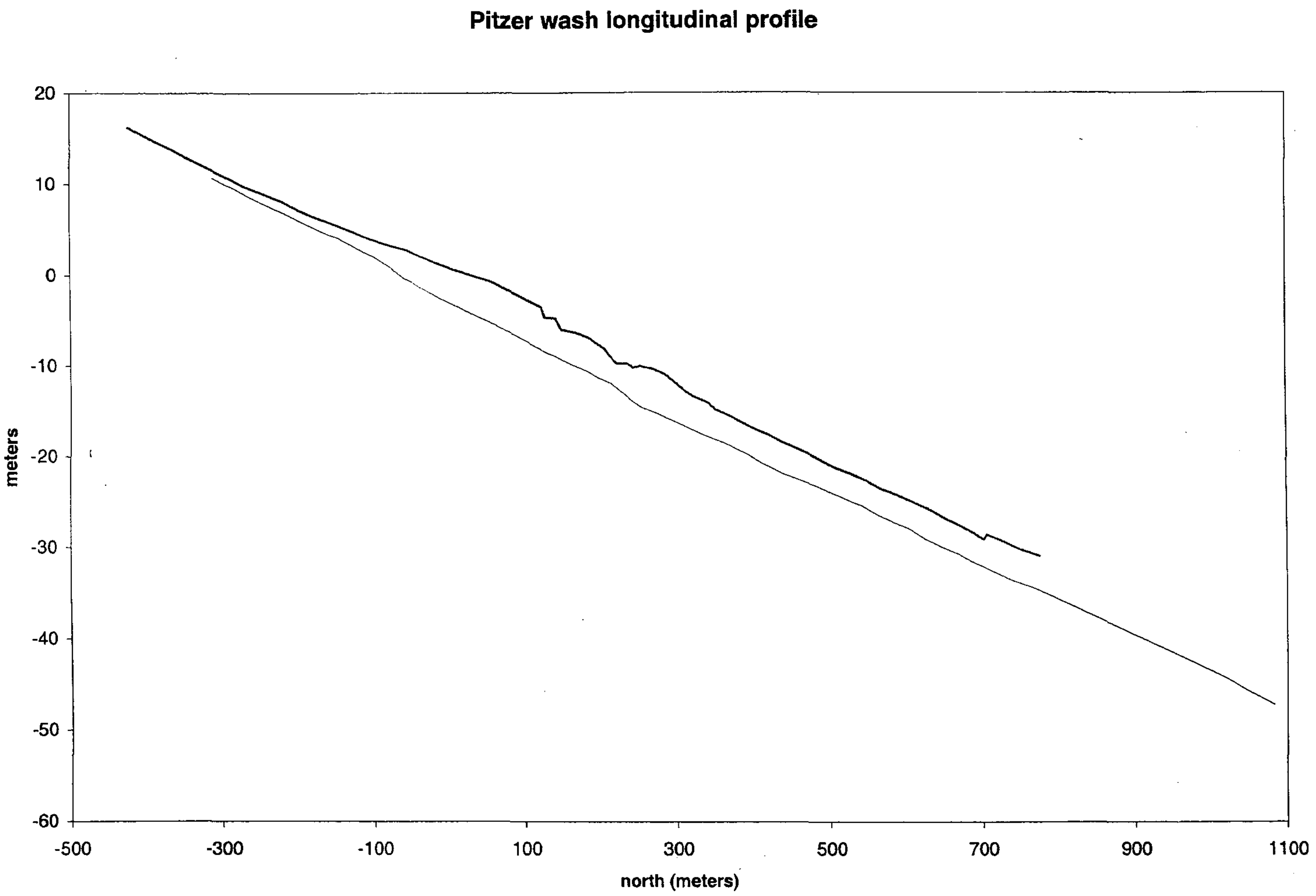


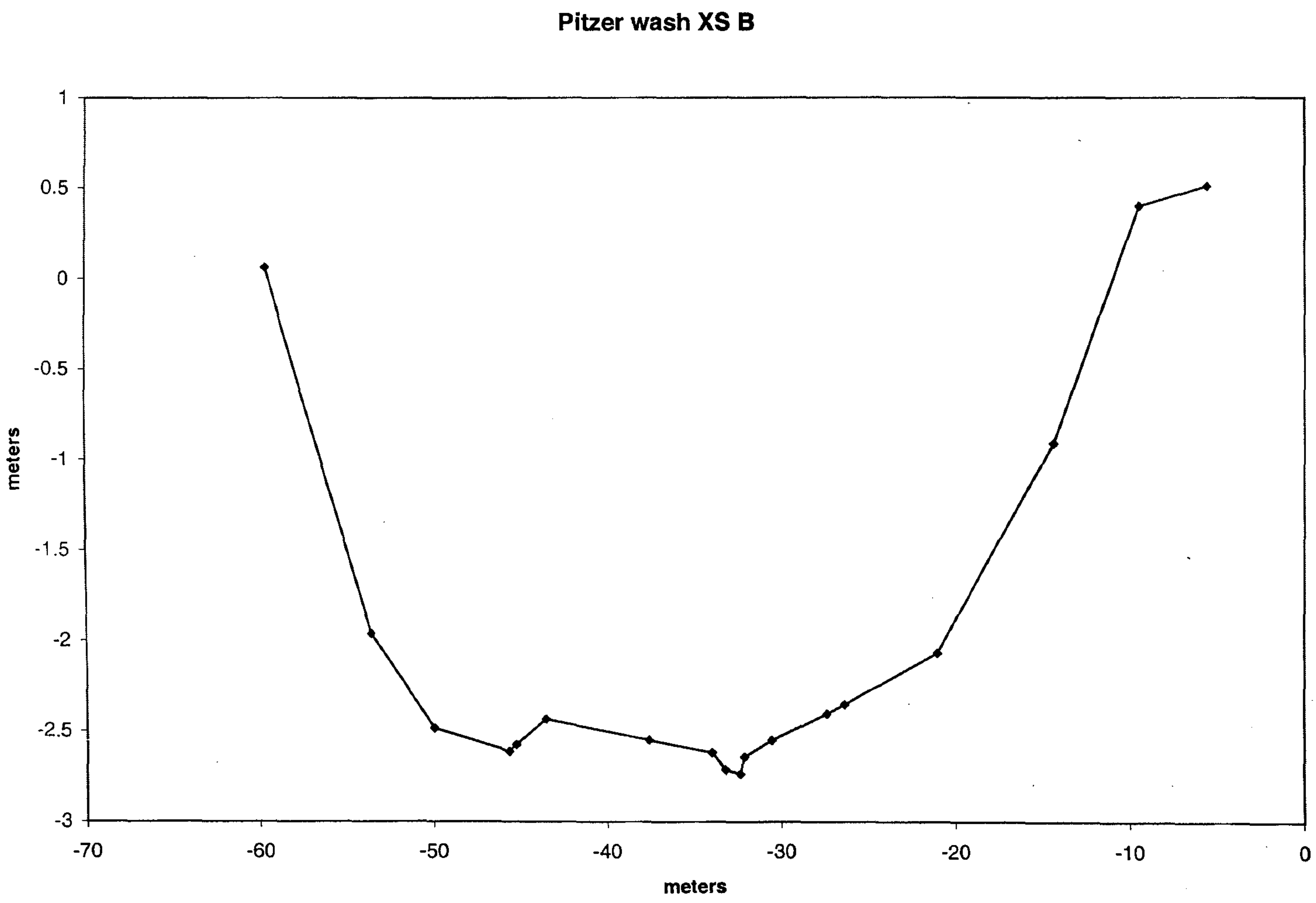
Control wash XS C

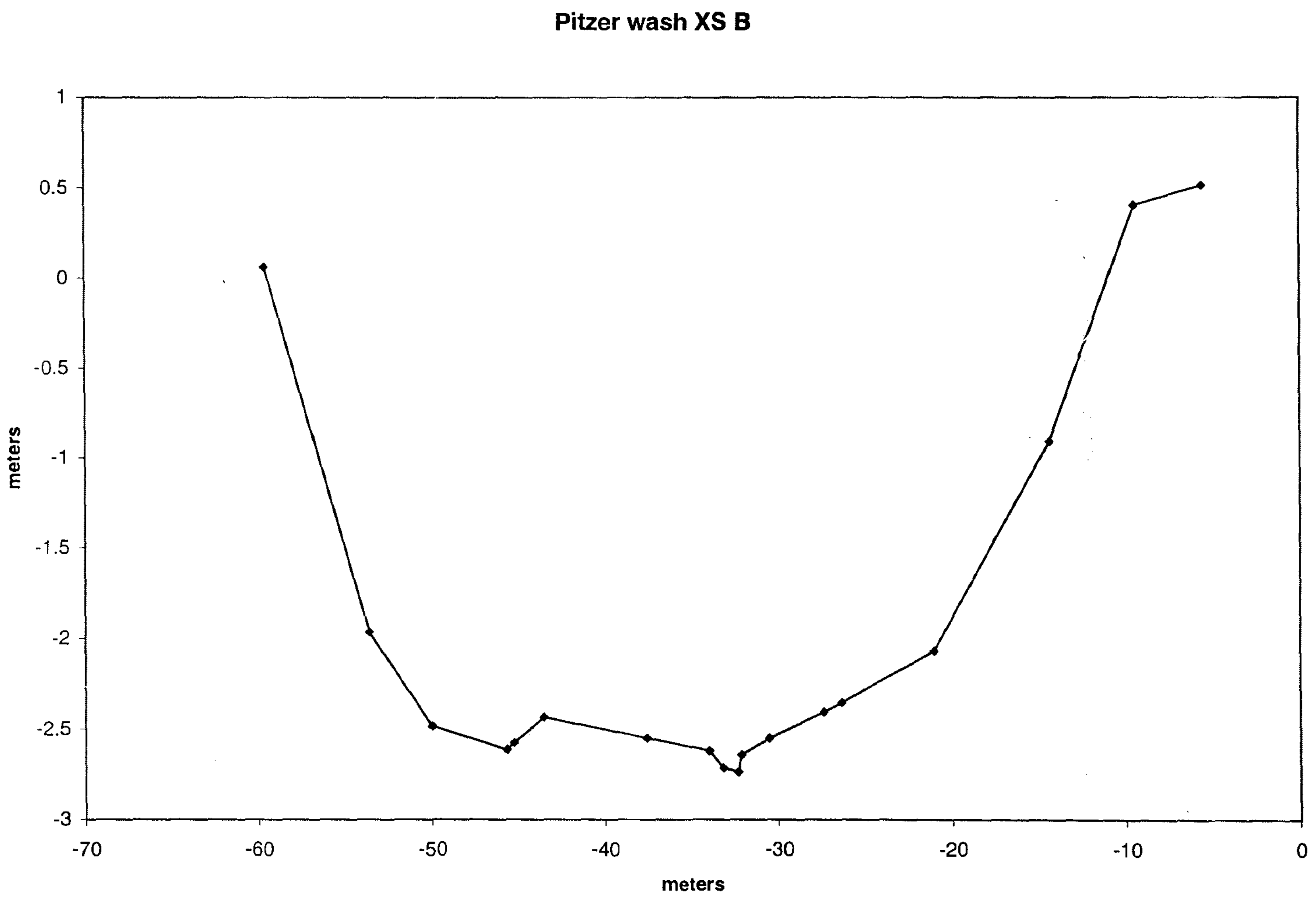

Control wash XS D
-10
-10.5
-11
-11.5
-12
-12.5
-13
-13.5
-14
-14.5
-15
meters
-160
-140
-120
-100
-80
-60
-40
-20
meters

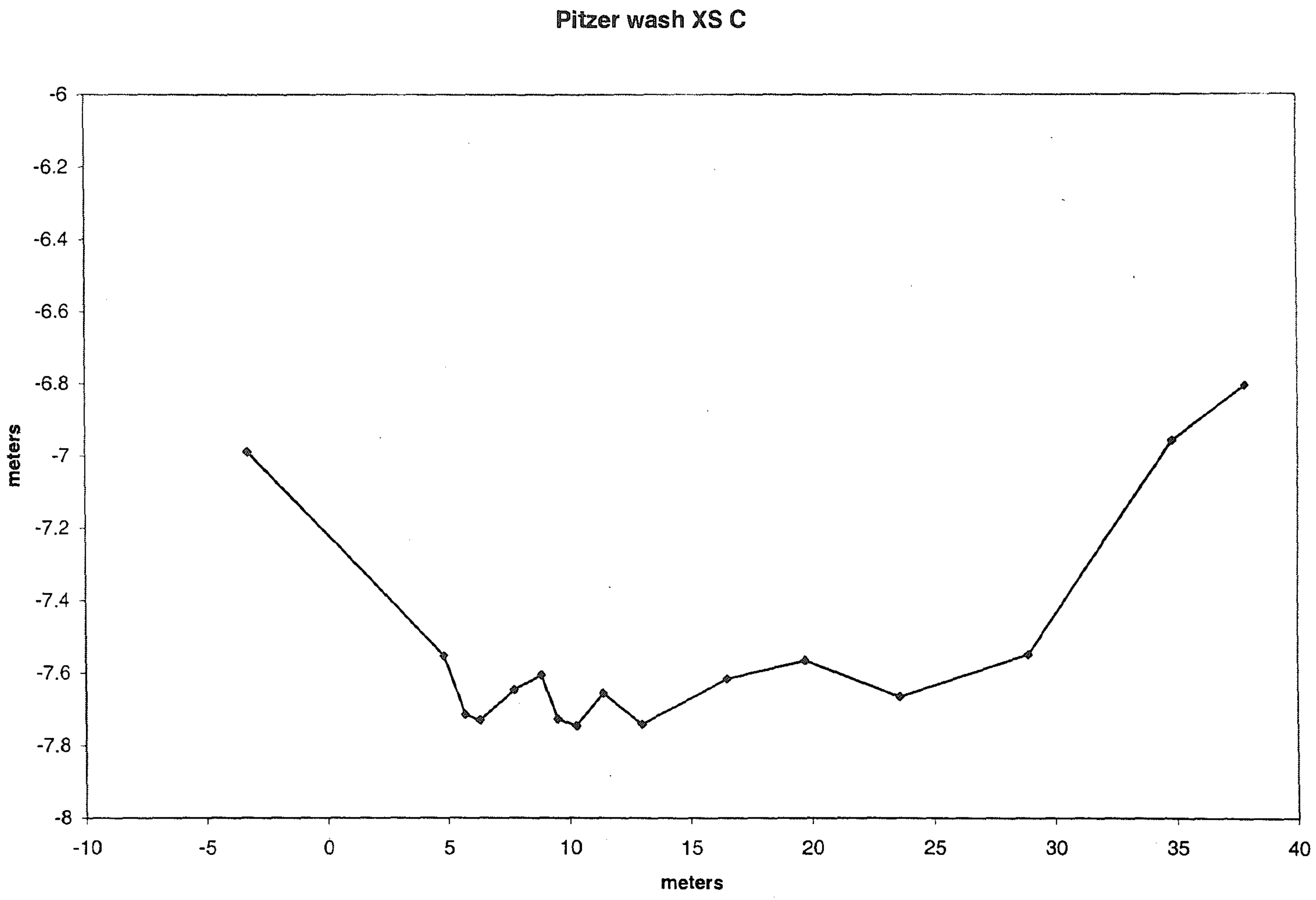

Control wash gradient
gradient (degrees)
1
0.1
0.01
-2000
-1500
-1000
-500
0
500
1000
north (meters)

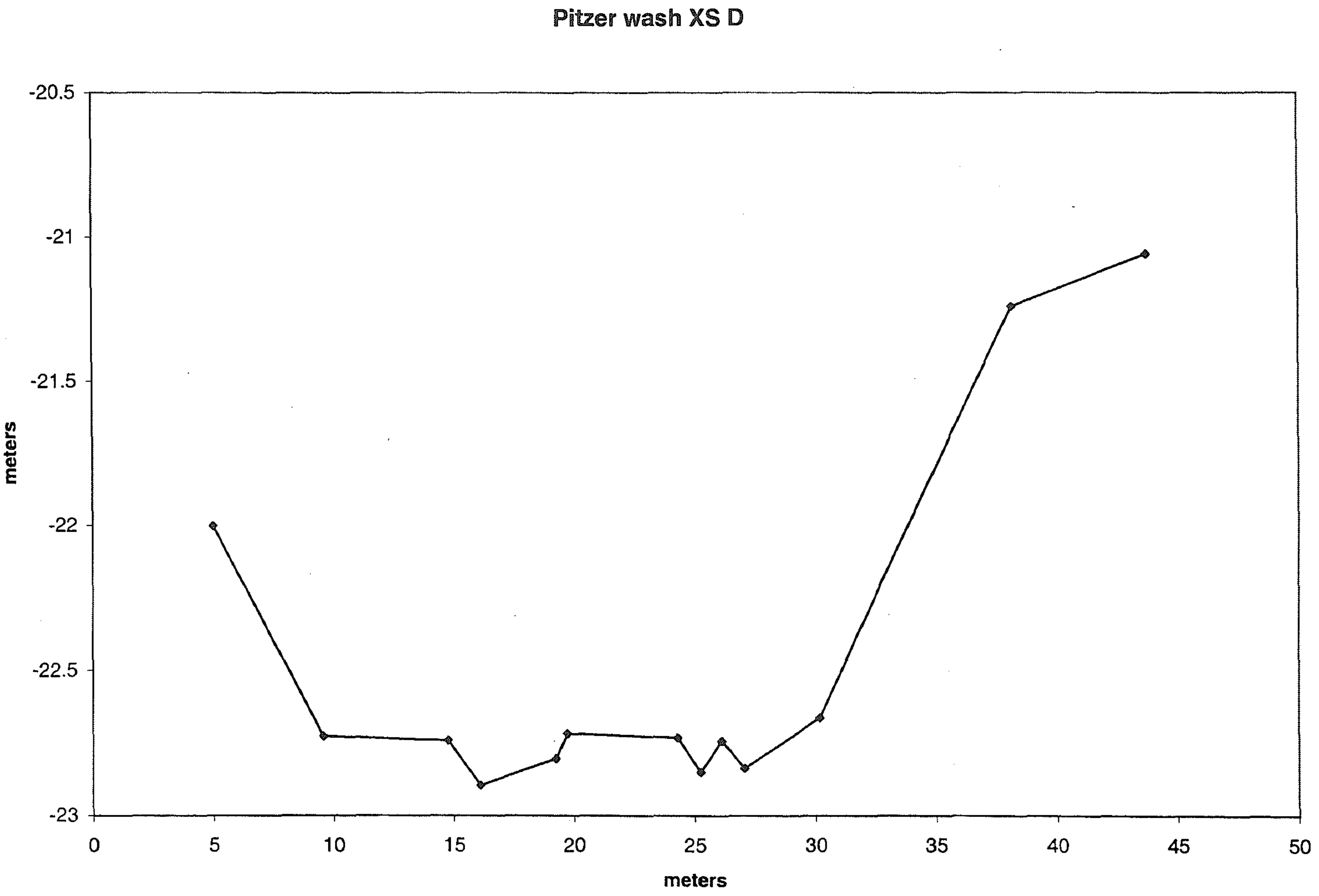

Pitzer wash mapview
-40
-20
0
20
40
60
80
100
east (meters)
-400
-200
0
200
400
600
800
1000
1200
north (meters)

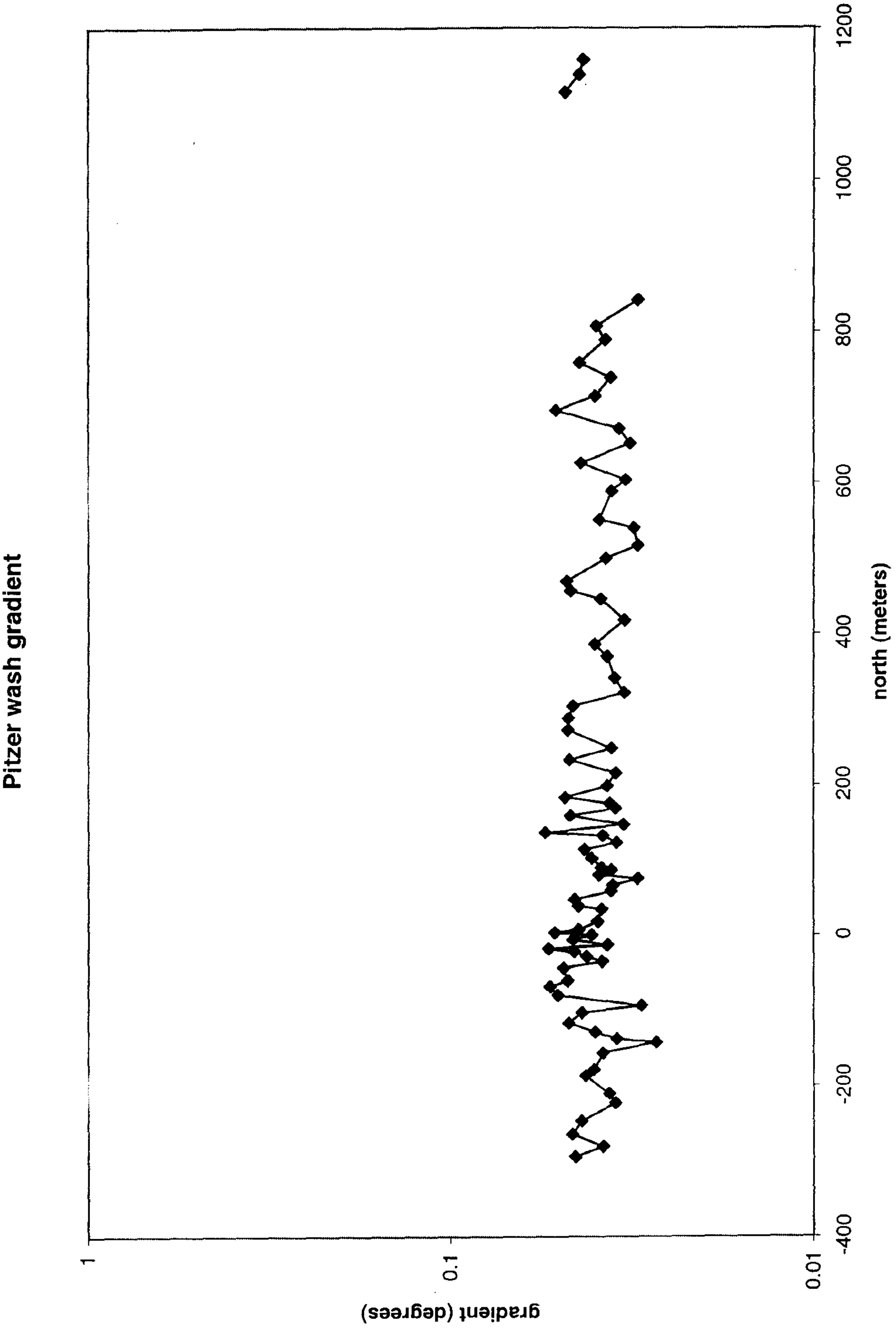

Pitzer wash longitudinal profile
20
10
0
-10
-20
-30
-40
-50
-60
meters
-500
-300
-100
100
300
500
700
900
1100
north (meters)


Pitzer wash XS B
meters
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-70
-60
-50
-40
-30
-20
-10
0
meters

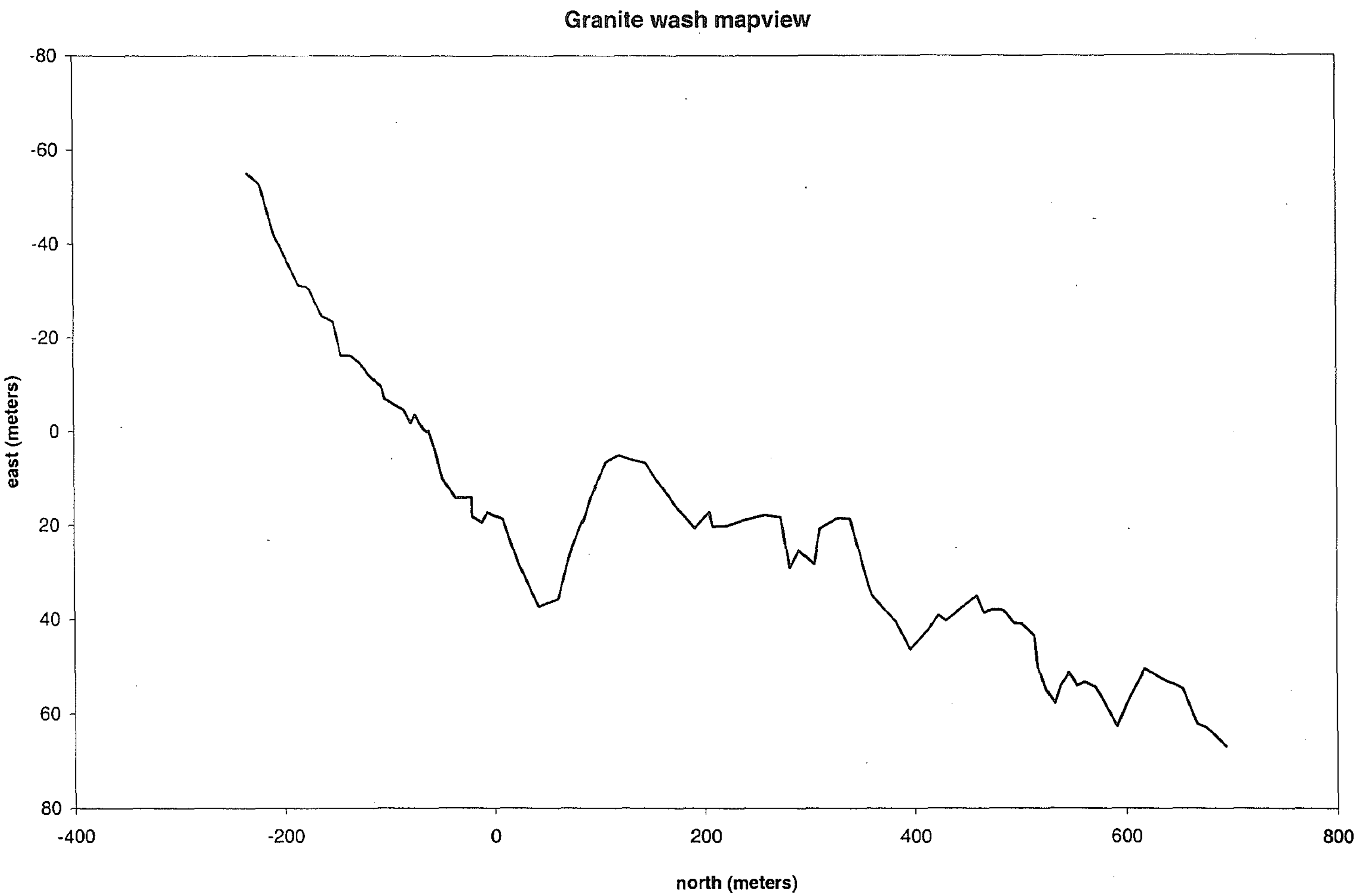

Pitzer wash XS B
meters
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-70
-60
-50
-40
-30
-20
-10
0
meters


Pitzer wash XS C
meters
-6
-6.2
-6.4
-6.6
-6.8
-7
-7.2
-7.4
-7.6
-7.8
-8
-10
-5
0
5
10
15
20
25
30
35
40
meters

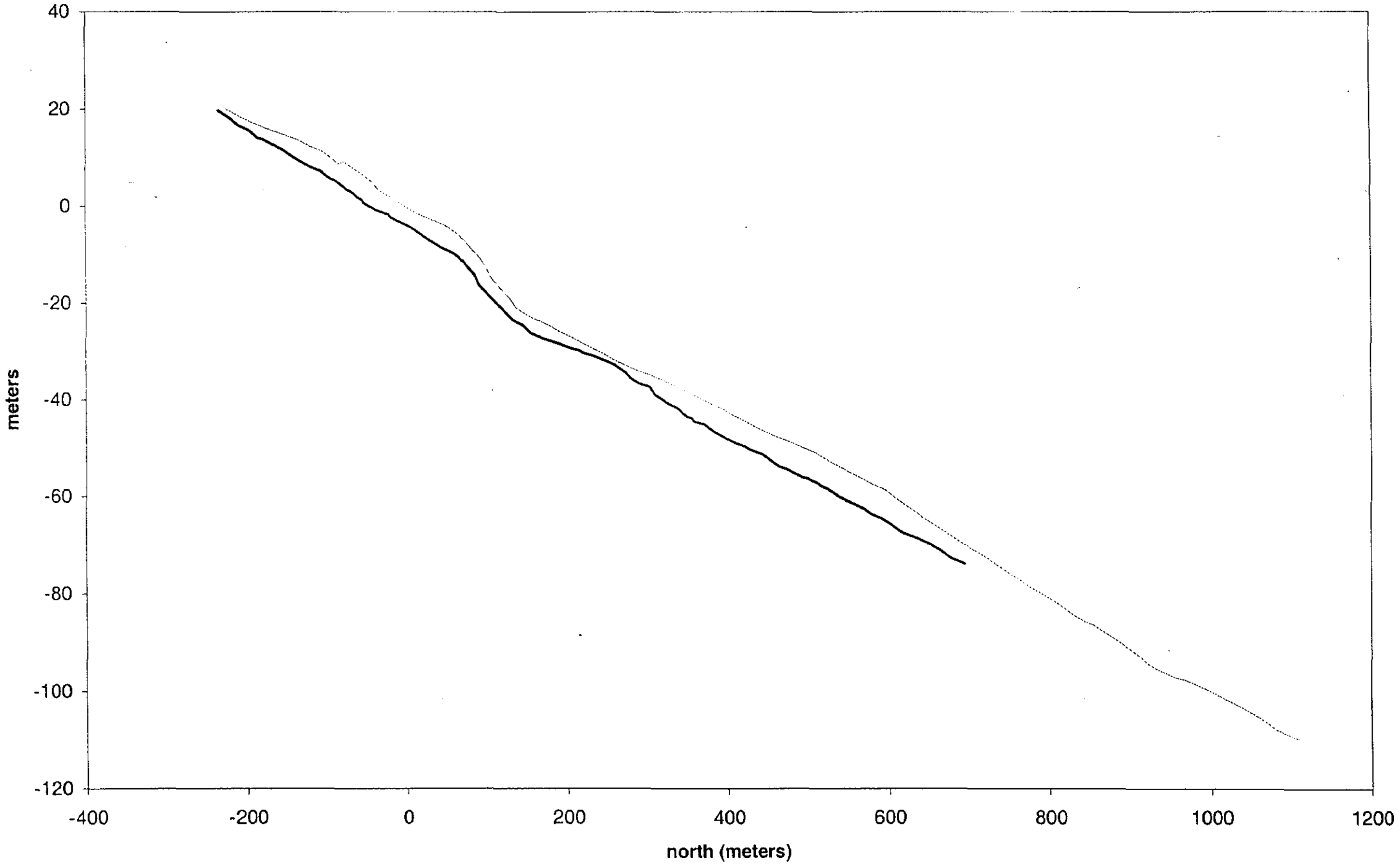

Pitzer wash XS D
-20.5
-21
-21.5
-22
-22.5
-23
meters
0
5
10
15
20
25
30
35
40
45
50
meters

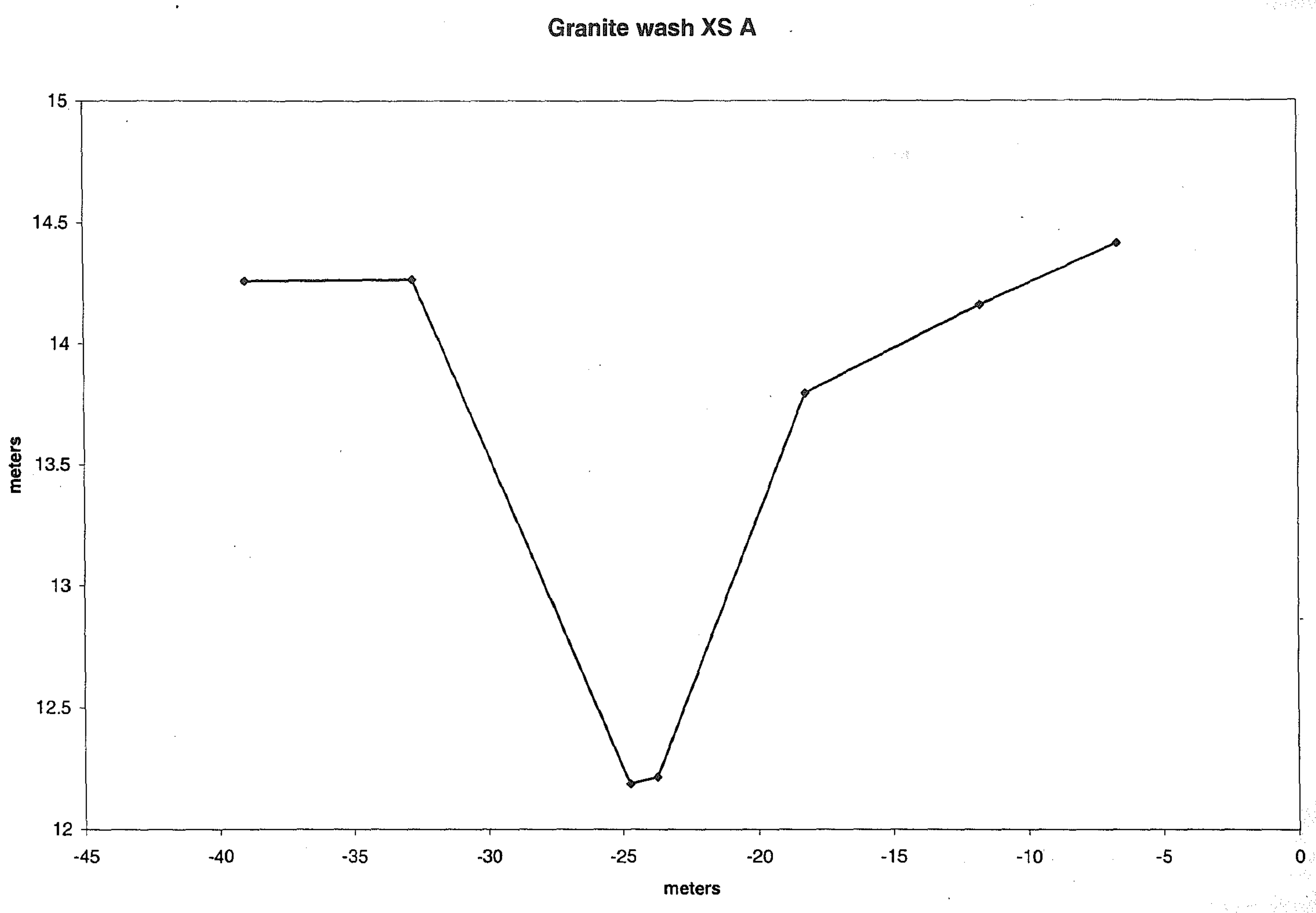


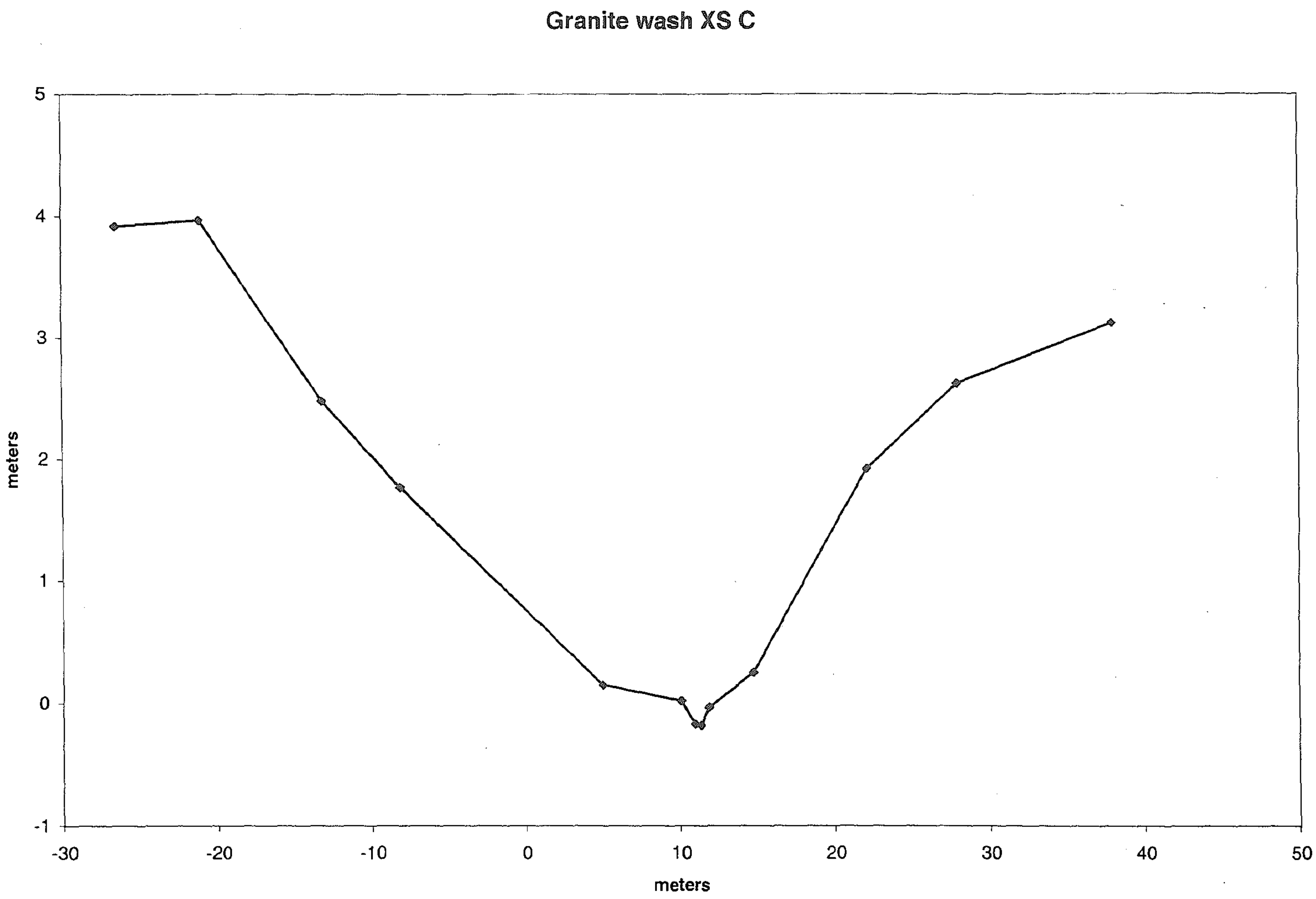
Pitzer wash gradient


Granite wash mapview
east (meters)
-80
-60
-40
-20
0
20
40
60
80
north (meters)
-400
-200
0
200
400
600
800

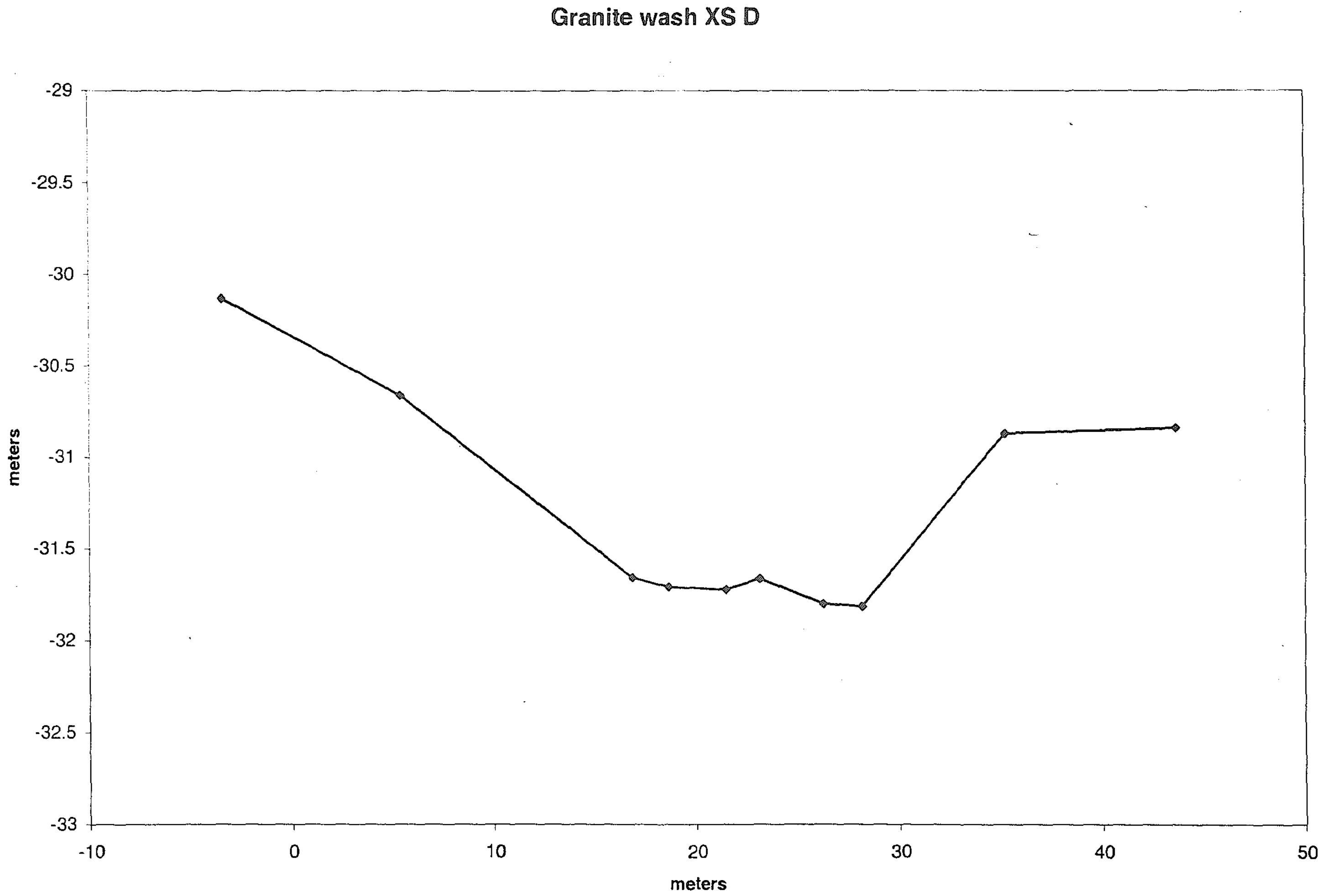
Granite wash longitudinal profile

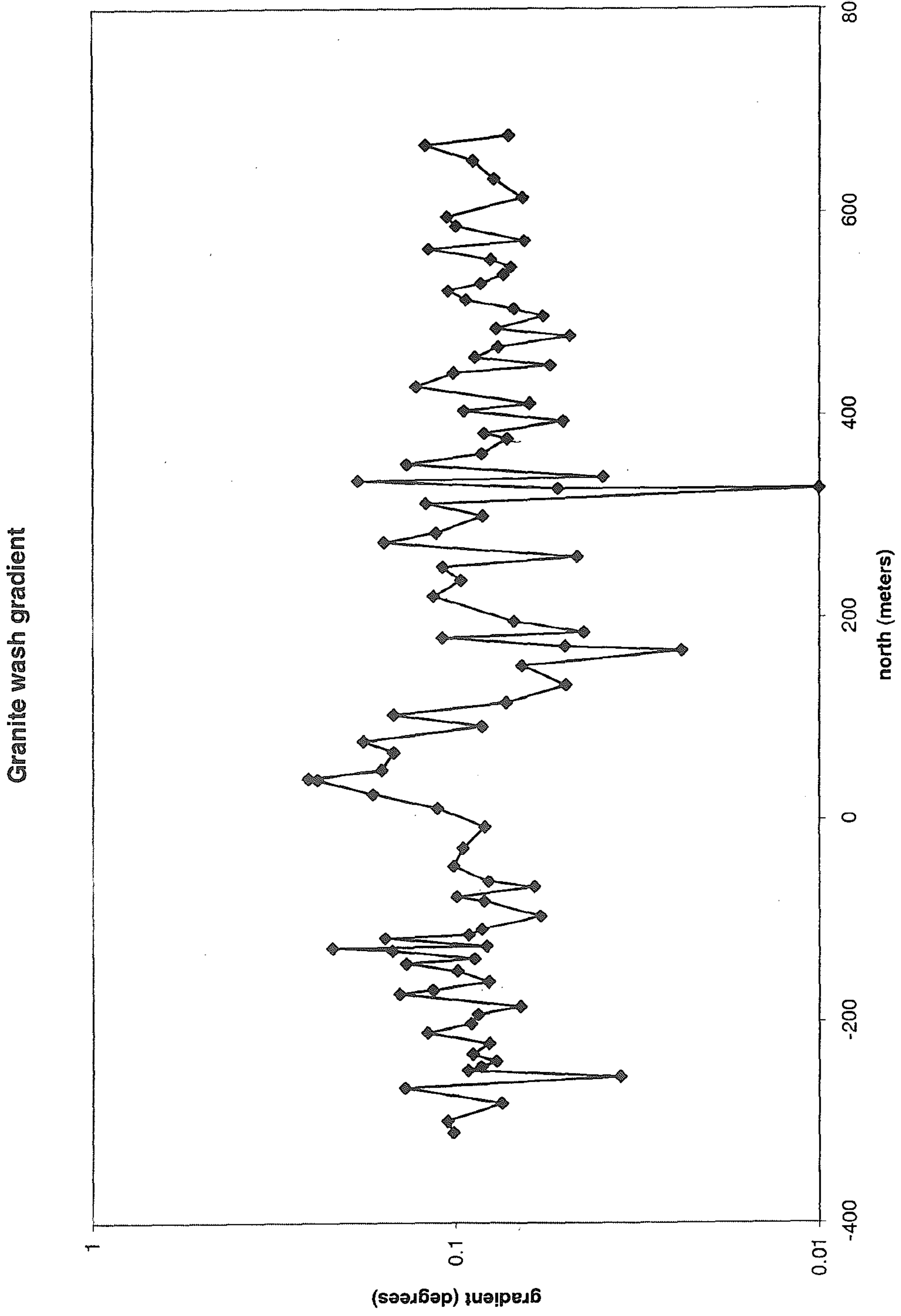



Granite wash XS A
15
14.5
14
13.5
13
12.5
12
meters
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
meters



Granite wash XS C


Granite wash XS D
-29
-29.5
-30
-30.5
-31
-31.5
-32
-32.5
-33
meters
-10
0
10
20
30
40
50
meters


Granite wash gradient
gradient (degrees)
1
0.1
0.01
north (meters)
-400
-200
0
200
400
600
800

Vita

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END

OF

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