The National Centre for Environmental Data and Surveillance

Validation of Statutory Sampling Sites Using Aerial Surveillance Case Study 4

Environment Agency

EA NCEDS

EXECUTIVE SUMMARY

An understanding of the spatial processes affecting sites for the collection of statutory samples is essential in interpreting water chemistry results. The ability of aerial surveillance to record information over a wide spatial area instantaneously recommends the use of this technique for investigation of spatial processes.

At any one pt in time though

This study has used aerial surveillance combined with intensive boat surveys to investigate variability around two sets of statutory sampling sites. The validity of the positions selected for these sites has been assessed.

The study has resulted in the following conclusions:

Hardly a new finding!

- Estuarine sampling sites are prone to a high degree of short term variability in water quality due to the interaction of tidal cycles, freshwater variability and effluent discharges; with tidal variability predominating in the examples studied.

- Tidal cycle variability can give rise to two basic sampling strategies; estimation of average concentration by taking large numbers of random samples, and trend analysis by comparing relatively small numbers of samples taken at the same tidal state. The end use of the monitoring data should determine which strategy is adopted. For example, the National (Marine) Monitoring Plan specifies sampling at High Water, whereas the Dangerous Substances Directive's need for reliable mean values implies that random sampling is more appropriate.

- Detailed investigation of spatial and temporal variability showed the Milford Haven and Tamar sampling locations to be well sited for their purposes. However, the Tamar NMP sites were selected by over-riding the program's own salinity criteria which are clearly inappropriate for this estuary.

But needed to cf with other estuaries.

- This study has shown airborne surveillance to be useful in determining the exact spatial location of a sample point to minimise short-term variation. It also has a high potential for visualising estuarine tidal cycles for modelling studies, thus contributing to a better understanding of estuarine dynamics and their effect on water quality.

The following recommendations are made for the use of these findings in marine monitoring:

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- NMP salinity based criteria for the selection of sampling sites should be revised in the light of the Tamar Estuary study.

- Airborne surveillance is useful to fix the exact sampling point for NMP sites away from areas of short-term variability, thus ensuring optimal representative samples.

- The use of airborne surveillance to visualise tidal variability is extremely valuable in developing estuarine water quality models, and should be treated as fundamental information in the development of such models.

Models aren't visual?

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1. INTRODUCTION

1.1 The Environment Agency has the responsibility to form an opinion on the state of pollution of the marine environment (Section 5, Environment Act, 1995) and in addition carries out statutory monitoring for compliance with various EC Directives, international and national commitments. These monitoring responsibilities address selection of sampling points in a variety of detail. Given the high probability of spatial and temporal variability in a sampling location, particularly in estuarine sites, the exact selection of sampling points within statutory constraints can have a significant influence on the monitoring results.

1.2 Results from the 1995 national coastal baseline survey indicated the importance of tidal state and seasonality in the collection of representative water quality samples. Many sampling sites showed the influence of estuarine inputs or coastal sediment flow features which resulted in high spatial and temporal variability which was both tidally and seasonally dependent. This would clearly effect the concentrations of naturally and anthropogenically derived determinands recorded in samples taken to test compliance with EC Directives, for example the Dangerous Substances Directive (76/464/EEC).

1.3 Sampling for EC Directive compliance has clearly defined sampling protocols. The National Marine Monitoring Plan states that sample sites should be placed in the main channel of the estuary in positions which reflect defined salinity bands. Sampling for the Dangerous Substances Directive should be carried out 100 m downstream of the point of discharge. Specific sampling points have in the past been determined based on local knowledge of water bodies within the estuary. This case study seeks to investigate whether aerial surveillance may provide further information on the applicability of these sites.

1.4 The ability of aerial surveillance to record information over a wide spatial area instantaneously recommends the use of this technique for investigation of spatial processes. An alternative technique is the production and application of a mathematical model of the study region which would simulate the spatial processes. The applicability of these two techniques will be investigated and conclusions drawn on which is the most suitable for the optimisation of statutory sampling sites.

2. OBJECTIVES

2.1 This case study will assess the value of aerial surveillance in further delineating the position of sampling sites for statutory measurements.

2.2 The use of aerial imagery to provide image animations for integration with numerical models will be assessed.

3. BACKGROUND

3.1 Statutory sampling sites for the measurement of water quality are at times in areas of high spatial and temporal variability. The sites investigated in this case study are within estuaries which are variable in space due to the interaction of riverine fresh water runoff and marine waters and in time due to the action of tides, in addition to seasonal and long term changes. Determination of the positions of sampling sites is to clearly defined criteria. An assessment of the variability around the sites will, however, determine how accurately spot sampling is monitoring water quality, and establish whether the criteria are being adhered to.

3.2 The criteria state that NMP sampling sites are positioned in the main channel of the estuary, with the three estuarine samples representing three key salinity bands at High Water neap tides, these being 0-10 psu, 10-20 psu and 20-30 psu. In most cases sites have been chosen by reference to local knowledge of the position of major water bodies, although spatial surveys have been carried out as part of the NMP on certain sites. Additional aspects such as access to sampling sites are taken into consideration when determining the exact location within the salinity band. Water samples for testing compliance with the Dangerous Substances Directive should be taken within the effluent plume 100 m downstream of the discharge point.

3.3 Aerial surveillance using both the CASI imaging spectrometer and thermal scanning systems has revealed the spatial and temporal variability of such regions, but the exact extent has not been established. Further analysis of aerial imagery will provide a potential solution for the investigation of such variability, allowing conclusions to be drawn on the suitability of sampling sites for the collection of representative samples. Estuaries are highly variable in suspended solids concentration due to the combined effects of freshwater river inputs and maritime influences. The CASI system records the reflected sunlight from the sea surface, the intensity of which is affected by the presence of suspended sediment within the water column. Thus CASI data provides an ideal means of assessing variability due to suspended solids. The interacting water bodies also result in high thermal variability, which may in part be measured using the digital thermal scanner. This system measures the skin surface temperature, however, with no estimation of the variation of temperature with depth.

3.4 Mathematical modelling also offers a clear potential for interpreting spatial processes, with the ability to simulate future conditions, with different scenarios representing different tidal states. Such models require boundary values and test data in order to validate the results. Remote sensing techniques produce a spatially dense data set which can be used both to establish boundary values and to validate the data. Within this case study the parallels between these two techniques will be investigated and possibilities for the integration of remote sensing measurements from both the CASI and the thermal system into mathematical models will be discussed.

4. DATA COLLECTION

4.1 Two geographical locations were selected for this case study. Milford Haven was selected to monitor variability around statutory sampling sites for the Dangerous Substances Directive (76/464/EEC). The Tamar Estuary provides a site to investigate variability around National (Marine) Monitoring Plan sampling sites. These two sites were chosen as estuaries having very differing characteristics. The Tamar would be expected to be highly variable with a number of riverine inputs along its length. The main channel of Milford Haven, in contrast, should represent a fairly homogeneous water mass.

4.2 Four key discharges are monitored for compliance with the Dangerous Substances Directive within the main body of Milford Haven. These are shown in Figure 1 and correspond to outfalls from three major oil refineries, Gulf, Elf and Texaco, and from Pembroke Power Station. The points shown on the map represent the effluent discharge point, with the surrounding circle delimiting the possible sampling location depending on tidal state.

4.3 Milford Haven was sampled on neap tides, on 23rd September 1996. Data collection on spring tides was prevented by poor weather conditions for aerial surveillance. The survey sampled for the full suite of determinands required under the Dangerous Substances Directive consisting of selected dissolved metals, tributyl-tin and triphenyl-tin. The times of data collection are tabulated in Table 4.1. In addition to the collection of water samples for laboratory analysis, the variability of the region was investigated using two techniques. Firstly, the variability in transmission, fluorescence, temperature and salinity was recorded using an underway towed body. Secondly, aerial imagery was collected using the CASI and digital thermal scanner to investigate the variability which this revealed in water colour and surface temperature respectively.

Sample Site	Grid Reference	Time of sample collection (GMT)					
Aircraft overflights		0750	0915	1115	1255	1515	1545
Gulf	9410004100	0708	0859	1109	1248	1454	1638
Power Station	9310003200	0726	0918	1125	1304	1508	1655
Texaco	9080004200	0745	0942	1148	1330	1530	1714
Elf	8860004700	0812	1002	1211	1350	1550	1736

Table 4.1 Sampling details for Milford Haven, 23rd September 1996

4.4 The Tamar Estuary is sampled as part of the NMP at three sites within the upper and middle reaches at Halton Quay, Warren Point and Hamoaze, as shown in Figure 2. The sites are designed to represent the 3 salinity bands, 0-10 psu, 10-20 psu and 20-30 psu, when sampled at High Water neap tides.

4.5 The three sites were sampled for the NMP determinand suite throughout a tidal cycle on both neap and spring tides on 7th and 14th September 1996. The times of data collection are tabulated in Table 4.2. Sampling between sites was undertaken with an underway towed body measuring temperature, salinity, fluorescence and transmission. The region was also overflown with CASI and thermal systems to allow an assessment of spatial variability to be carried out.

Sample Site	Grid Reference	Time of sample collection (GMT)					
7th September 1996							
Aircraft overflights		0718	0935	1135	1330	1540	1725
Hamoaze	SX442558	0715		1130		1441	
Warren Point	SX440605	0830	1050	1212	1405	1540	1735
Halton Quay	SX412655	0919		1307		1642	1808
14th September 1996							
Aircraft overflights		0745	0910	1100	1300	1500	1700
Hamoaze	SX442558	0739		1104	1308		
Warren Point	SX440605	0830	1031	1143	1344	1605	
Halton Quay	SX412655	0939			1444		

Table 4.2 Sample collection in the Tamar Estuary, 7th and 14th September 1996

5. DATA ANALYSIS

5.1 LABORATORY SAMPLES

5.1.1 Water samples were analysed for the appropriate determinand suite for each of the surveys using standard analysis techniques. All laboratory samples below the laboratory limit of detection were assumed to be 50% of the limit of detection concentration for further calculations. This assumption is consistent with the accepted practice for dealing with values below the limit of detection.

where ?

5.1.2 The mean concentration recorded at each site throughout the sampling day was calculated, in addition to the relative standard deviation to provide an indication of the variability. When the majority of samples from any one site recorded concentrations below the limit of detection, the mean was not calculated as this was not truly representative.

5.1.3 Each site was sampled on a maximum of six occasions. This means that interpretation of the mean and standard deviation should be cautious. However, the results will provide some indication of temporal variability at each site.

5.2 CONTINUOUS SAMPLING DATA

5.2.1 The continuous sampling salinity and temperature data were used to assess the variability over short spatial scales. Geographical buffers of varying size were calculated around the position at which the water sample for laboratory analysis was taken.

5.2.2 The mean and standard deviation of each parameter was calculated for each geographical buffer. The sample size was also noted to allow an indication of the robustness of the statistical relationships.

5.3 AERIAL IMAGERY

5.3.1 CASI imagery was radiometrically calibrated to spectral radiance units. An empirical correction was then applied to account for the enhanced brightening of the imagery towards the edges of the swath. This brightening results from the increased pathlength of the signal at the edge of the image caused by the wide field of view of the instrument. This empirical correction is similar to the Rayleigh correction step applied as part of a typical atmospheric correction.

5.3.2 The images were first order geometrically rectified using data from the on-board ground positioning system. Second order geo-rectification was carried out using a series of ground control points to provide an accurate fit with the Ordnance Survey Grid.

5.3.3 The digital thermal imagery was also geo-corrected. No calibration was applied to this thermal data, as the temperatures recorded are relative rather than absolute.

5.3.4 Geographical buffers were drawn around the position of sampling sites within both the CASI and thermal imagery at varying distances from the sample point. These buffers took the form of boxes of increasing dimension, with the central pixel representing the sample point. The mean and standard deviation of both the radiance and the temperature within these buffers were calculated to enable a discussion on the spatial variability and thus the extent to which samples are representative of surrounding waters. The results have been displayed for channels 6 and 13 of the CASI imagery, representing 625 and 750 nm. These wavelengths were the most commonly occurring wavelengths found in the development of a global algorithm for suspended solids (Environment Agency 1997). The values displayed are spectral radiance units scaled between 0 and 4095. The thermal variability is scaled between 0 and 255 representing a range of 0-16°C.

5.3.5 The data set collected in the Tamar Estuary on 14th September was of sufficient quality to produce image animations for integration and comparison with numerical models. Data collected from the Tamar on 7th September shows the presence of clouds and haze which meant that calibration of the data set for suspended solids was not possible. Data collected over Milford Haven was taken at low altitude beneath cloud and this again proved unsuitable for animation.

5.3.6 The CASI imagery was calibrated for suspended solids concentration using the hierarchical approach developed by the National Centre. This used the laboratory samples of suspended solids concentration to calibrate the continuous track transmissometer measurements. This calibrated continuous track data was then used to calibrate the imagery. Development of a global algorithm for suspended solids has proven difficult due to the differing morphologies encountered in UK coastal waters. However, the algorithm development showed that the ratio of two of the 72 channels was well correlated with suspended solids concentration in all cases. This channel ratio, modified for use with spatial data, was used in order to calibrate the CASI imagery of the Tamar.

5.3.7 In order to produce an animation sequence the calibrated imagery was interpolated to produce simulated image surfaces at fifteen minute intervals. This type of output is directly comparable with the output from two-dimensional surface numerical models of suspended solids concentration.

6. RESULTS

6.1 MILFORD HAVEN

6.1.1 Laboratory samples

6.1.1.1 The mean concentrations and the relative standard deviations of selected determinands at each site in Milford Haven are shown in Table 6.1. Determinands which showed the majority of concentrations below the laboratory limit of detection have not been included in the table.

What is n ?

	Gulf	Power Station	Texaco	Elf
Suspended solids @105°C (mg/l)	2.583 ±307%	1.75 ±45%	3.292 ±53%	2.917 ±74%
Chlorophyll-*a* (µg/l)	3.032 ±11%	3.548 ±16%	4.002 ±20%	5.052 ±12%
Salinity (psu)	33.903 ±0.5%	33.895 ±0.3%	33.643 ±0.8%	33.96 ±1%
Dissolved copper (µg/l)	1.145 ±100%	1.171 ±109%	0.342 ±59%	0.431 ±37%
Dissolved lead (µg/l)	0.734 ±179%	0.132 ±68%	0.158 ±99%	0.124 ±49%
Dissolved zinc (µg/l)	4 ±54%	4.95 ±46%	4.4 ±38%	6.017 ±61%
Dissolved iron (µg/l)	*	4.75 ±80%	24.25 ±57%	3.5 ±81%
Dissolved nickel (µg/l)	0.288 ±22%	0.241 ±21%	0.285 ±22%	0.534 ±84%

Some v large SD

Table 6.1 Summary of laboratory samples from Milford Haven

* It was not possible to calculate a mean due to the majority of samples having concentrations below the LOD.

6.1.1.2 The laboratory data collected throughout the tidal cycle shows a wide range in concentration, with relative standard deviations in excess of 100%. The dissolved copper and dissolved lead standard deviations for the Gulf refinery site are influenced by a single sample in each case which is much greater than the remaining five. At 0708 GMT dissolved copper reaches a maximum concentration of 3.7 μg/l Cu, with the concentration of dissolved lead recording a maximum of 3.67 μg/l Pb at 0859 GMT.

6.1.1.3 None of the sampling sites showed mean concentrations for dissolved metals in excess of the Environmental Quality Standard (EQS) values. Samples were also analysed for concentrations of tri-butyl tin and tri-phenyl tin, in addition to dissolved arsenic, chromium and iron. The concentrations of these determinands was mainly below the laboratory limit of detection, and as such a mean could not be calculated.

6.1.2 Continuous sampling data

6.1.2.1 Visual observations of the continuous sampling data for Milford Haven revealed the homogeneous nature of this section of the estuary. The salinity values indicated a high maritime influence, with concentrations in excess of 34 psu at all times. The temperature recorded were between 14.5°C and 15°C throughout the day. Figures 3 and 4 show typical temperature and salinity plots, collected at Low Water.

6.1.2.2 The temperature and salinity data were used to assess the short scale spatial variability using the method described in section 5. The geographical buffers selected in this case were circular, with a radius of 50m, 100m and 250m. The buffer of 100m represents the accuracy with which samples can be taken using portable Global Positioning Systems. The 50m buffer allows an assessment to be made of any improvement in how representative a sample may be achieved by more accurate positioning. The 250m buffer will indicate the increased error which will be incurred by using less accurate positioning systems.

6.1.2.3 The mean value of temperature and salinity within the three geographical buffers around each sampling point on each sampling occasion are shown in Table 6.2.

Site	Time (GMT)	Buffer Size	Temperature °C		Salinity psu	
			Mean	Standard Deviation	Mean	Standard Deviation
Gulf	07:08	50m 100m 250m	14.798 14.798 14.800	0.0050 0.0086 0.0071	34.640 34.758 34.643	0.0064 0.0604 0.0056
	08:59	50m 100m 250m	14.768 14.770 14.776	0.0136 0.0144 0.0166	34.632 34.633 34.637	0.0138 0.0137 0.0135
	11:09	50m 100m 250m	14.837 14.836 14.828	0.0039 0.0041 0.0176	34.646 34.647 34.662	0.0111 0.0119 0.0318
	12:48	50m 100m 250m	14.940 14.933 14.920	0.0530 0.0575 0.0594	34.738 34.743 34.758	0.0416 0.0486 0.0544
	14:54	50m 100m 250m	14.886 14.889 14.899	0.0301 0.0335 0.0388	34.674 34.675 34.676	0.0153 0.0199 0.0256
	16:38	50m 100m 250m	14.851 14.850 14.851	0.0025 0.0032 0.0042	34.794 34.793 34.790	0.0092 0.0105 0.0110

Table 6.2a Mean and standard deviations of temperature and salinity around laboratory sampling sites from continuous sampling data, Milford Haven, 23rd September 1996.

Site	Time (GMT)	Buffer Size	Temperature °C		Salinity psu	
			Mean	Standard Deviation	Mean	Standard Deviation
Power Station	07:26	50m	14.604	0.0026	34.708	0.0050
		100m	14.604	0.0022	34.708	0.0063
		250m	14.600	0.0126	34.708	0.0094
	09:18	50m	14.632	0.0120	34.691	0.0068
		100m	14.634	0.0109	34.689	0.0072
		250m	14.633	0.0105	34.689	0.0066
	11:25	50m	14.601	0.0604	34.750	0.0128
		100m	14.641	0.0829	34.755	0.0149
		250m	14.690	0.0999	34.760	0.0152
	13:04	50m	14.852	0.0261	34.781	0.0101
		100m	14.866	0.0311	34.783	0.0099
		250m	14.869	0.0298	34.785	0.0107
	15:08	50m	14.933	0.0295	34.796	0.0088
		100m	14.919	0.0219	34.801	0.0082
		250m	14.916	0.0234	34.806	0.0110
	16:55	50m	14.875	0.0026	34.823	0.0051
		100m	14.873	0.0045	34.824	0.0067
		250m	14.869	0.0086	34.832	0.0146
Texaco	07:45	50m	14.657	0.0085	34.769	0.0053
		100m	14.653	0.0116	34.768	0.0086
		250m	14.654	0.0213	34.770	0.0169
	09:42	50m	14.746	0.0138	34.775	0.0596
		100m	14.744	0.0138	34.778	0.0534
		250m	14.734	0.0421	34.775	0.0783
	11:48	50m	14.784	0.0100	34.829	0.0404
		100m	14.785	0.0128	34.826	0.0483
		250m	14.787	0.0168	34.821	0.0561
	13:30	50m	14.806	0.0181	34.925	0.0692
		100m	14.806	0.0170	34.927	0.0647
		250m	14.815	0.0276	34.915	0.0730
	15:30	50m	14.861	0.0305	34.848	0.1118
		100m	14.858	0.0298	34.854	0.1077
		250m	14.860	0.0281	34.856	0.1021
	17:14	50m	14.917	0.0192	34.762	0.0831
		100m	14.918	0.0198	34.758	0.0874
		250m	14.917	0.0193	34.767	0.0853
Elf	08:12	50m	14.767	0.0023	34.820	0.0154
		100m	14.767	0.0024	34.819	0.0147
		250m	14.768	0.0036	34.822	0.0180
	10:02	50m	14.803	0.0299	34.824	0.0350
		100m	14.803	0.0275	34.825	0.0321
		250m	14.802	0.0250	34.823	0.0307
	12:11	50m	14.827	0.0053	35.053	0.0057
		100m	14.827	0.0054	35.053	0.0058
		250m	14.829	0.0069	35.053	0.0064
	13:50	50m	14.878	0.0043	35.059	0.0170
		100m	14.877	0.0044	35.060	0.0164
		250m	14.877	0.0042	35.063	0.0152
	15:50	50m	14.876	0.0047	35.072	0.0112
		100m	14.877	0.0054	35.074	0.0109
		250m	14.878	0.0057	35.074	0.0103
	17:36	50m	14.838	0.0064	34.973	0.0126
		100m	14.838	0.0070	34.970	0.0189
		250m	14.837	0.0070	34.970	0.0185

Table 6.2b **Mean and standard deviations of temperature and salinity around laboratory sampling sites from continuous sampling data, Milford Haven, 23rd September 1996.**

6.1.2.4 Both the temperature and the salinity showed low variability with standard deviations less than 1% in both cases at all times. The manufacturers calibration accuracy of the underway salinity sensor is ±0.01 psu, which is greater than the standard deviation observed in the above data, showing that the variation observed is within the accuracy of the instrument. The manufacturer's calibration accuracy of the temperature sensor is ±0.005 °C. The standard deviation exceeds this in the majority of the above data, indicating that further variability is present than that due simply to instrument calibration. However, the small magnitude of the variation indicates that variation is caused by turbulent flow through the monitor during towing. The data therefore support the assumption that the region is homogeneous.

6.1.3 Aerial imagery

6.1.3.1 The degree to which each sampling point is spatially representative of surrounding water was measured in the image data using the methods described in section 5.3.4. Differing buffer sizes were used depending on the presence of physical barriers within the imagery, for example jetties or small boats which would result in inaccurate mean and standard deviation calculations. The buffer size is also dependent on image resolution, which varies between 2m and 10m.

6.1.3.2 The results of this procedure for data from Milford Haven are included as Appendix I. These numerical data are difficult to interpret and have therefore been displayed graphically in figures 5 to 18. The graphs show the standard deviation relative to the mean radiance or temperature value plotted against the buffer size in metres. Any changes in water body which would affect the collection of representative water samples would result in a distinct change in the standard deviation.

6.1.3.3 Each site was overflown more than once on each tidal state due to the necessity to collect data beneath clouds. The flight lines have therefore been grouped into five sets corresponding to the five different tidal states measured.

6.1.3.4 Data from the Elf refinery have been plotted on figures 5 to 7. The majority of images record only a small increase in the standard deviation as the buffer size is increased. Two exceptions, shown as image 2567 and image 2588, show are greater increase in standard deviation. The changes seen are both caused by the presence of a discharge within the water which is affecting the water colour.

6.1.3.5 Data from the Pembroke power station sampling site is shown in figures 8 and 9. On the majority of sampling occasions there is a slight increase in standard deviation as the buffer size is increased. Again, two images record a steeper increase, which is due by the variation in water colour signal caused by the inflow of water from a small creek to the west of the power station outfall.

6.1.3.6 The sampling site for the Texaco oil refinery is located directly beneath the jetty structure. The buffers have therefore been drawn both to the north and south of the jetty, although investigation of the graphs (figures 10 to 15) shows that each pair of buffers gives very similar results. Most of the images show a gradual increase in standard deviation with no apparent changes in water body within the data.

6.1.3.7 The data from the Gulf sampling site (figures 16 to 18) shows similar results to the other three sites, with only a gradual increase in standard deviation with increasing buffer size. One site shows a particular feature which is caused by a plume of smoke within the data. This increases the standard deviation over a short scale, but the effect is smoothed when more pixels are introduced into the mean calculation.

6.1.3.8 The low variability within the imagery is consistent with that found in the continuous sampling data, which reflects the fairly homogeneous nature of this section of Milford Haven. The major influence on the CASI imagery is the presence of shallow water close to the shoreline, which has a more dominant effect than changes in suspended solids concentration. The implications of this for collection of samples for the Dangerous Substance Directive will be discussed in section 7.

6.2 THE TAMAR ESTUARY

6.2.1 Laboratory sampling data

6.2.1.1 The mean and standard deviation for each determinand at each sampling point are detailed in the following tables (Tables 6.3 - 6.5). This allows an estimation of the applicability of spot sampling for the measurement of water quality to be made as described in section 5. The statistical robustness of the results is low due to the small number of samples, but basic conclusions may be drawn on the data.

How many ?

Hamoaze	07/09/96		14/09/96	
	Mean	**%STD**	**Mean**	**%STD**
Suspended solids @105°C (mg/l)	1.875	71	6.187	88
Chlorophyll-*a* (µg/l)	6.235	25	3.337	45
Total Oxidised Nitrogen (µg/l)	118.5	17	70.250	34
Ammoniacal Nitrogen (µg/l)	35	15	48.250	13
Silicate (µg/l)	180.548	16	140.902	13
Orthophosphate (µg/l)	23	13	22.250	28
Nitrite (µg/l)	7.1	13	4.800	26
Dissolved copper (µg/l)	2.163	38	1.355	37
Dissolved nickel (µg/l)	0.790	10	0.716	23
Dissolved zinc (µg/l)	7.375	11	10.225	58
Dissolved lead (µg/l)	0.225	24	0.266	43

Table 6.3 **Summary of mean and relative standard deviation for laboratory analysis of water samples from Hamoaze, 7th and 14th September 1996**

Warren Point	07/09/96		14/09/96	
	Mean	%STD	Mean	%STD
Suspended solids @105°C (mg/l)	2.958	46	14.4	37
Chlorophyll-*a* (µg/l)	7.645	40	8.204	55
Total Oxidised Nitrogen (µg/l)	257.333	43	182.2	55
Ammoniacal Nitrogen (µg/l)	68	70	53.2	9
Silicate (µg/l)	508.962	57	321.45	54
Orthophosphate (µg/l)	29	26	36.6	20
Nitrite (µg/l)	12.383	25	8.04	25
Dissolved copper (µg/l)	2.212	6	1.702	17
Dissolved nickel (µg/l)	1.009	13	1.042	35
Dissolved zinc (µg/l)	8.467	15	6.62	20
Dissolved lead (µg/l)	0.188	35	0.197	13

Table 6.4 **Summary of mean and relative standard deviation for laboratory analysis of water samples from Warren Point, 7th and 14th September 1996**

Halton Quay	07/09/96		14/09/96	
	Mean	%STD	Mean	%STD
Suspended solids @105°C (mg/l)	12.667	48	120.5	87
Chlorophyll-*a* (µg/l)	26.493	27	21.63	38
Total Oxidised Nitrogen (µg/l)	795	19	1135.5	40
Ammoniacal Nitrogen (µg/l)	57	34	129.5	57
Silicate (µg/l)	1536.327	43	1541.888	30
Orthophosphate (µg/l)	41	20	46	2
Nitrite (µg/l)	31	15	24.75	38
Dissolved copper (µg/l)	2.913	37	2.875	3
Dissolved nickel (µg/l)	1.967	9	2.745	10
Dissolved zinc (µg/l)	12.967	21	13.5	1
Dissolved lead (µg/l)	0.192	2	0.2445	8

Table 6.5 **Summary of mean and relative standard deviation for laboratory analysis of water samples from Halton Quay, 7th and 14th September 1996**

6.2.1.2 Many of the measured determinands show varying concentrations during the day reflected in the high standard deviations. This indicates the importance of tidal state in taking representative water samples. The data collected on spring tides are generally more variable. However, NMP sampling protocol states that samples should be taken on neap tides which means that this is currently accounted for.

6.2.1.3 At all sites the mean dissolved metals concentrations are below the Environmental Quality Standard for each determinand. The concentrations are similar between sites, with no apparent geographical trend noted. For example greater metals concentrations are not found in the upper reaches of the estuary. This reflects the importance of resuspension of metals from bottom sediments in this estuary. Of particular note are the concentrations of dissolved arsenic which were found to be mainly below the laboratory limit of detection. Other surveys, including the NMP, have recorded elevated arsenic concentrations due to previous mining activities.

6.2.1.4 The nutrient data, however, show a clear geographical trend, with highest nutrient concentrations recorded at Halton Quay in the Upper Estuary at all times. This suggests that the main source of nutrients to the Tamar Estuary is from the River Tamar, with other tributaries not substantially increasing the nutrient loading in the middle and lower reaches of the estuary.

Depends on estuary processes too.

6.2.1.5 The nutrient concentrations measured at the lower and middle estuarine sites were greater on neap tides than on springs. This is probably due to the more effective flushing of nutrients out of the estuary on spring tides and the increased influence of marine waters. The upper site shows similar results between the two surveys, again indicating a lower marine influence, with the major determining factor being the riverine input.

6.2.2 Continuous sampling data

6.2.2.1 The continuous sampling data showed the expected spatial variation with clear fresh water characteristics at the upper end of the estuary and varying degrees of marine influence. The two surveys were carried out directly upon spring and neap tides. The data therefore showed highly differing characteristics between the two surveys.

6.2.2.2 The salinity range throughout 7th September was 15-35 psu, with most samples being in excess of 20 psu. The increasing influence of marine waters is clearly shown towards High Water, with salinities of 30-35 psu extending to north of Cargreen.

6.2.2.3 The salinity ranges recorded on both spring and neap tides showed that some of the sites were not within the salinity bands stated in the NMP criteria. These salinity bands are valid only at High Water neap tides, at which time the upper sampling site (Halton Quay) was not sampled. The middle site at Warren Point which should have a salinity of between 10 and 20 psu recorded salinities in excess of 30 psu one hour before and after High Water, although sampling was not carried out closer to High Water. The lower site at Hamoaze recorded a salinity above 30 psu at these times, even though the point should be representative of 20-30 psu. These discrepancies may be due to low river flow at the end of the summer, but clearly show that the criteria may not always adhered to. Figures 19 and 20 show the salinity measured around High Water on 7th September.

6.2.2.4 The temperature range extends from 15.5°C to 19°C during 7th September with higher temperatures recorded at the upper end of the estuary. Marine waters, considered as having a temperature below 16.5°C were seen to extend upstream as far as Warren Point at High Water, with warmer temperatures extending to the Hamoaze site at Low Water. On 14th September, the average temperatures recorded are lower.

6.2.2.5 This general temperature decrease of approximately 3°C between the two surveys may be due to meterological effects or may be explained by a difference in hydrodynamics between neap and spring tidal conditions. On spring tides the estuary would experience more efficient flushing, which means that the water is held within the estuary for a shorter time period allowing less solar warming. This is verified by the stable temperatures recorded at the lower end of the estuary, around Hamoaze, which would be fully flushed on both spring and neap tides.

6.2.2.6 The transmission results show that the waters are generally more turbid when sampled in spring tide conditions, with typical transmission below 20% for much of the estuary. This has a dual explanation. Firstly, tidal currents will be stronger, thus increasing the mixing and stirring of bottom sediments into the water column. Secondly, the tidal range is much greater, meaning that measurements are often recorded in very shallow water.

6.2.2.7 Two geographical buffers were used to investigate the variability in temperature and salinity on short spatial scales. The small number of underway sampling points within a 50m geographical buffer made calculation of means and standard deviations unviable. Two circular buffers were thus selected having radii of 100m and 250m from the sample point. The 100m buffer represents the accuracy with which samples may be positioned using a GPS system. The 250m buffer allows an assessment to be made of the inaccuracies introduced by less accurate positioning techniques.

Table 6.6: Spatial variability using continuous sampling data Tamar Estuary - 7th September 1996

Site	Time (GMT)	Buffer Size	Temperature °C		Salinity psu	
			Mean	Standard Deviation	Mean	Standard Deviation
Hamoaze	11:30	100	16.671	0.0457	33.228	0.2763
		250	16.668	0.0585	33.150	0.3207
	14:41	100	16.130	0.1776	33.996	0.2522
		250	16.186	0.2487	33.071	0.3417
	18:08	100	16.618	0.2090	33.251	0.3077
		250	16.679	0.2465	33.163	0.3635
Warren Point	08:30	100	16.746	0.0780	32.694	0.4374
		250	16.791	0.1123	32.290	0.8267
	10:50	100	16.844	0.0377	32.397	0.1527
		250	16.833	0.0714	32.487	0.1331
	12:12	100	16.392	0.2638	33.419	0.7089
		250	16.551	0.4079	32.978	1.1191
	14:05	100	16.434	0.2308	33.481	0.4657
		250	16.570	0.3504	33.223	0.6660
	15:40	100	16.918	0.4880	32.828	0.8116
		250	17.108	0.5347	32.515	0.8855
	17:35	100	16.878	0.5129	32.958	0.8629
		250	17.111	0.6703	32.504	1.2309
Halton Quay	09:19	100	17.365	0.0478	26.150	0.4741
		250	17.328	0.0935	25.601	1.4172
	13:07	100	17.307	0.1342	28.812	1.2650
		250	17.324	0.1490	28.555	1.4557
	16:42	100	17.548	0.3281	26.591	2.6810
		250	17.698	0.4067	25.485	3.1457

Table 6.7: Spatial variability using continuous sampling data - 14th September 1996

Site	Time (GMT)	Buffer Size	Temperature °C		Salinity psu	
			Mean	Standard Deviation	Mean	Standard Deviation
Hamoaze	07:39	100	15.558	0.0097	34.524	0.0306
		250	15.546	0.0160	34.514	0.0493
	11:04	100	15.587	0.0049	33.566	0.0128
		250	15.595	0.0196	33.561	0.0158
	13:08	100	15.682	0.0681	33.423	0.0656
		250	15.717	0.1103	33.390	0.1054
Warren Point	08:30	100	15.455	0.0346	33.472	0.0722
		250	15.466	0.0752	33.462	0.1265
	10:31	100	15.615	0.0361	32.286	0.1457
		250	15.633	0.0510	32.341	0.1840
	11:43	100	15.801	0.0682	30.525	0.2817
		250	15.852	0.1086	30.420	0.3054
	13:44	100	16.320	0.1530	29.708	0.2932
		250	16.323	0.1394	29.570	0.3827
	16:05	100	15.720	0.0112	33.648	0.0388
		250	15.737	0.0355	33.622	0.0591
Halton Quay	09:39	100	16.003	0.0395	22.465	0.4630
		250	16.017	0.0541	22.397	0.4850
	14:44	100	16.665	0.0024	8.675	0.0552
		250	16.664	0.0047	8.762	0.0999

6.2.2.8 The thermal variability within both the 100m buffer and the 250m buffer is low for both surveys, although in most cases it exceeds the manufacturer's calibration accuracy of 0.005 °C. Typical standard deviations are below 3% for the 100m buffer and below 4% for the 250m buffer on 7th September when variability was greatest, decreasing to below 1% for both buffers on 14th September. The increased buffer size does not result in a large increase in the variation, signifying that the position of the sampling location may be varied to within 250m of the exact site without loss of accuracy in sample value.

6.2.2.9 The variation in salinity is generally low, although again it is higher than may be explained simply by the manufacturer's calibration accuracy of 0.01 psu. Lower variability is again found on 14th September. The Halton Quay sampling site at

16:42 GMT on 7th September shows a high variability of ±12%. The increase in buffer size does not alter the accuracy, thus showing that no decrease in sample accuracy would be expected by sampling 250m from the sampling site position. the variability at this site is also shown in the aerial imagery (see section 6.2.3) and may be explained by the interaction of riverine and estuarine waters.

6.2.3 Aerial imagery

6.2.3.1 The image data have been assessed to establish spatial variability as described in section 5. The results of the application of this procedure to data from the Tamar Estuary on both survey days in shown in Appendix II. This information is difficult to assimilate and has thus been expressed graphically in figures 21 to 31. The graphs show the relative or percentage standard deviation as the buffer size is increased. When different image resolutions are found the graphs have been plotted separately.

6.2.3.2 The variation in the standard deviation moving away from the position of the sample site may be used to assess variability. A site showing low variability will show little increase in standard deviation with buffer size. If a water body were crossed at some distance from the site this would be immediately apparent from the graph as a distinct increase in standard deviation.

6.2.3.3 Figures 21 and 22 show the data for the Hamoaze site on 7th September. The first graph, showing those images sampled at 2m resolution, shows low variability with an increase of approximately 1% over the first 170m. Image 2412 shows a distinct increase in variability in CASI radiance after this point which may signify a change in water body being measured. The majority of images shown on the second graph show similarly low variability. Image 2408 shows high variability in CASI radiance from approximately 70m. This image was collected one hour before High Water, when marine influences would be greatest.

6.2.3.4 This site shows similarly low variability for most images collected on 14th September (figures 23 and 24). However, image 2478 shows a distinct increase in variability 130m from the site. This would signify the presence of a different water body within the sampling buffer. Image 2458 shows an increase in variability after only 90m which again may signify the presence of two water bodies. This site is more variable on 14th September than on 7th September which is due to the spring/neap difference also noted in the continuous track transmission data. On spring tides there is increased mixing due to stronger tidal currents which would result in more variable suspended solids within the water column.

6.2.3.5 Figures 25 and 26 show the variability around the Warren Point site on 7th September. The first graph showing data collected at 2m resolution shows a slight increase in variability with distance for most of the images. Image 2415 shows a distinct change in CASI radiance at 200m, which probably reflects the presence of a different water body having different suspended solids loading. This change may mark the presence of the front between marine and fresh water, which might occur at this mid point in the estuary between High and Low Water. The imagery does not, however, clearly show a frontal feature at this point. The data collected at 10m resolution shows low variability for the majority of the images, with an exception for image 2405. This shows high variability in CASI radiance signifying that samples taken away from the sampling point may not be truly representative at this time. The low variability encountered in each of the other images, however, suggests that at most tidal states this site is representative of surrounding waters.

6.2.3.6 The Warren Point site also shows generally low variability on 14th September. Figures 27 and 28 show the increase in relative standard deviation for all flight lines. Two figures are included for ease of interpretation. The majority of sites show a gradual increase in standard deviation away from the sampling site. Image 2456, however, shows the presence of a different water body by a distinct change in standard deviation approximately 70m from the sampling site. Additionally the thermal data from image 2455 shows high variability which is not reflected in the CASI data. The data from 14th September is again more variable than that from 7th September.

6.2.3.7 The Halton Quay site is more variable than the two lower sites on both 7th and 14th September. Figures 29 and 30 shows the increase in variability with buffer size for this site which was only sampled at 10m resolution on the 7th September. All images show high variability from as little as 70m from the sampling site.

6.2.2.8 The Halton Quay data from 14th September is shown in figure 31. All images again recorded high variability with samples taken at the sampling point being only representative of waters less than 90m distant. This variability may be explained by the position of this sampling site close to riverine sources. The interactions of these with estuarine waters will lead to higher variability in suspended solids loading which will be the most dominant effect on the CASI signal. The thermal data also records higher variability here than at the other sites, again due to the interaction of warm riverine waters with cooler estuarine waters.

6.2.3.9 Thus on both 7th September and 14th September the lower two estuarine sites show low variability in image data collected around the sampling site. This implies that data collection at this point is truly representative of waters within a radius of approximately 250m of the sampling site. The Warren Point sampling site shows indications of two different water bodies within the data collected from a number of images, which may correlate with the front between riverine and estuarine waters. The Halton Quay site, however is highly variable over a short distance of approximately 70m. This means that samples taken from this site are not representative of a wide area of water. However, the variability is due to the interaction of riverine and estuarine sources and it is therefore unlikely that any sampling site within the correct salinity band would better reflect a wide area.

Image animation

6.2.3.10 Figure 32(a-c) show snapshots from the animation of CASI images for suspended solids concentration for 14th September 1996. The images within the plates which display an aircraft in the top right corner are true images, with simulated image surfaces shown at fifteen minute intervals between the overflights.

6.2.3.11 The imagery shows the decrease in water level towards low water with mudbanks at the edge of the estuary becoming exposed. The algorithm does not fully distinguish between shallow water and high suspended solids concentrations. This is particularly evident as the imagery was collected on spring tides.

6.2.3.12 A clear tidal variation in suspended solids concentration and variability is noted. At 07:45 GMT, the image collected nearest to High Water at 06:31 GMT, the estuary displays similar suspended solids concentrations throughout its length. At Low Water the estuary shows the differing influences of riverine runoff and marine waters, with higher concentrations upstream close to riverine sources and lower concentrations downstream close to the open sea. As the animation moves towards High Water once more at 18:44 GMT the estuary becomes more homogeneous.

6.2.3.13 Thus, although the suspended solids imagery does not show the presence of a clear tidal front which might be expected to be marked by a boundary in suspended solids concentration, the variation in suspended solids concentration is immediately evident. Figure 32(a-c) is simply snapshots from the animation, which may be run interactively on a computer with the correct time steps to envisage the variability more clearly.

6.2.3.14 It was intended that the results of the suspended solids animation would be integrated into numerical models and the synergies of the two techniques investigated. Numerical models have been derived for the Tamar Estuary by Plymouth Marine Laboratory on behalf of the Environment Agency (Murdoch, *Pers. Comm.*). It was not possible, however, within the timescales of this project to initiate a collaborative study to investigate these. The use of such image animations for modelling is immediately apparent from figures 32(a-c). The image surfaces could provide a direct comparison with model output, thus enabling model validation against measured parameters. Equally this image data could be used to provide input data when establishing models for previously unmodelled regions, or in deriving more spatially representative models.

6.2.3.15 The image animation shows the distinct change in suspended solids loading along the length of the estuary. The laboratory samples for suspended solids reflect this with higher concentrations at the upper end of the estuary close to riverine sources. The nutrients data also indicate change. However, the concentrations of dissolved metals recorded to not adequately reflect the geographical variation, which indicates the problem with relying ion spot samples to investigate such dynamic environments.

7. DISCUSSION

7.1 Data collected from laboratory analysis of water samples collected throughout a tidal cycle, continuous sampling using a towed underway body and aerial remote sensing have been used to assess both the spatial and temporal variability of the two water bodies studied. This information can be used to determine the level to which laboratory samples taken at designated sampling sites are representative of the surrounding water bodies at varying tidal states. In addition the numeric values allow a determination of the level to which sampling sites fulfil established criteria.

7.2 The survey of the Tamar Estuary on neap tides showed that neither the Hamoaze nor the Warren Point sampling sites were situated in the stated salinity bands. This may be due to low flow conditions at this time of the year, but clearly illustrates that the sites are not correctly located according to the established criteria. Figures 19 and 20 shows continuous salinity data collected approximately 1 hour before and one hour after High Water on 7th September (neap tides). These show that no part of the measured water body recorded a salinity below 20 psu, although as stated earlier sampling was not carried out as far upstream as the sampling site. This means that the NMP criteria for both the 0-10 psu and the 10-20 psu sampling sites can not be fulfilled by altering the position of the sampling site within the estuary. The lower site at Hamoaze is located in waters having too high salinities which are more representative of the NMP intermediate site. In order for this site to be within the correct salinity band it would need to be located upstream towards Weir Quay. The NMP instructions are therefore not sufficiently flexible to define sampling sites within the Tamar.

7.3 The laboratory samples showed the level to which sampling sites were representative of data collected at other points over a tidal cycle. The major source of variability in these estuarine regions over the short timescale sampled would be tidal. The National Marine Monitoring Plan states that samples should be taken at High Water, which will facilitate trend identification. Sampling for the Dangerous Substances Directive states that samples should be taken within the discharge plume, 100m downstream. This should ensure that the plume effected water body is being sampled randomly, irrespective of tidal variability which, although inhibiting trend identification, leads to more realistic mean values.

7.4 The level to which the sampling sites represent surrounding waters was assessed using both the continuous temperature and salinity data and the aerial imagery. Results for Milford Haven showed very low variability for salinity and temperature, with the salinity variation being within the manufacturer's calibration accuracy suggesting a homogeneous water body. Results for the Tamar Estuary showed slightly higher variability. The results showed that there was no decrease in accuracy between the 100m and 250m geographical buffer for the Hamoaze and Warren Point sites, although the Halton Quay site showed higher variability, consistent with inputs of riverine water at this site.

7.5 Investigation of the image data for the Tamar Estuary showed low variability in both CASI radiance and temperature for the two sites lower in the estuary, Hamoaze and Warren Point. The Warren Point sampling site showed the possible presence of two different water bodies at some tidal states. Movement of this site away from the inputs of the Rivers Tavy and Tamar and the two further creeks to the east and west may remove this effect. However, the different water bodies may simply mark the boundary between riverine and estuarine waters which would occur at some stage in the tidal cycle at any point in the estuary. The Halton Quay site showed high variability in image parameters over a short spatial scale, correlating well with the results of the continuous data. The explanation for the high variability seen is the position of this site in an area of interaction between riverine and estuarine sources. The movement of the site further upstream, thus positioning it in the correct salinity band may remove some of the variability. Further data collection would be required to establish the optimum position for the sampling site.

7.6 The image animation shows the high potential of aerial surveillance imagery to provide temporal descriptions of highly dynamic systems such as estuaries. The animation sequence shows the concentration of suspended solids throughout the tidal cycle, thus describing the movement of water bodies within the estuary. This information would provide useful input to numerical models, either as validation data for existing models or in the model initialisation process. The integration of such data sets will be explored further.

7.7 The above analysis allows a discussion on the position of sampling sites in the two estuaries surveyed. The two estuaries, as expected, showed highly differing characteristics with the Tamar Estuary shown to be less homogeneous. Higher variability would be expected if the entire length of Milford Haven had been investigated, for the examination of NMP sites. Thus the results should be considered in relation to the sampling sites against which they were sampled.

7.8 The definition of sampling for the Dangerous Substances Directive which states that samples should be collected within 100m of the discharge point allows the collection of representative samples. However, the laboratory samples recorded high standard deviations indicating that collection of samples on the same tidal state would allow more accurate comparisons between samples. Essentially, the collection of point samples for investigation of compliance with the Dangerous Substance Directive represents a potentially highly accurate means of sampling for this diverse set of determinands.

7.9 The results from the Tamar Estuary showed the difficulty in positioning sampling sites for monitoring the environmental quality of estuaries, such as the NMP, in highly dynamic estuaries. The upper estuarine site at Halton Quay is in a region of high variability due to the interaction of riverine and estuarine waters. Accurate positioning of this site within the 0-10 psu salinity band may decrease the variability encountered. The middle and lower sites show less variability and as such are more truly representative. It is probable that this scenario would be repeated in other estuaries, with the upper site showing higher variability. — a natural feature of estuaries if you think about it.

Is it ever likely to be in this range? Wrong sort of estuary perhaps

7.10 The collection of representative water samples from estuarine environments has been shown from this case study to be impeded by the high temporal and spatial variability in these regions due to the actions of tides, in addition to longer scale processes. Alternative sampling techniques may therefore be required in order to collect fully representative samples. The use of continuous monitoring buoys would allow collection of samples around a tidal cycle enabling an average concentration of some determinands to be accurately determined rather than inferred from a single sample. To assess spatial distribution of certain parameters continuous sampling techniques could be used. These have already been used successfully as part of the National Coastal Baseline Survey to measure for physical parameters and nutrient concentrations. However, there as yet no realistic methods for the continuous analysis of metals, meaning that collection of water samples for laboratory analysis remains necessary.

8. CONCLUSIONS

- This study has verified that estuarine sampling sites are prone to a high degree of short term variability in water quality due to the interaction of tidal cycles, freshwater variability and effluent discharges; with tidal variability predominating in the examples studied.

- Tidal cycle variability can give rise to two basic sampling strategies; estimation of average concentration by taking large numbers of random samples, and trend analysis by comparing relatively small numbers of samples taken at the same tidal state. The end use of the monitoring data should determine which strategy is adopted. For example, the National (Marine) Monitoring Plan specifies sampling at High Water, whereas the Dangerous Substances Directive's need for reliable mean values implies that random sampling is more appropriate.

- Detailed investigation of spatial and temporal variability showed the Milford Haven and Tamar sampling sites to be well sited for their purposes. However, the Tamar NMP sites were selected over-riding the program's own salinity criteria which are clearly inappropriate for this estuary.

- This study has shown airborne surveillance to be useful in determining the exact spatial location of a sample point to minimise short-term variation. It also has a high potential for visualising estuarine tidal cycles for modelling studies, thus contributing to a better understanding of estuarine dynamics and their effect on water quality.

9. RECOMMENDATIONS

- NMP salinity based criteria for the selection of sampling sites should be revised in the light of the Tamar Estuary study.

- Airborne surveillance is useful to fix the exact sampling point for NMP sites away from areas of short-term variability, thus enabling the collection of representative samples.

- The use of airborne surveillance to visualise tidal variability is extremely valuable in developing estuarine water quality models, and should be treated as fundamental information in the development of such models.

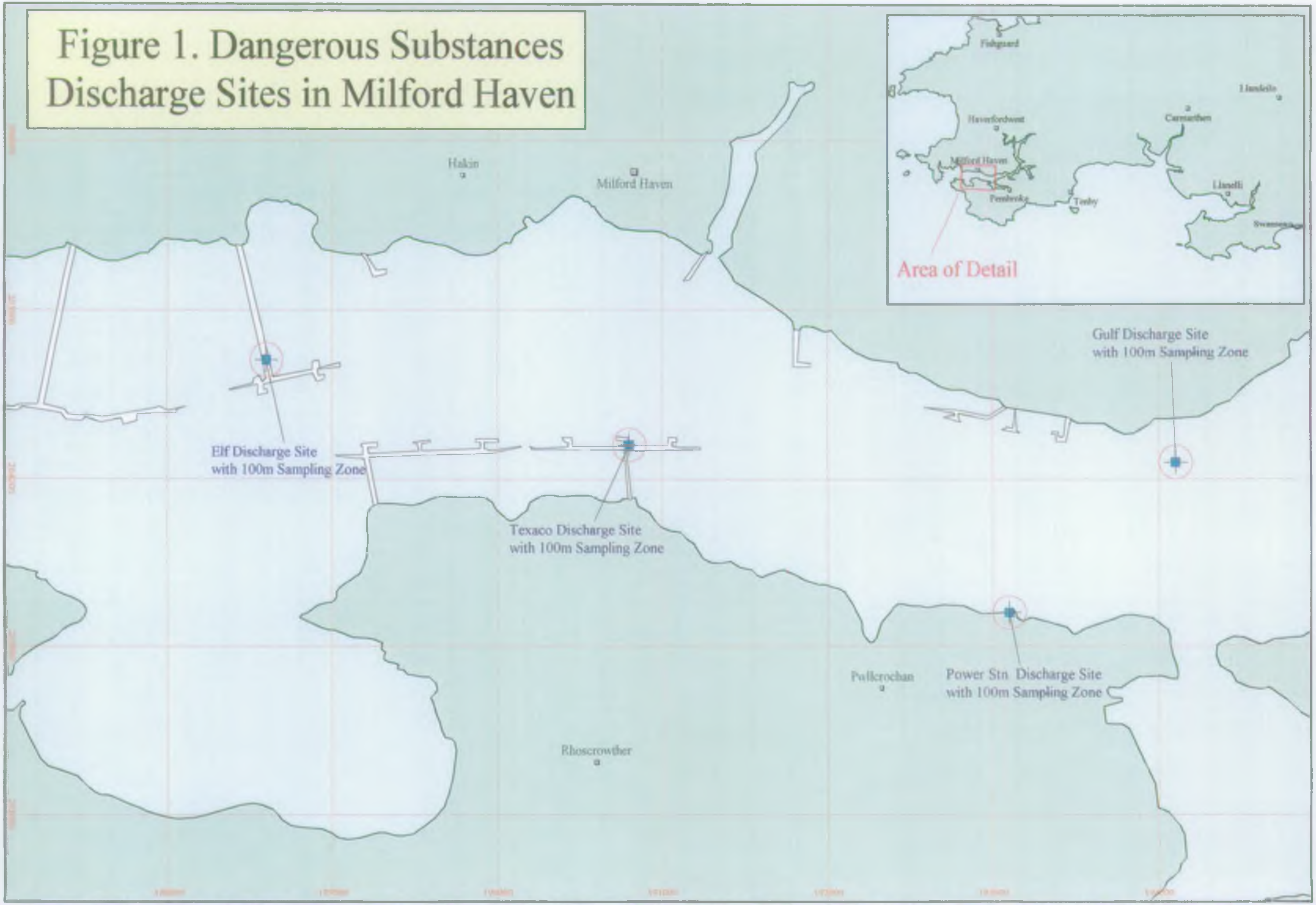

Figure 1. Dangerous Substances Discharge Sites in Milford Haven

Figure 2. NMP Sampling Sites in The Tamar Estuary


Figure 3. Milford Haven Continuous Salinity Data, 23-Sep-96, Line 3.
Honeyborough
Hakin
Milford Haven
Waterston
09:53:38
09:58:34
09:49:32
09:34:02
Gulf Discharge Site
Elf Discharge Site
Texaco Discharge Site
09:28:30
09:25:00
09:08:08
08:59:18
09:19:58
Pwllcrochan
Power Stn Discharge Site
Rhoscrowther
Salinity
30 to 35 psu
25 to 30 psu
20 to 25 psu
15 to 20 psu


Figure 4. Milford Haven Continuous Temperature Data, 23-Sep-96, Line 3.
Honeyborough
Hakin
Milford Haven
Waterston
09:53:38
09:38:34
09:49:32
09:34:02
Gulf Discharge Site
Elf Discharge Site
Texaco Discharge Site
09:28:30
09:25:00
09:08:08
08:59:18
09:19:58
Pwllcrochan
Power Stn. Discharge Site
Rhoscrowther
Temperature
15 to 15.25°C
14.75 to 15°C
14.5 to 14.75°C
14.25 to 14.5°C
14 to 14.25°C
invalid data

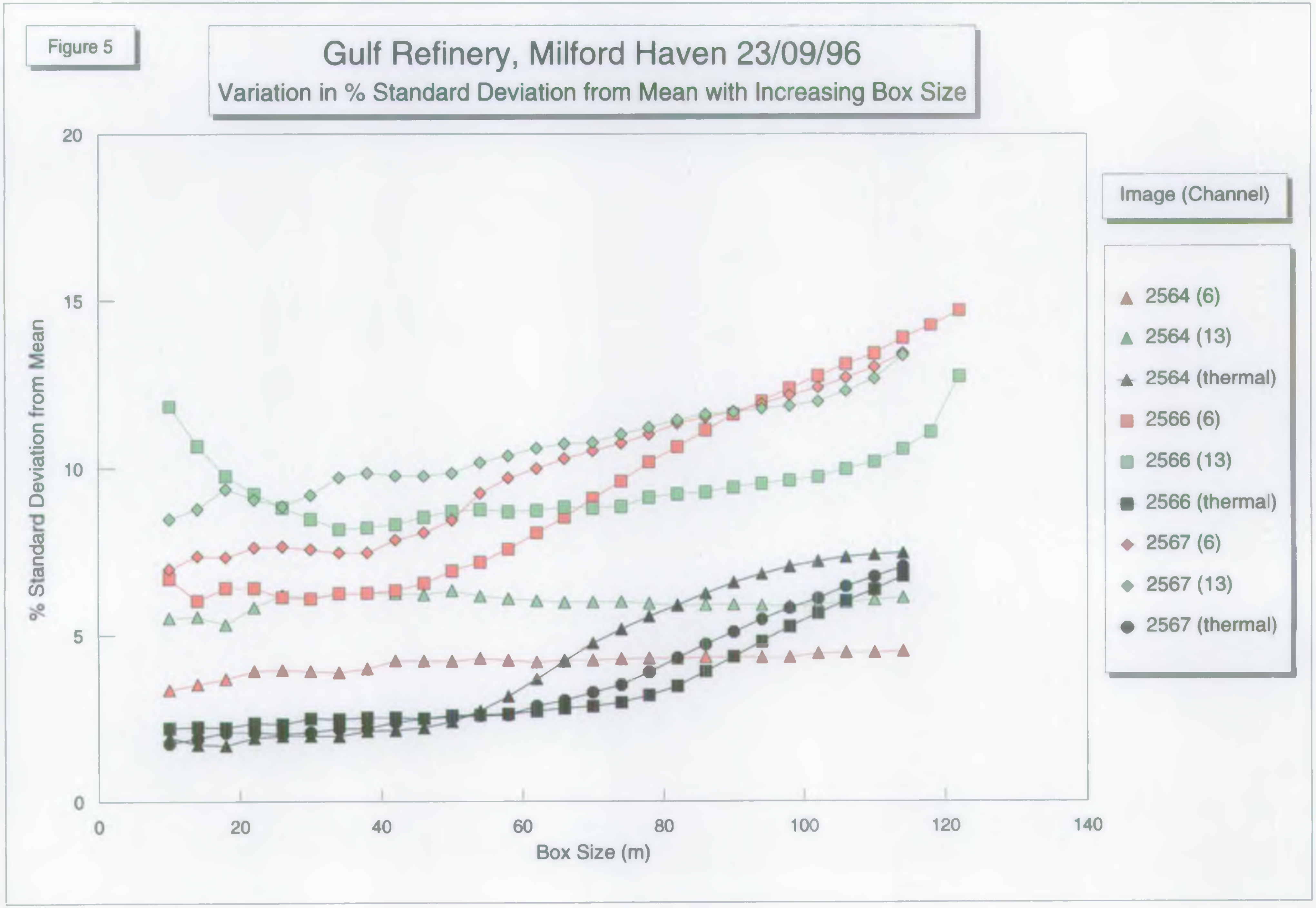

Figure 5
Gulf Refinery, Milford Haven 23/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
5
10
15
20
0
20
40
60
80
100
120
140
Image (Channel)
2564 (6)
2564 (13)
2564 (thermal)
2566 (6)
2566 (13)
2566 (thermal)
2567 (6)
2567 (13)
2567 (thermal)

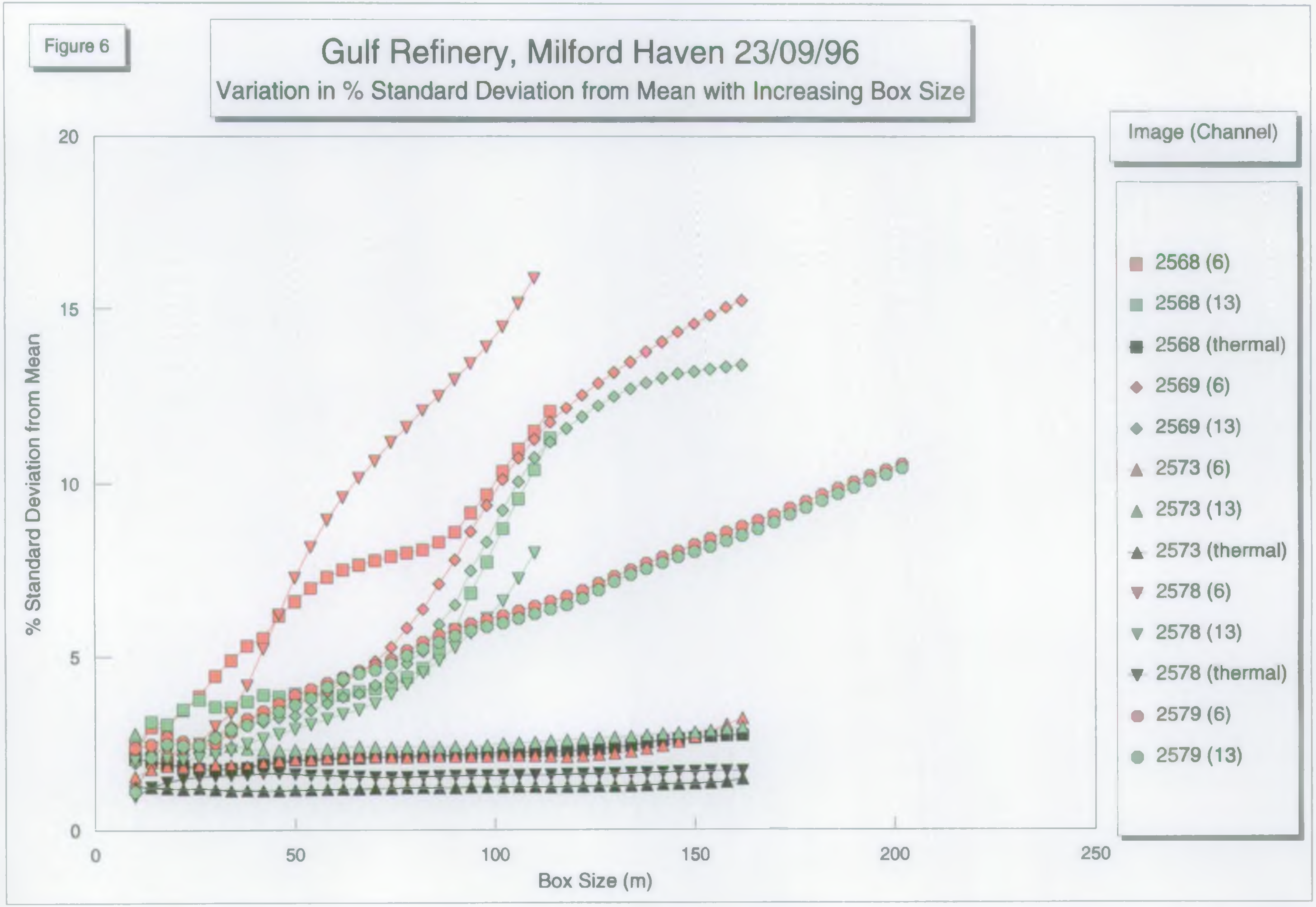

Figure 6
Gulf Refinery, Milford Haven 23/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
5
10
15
20
0
50
100
150
200
250
Image (Channel)
2568 (6)
2568 (13)
2568 (thermal)
2569 (6)
2569 (13)
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2579 (6)
2579 (13)

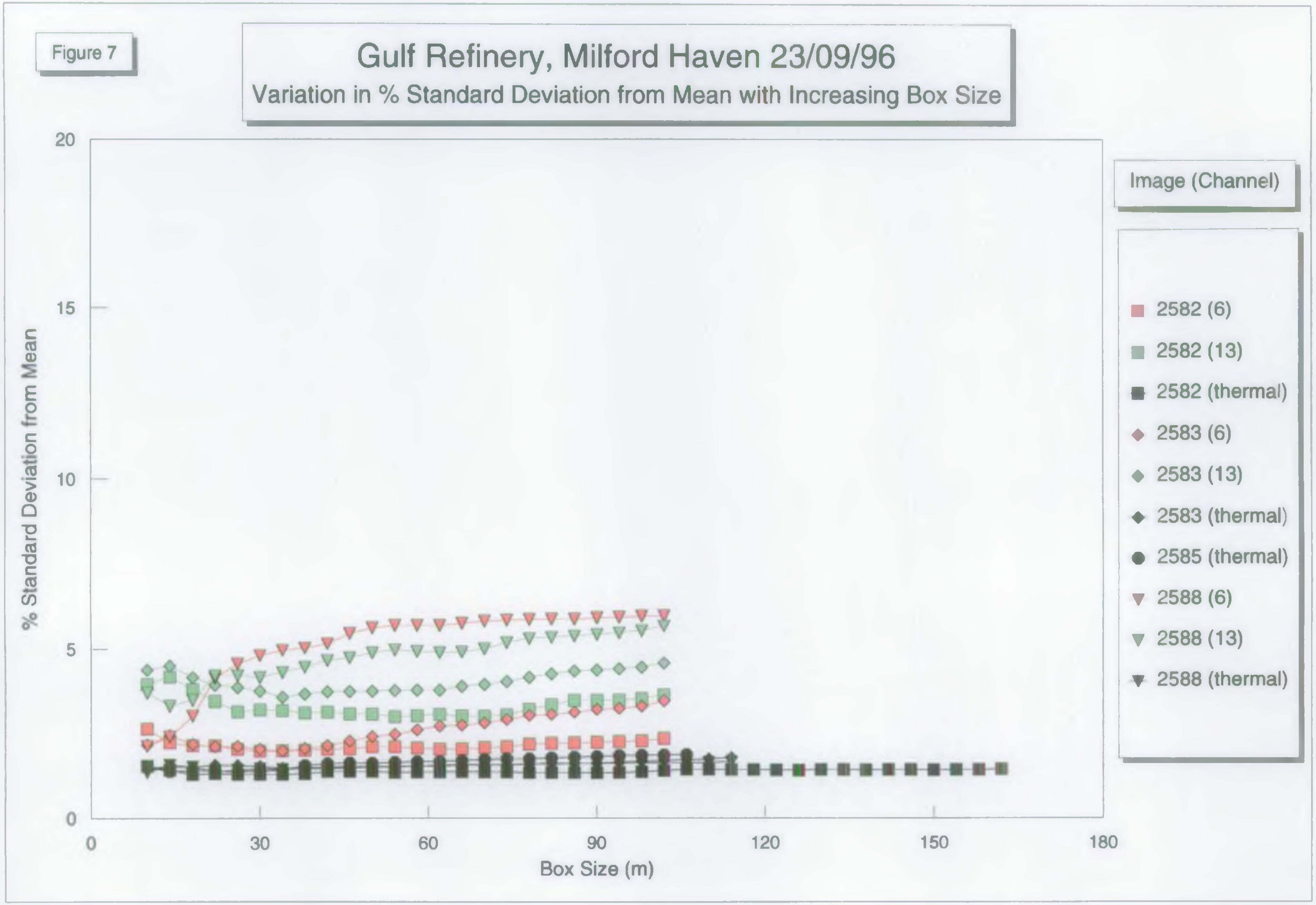
Figure 7
Gulf Refinery, Milford Haven 23/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
5
10
15
20
0
30
60
90
120
150
180
Image (Channel)
2582 (6)
2582 (13)
2582 (thermal)
2583 (6)
2583 (13)
2583 (thermal)
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2588 (13)
2588 (thermal)

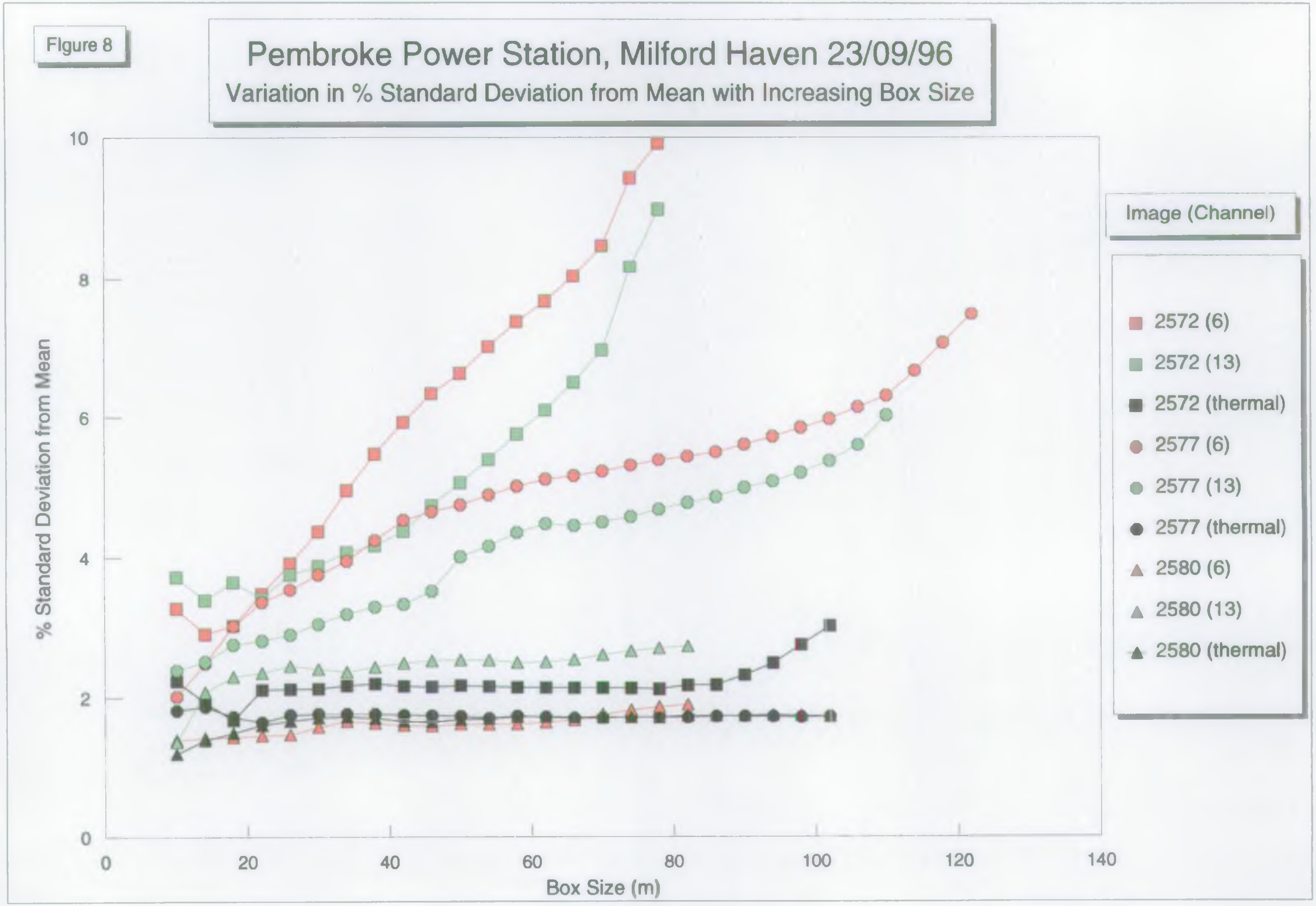


Figure 8
Pembroke Power Station, Milford Haven 23/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
2
4
6
8
10
0
20
40
60
80
100
120
140
Image (Channel)
2572 (6)
2572 (13)
2572 (thermal)
2577 (6)
2577 (13)
2577 (thermal)
2580 (6)
2580 (13)
2580 (thermal)

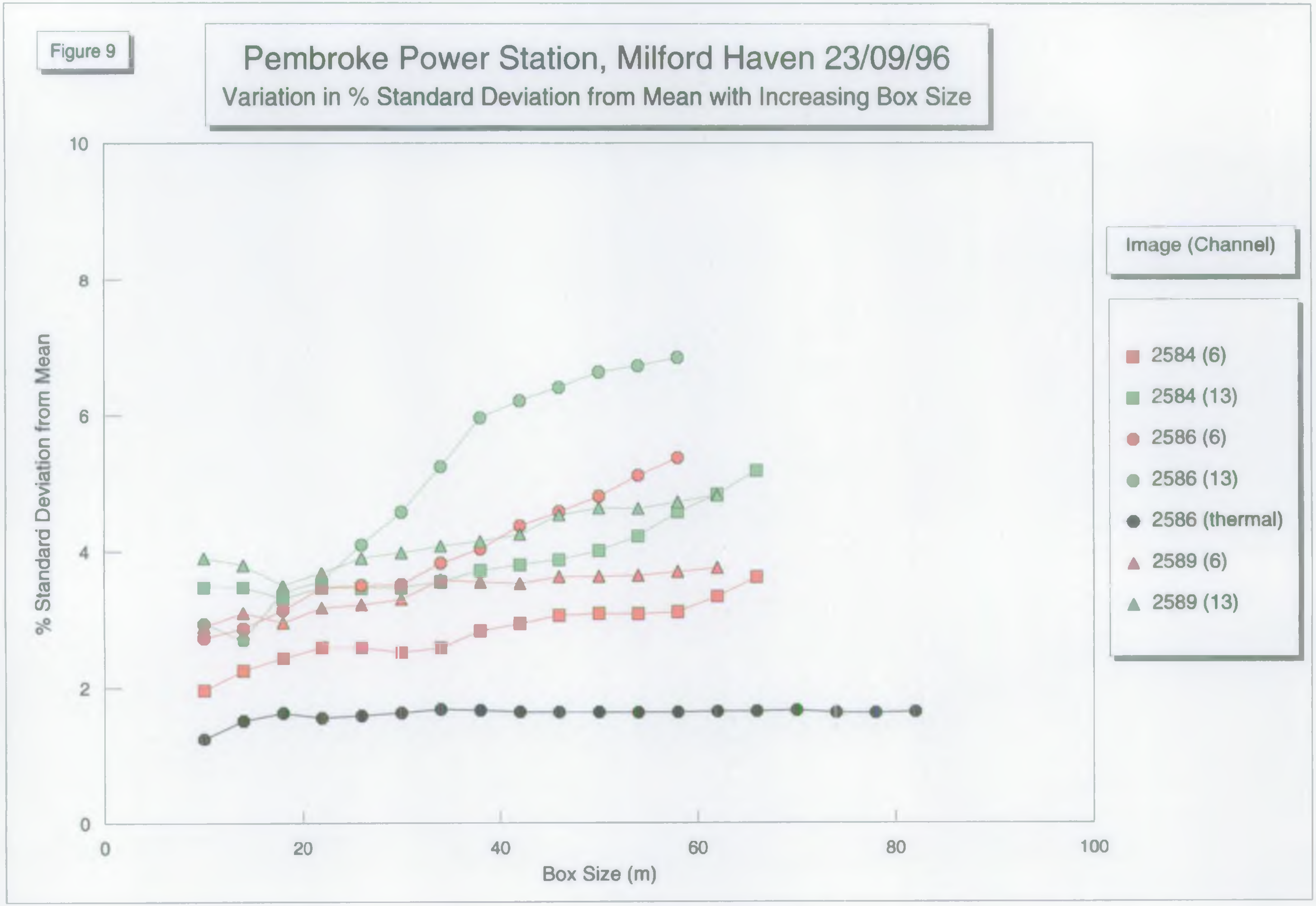
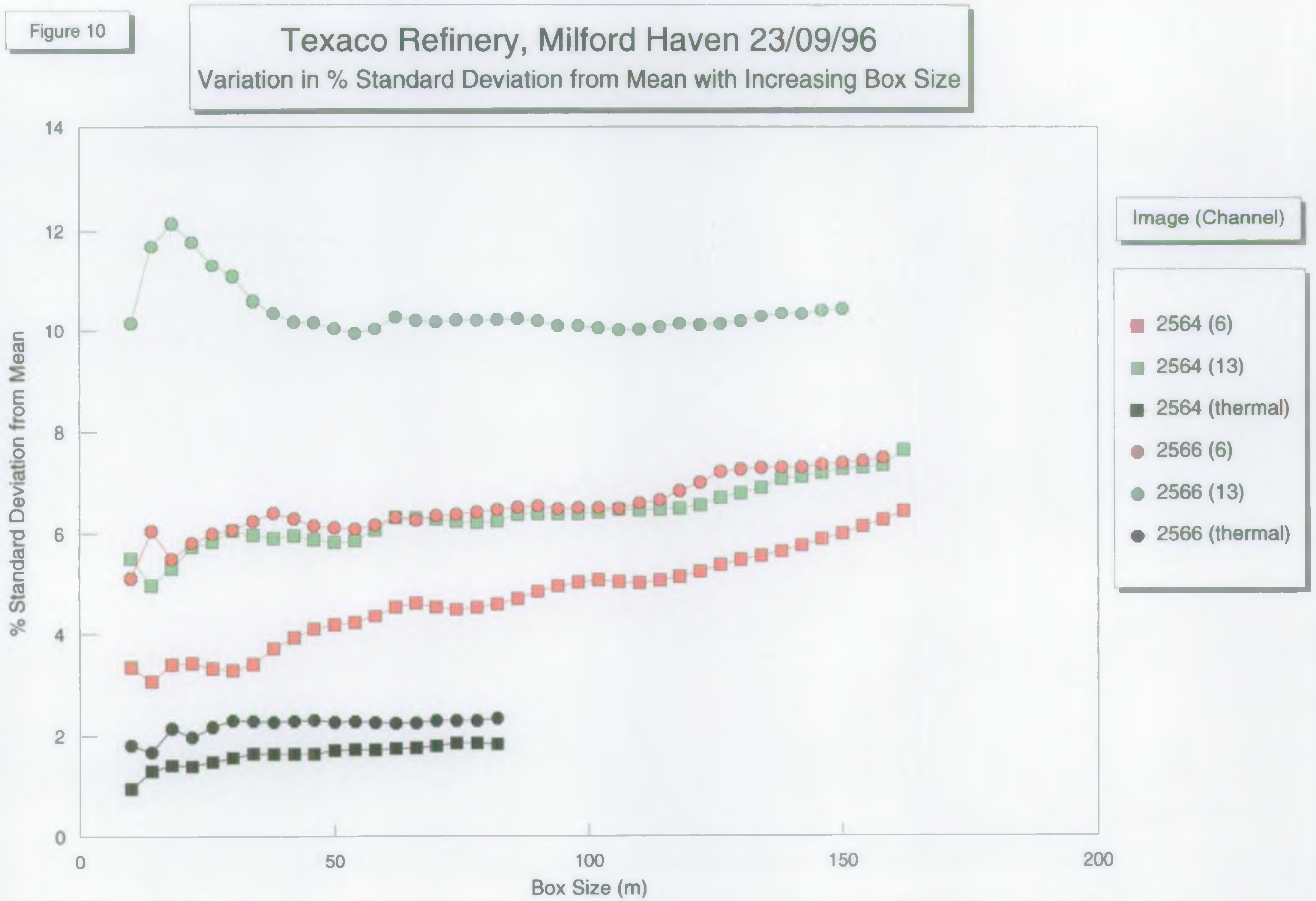


Figure 9
Pembroke Power Station, Milford Haven 23/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
2
4
6
8
10
0
20
40
60
80
100
Image (Channel)
2584 (6)
2584 (13)
2586 (6)
2586 (13)
2586 (thermal)
2589 (6)
2589 (13)

Figure 10



Texaco Refinery, Milford Haven 23/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
2
4
6
8
10
12
14
0
50
100
150
200
Image (Channel)
2564 (6)
2564 (13)
2564 (thermal)
2566 (6)
2566 (13)
2566 (thermal)

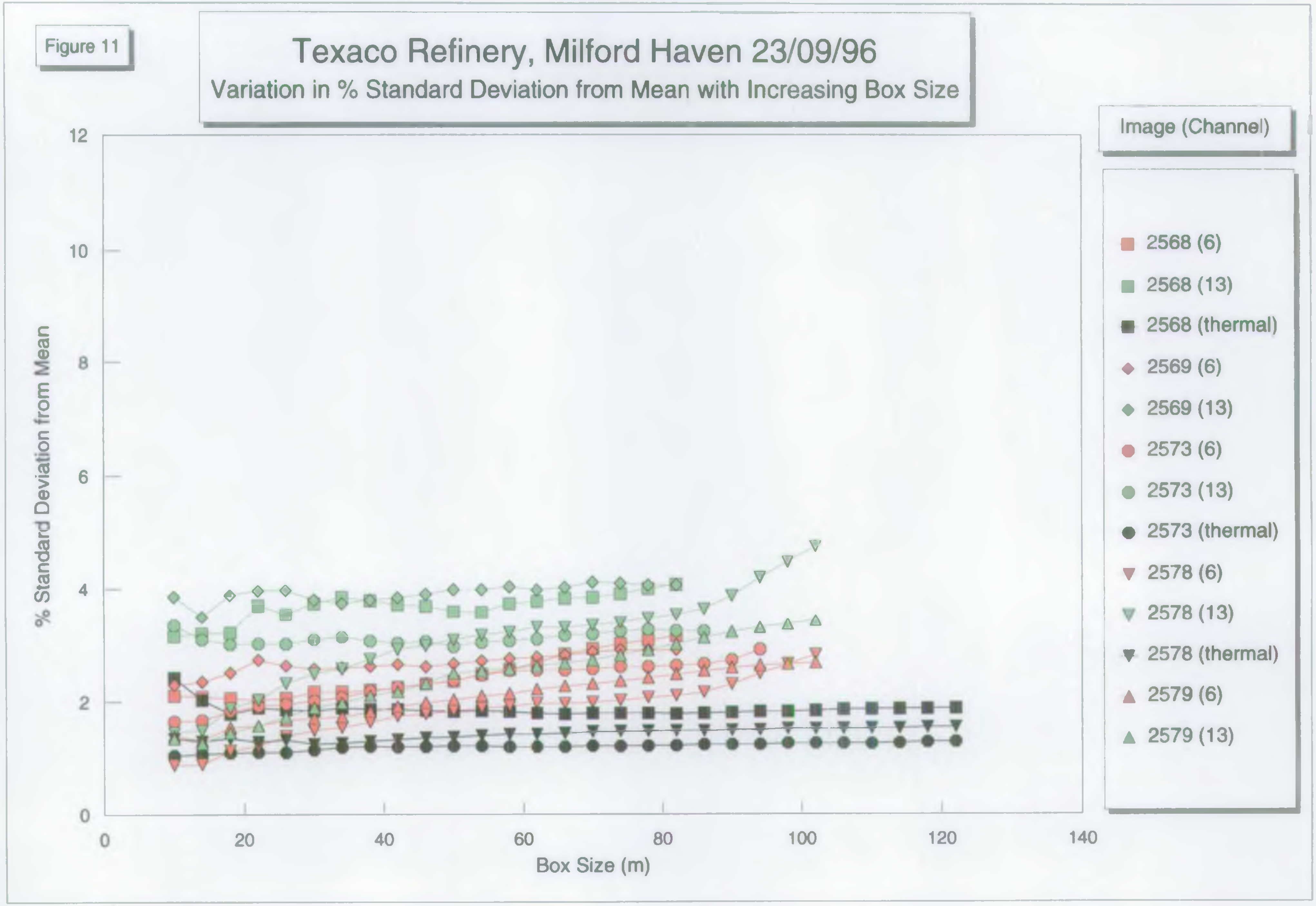


Figure 11
Texaco Refinery, Milford Haven 23/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
2
4
6
8
10
12
0
20
40
60
80
100
120
140
Image (Channel)
2568 (6)
2568 (13)
2568 (thermal)
2569 (6)
2569 (13)
2573 (6)
2573 (13)
2573 (thermal)
2578 (6)
2578 (13)
2578 (thermal)
2579 (6)
2579 (13)

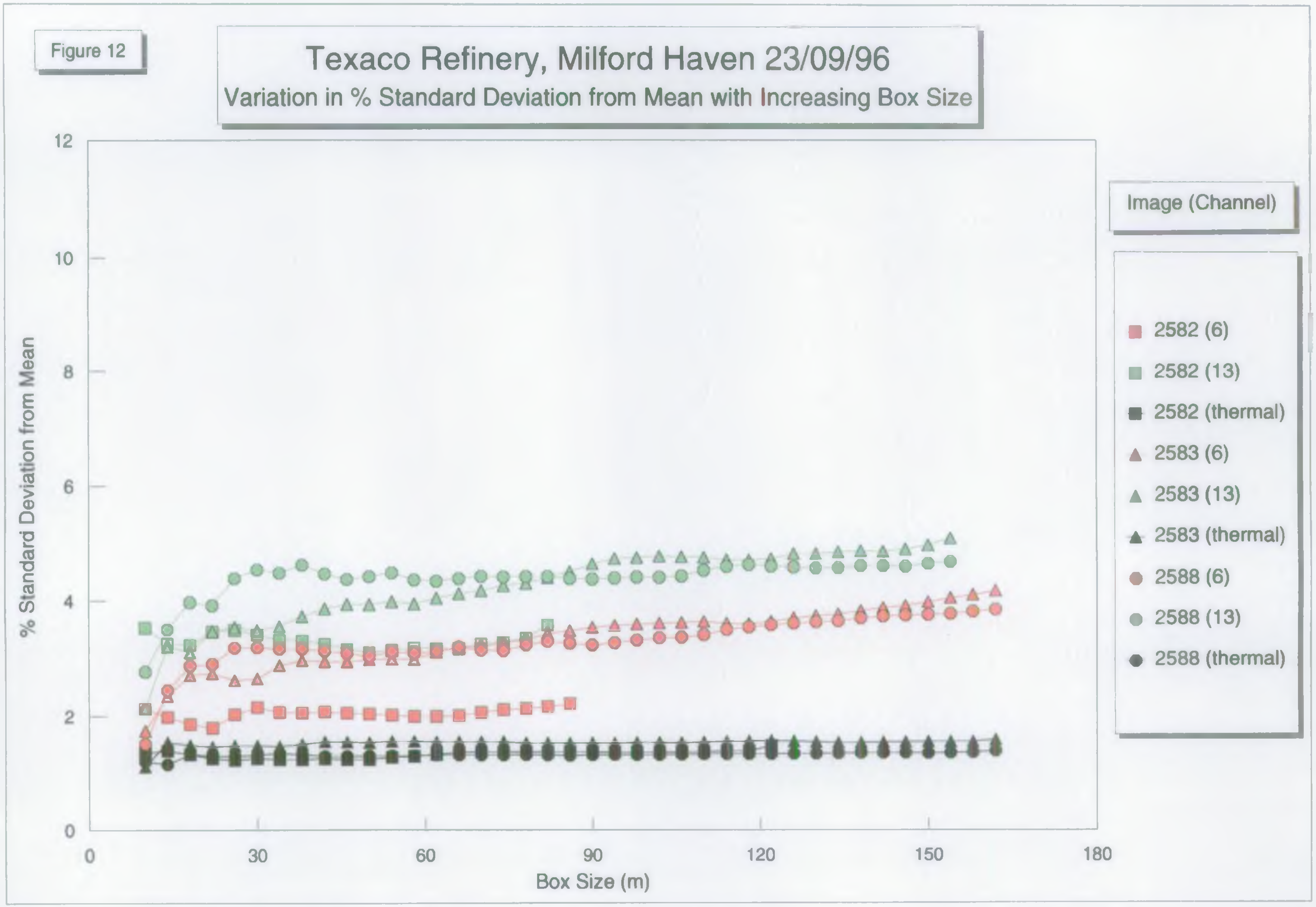
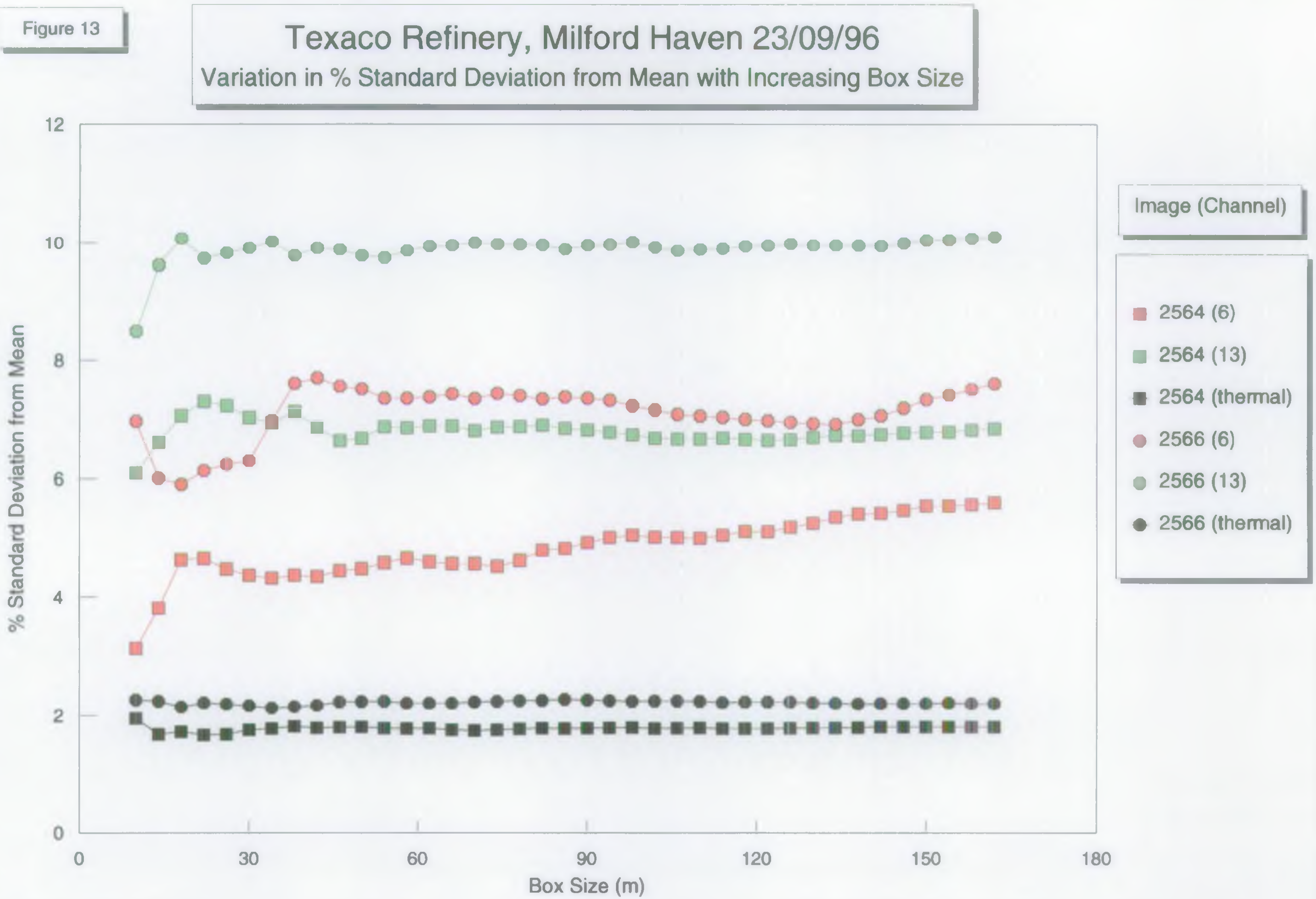


Figure 12
Texaco Refinery, Milford Haven 23/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
2
4
6
8
10
12
0
30
60
90
120
150
180
Image (Channel)
2582 (6)
2582 (13)
2582 (thermal)
2583 (6)
2583 (13)
2583 (thermal)
2588 (6)
2588 (13)
2588 (thermal)

Figure 13



Texaco Refinery, Milford Haven 23/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
2
4
6
8
10
12
0
30
60
90
120
150
180
Image (Channel)
2564 (6)
2564 (13)
2564 (thermal)
2566 (6)
2566 (13)
2566 (thermal)

Figure 14

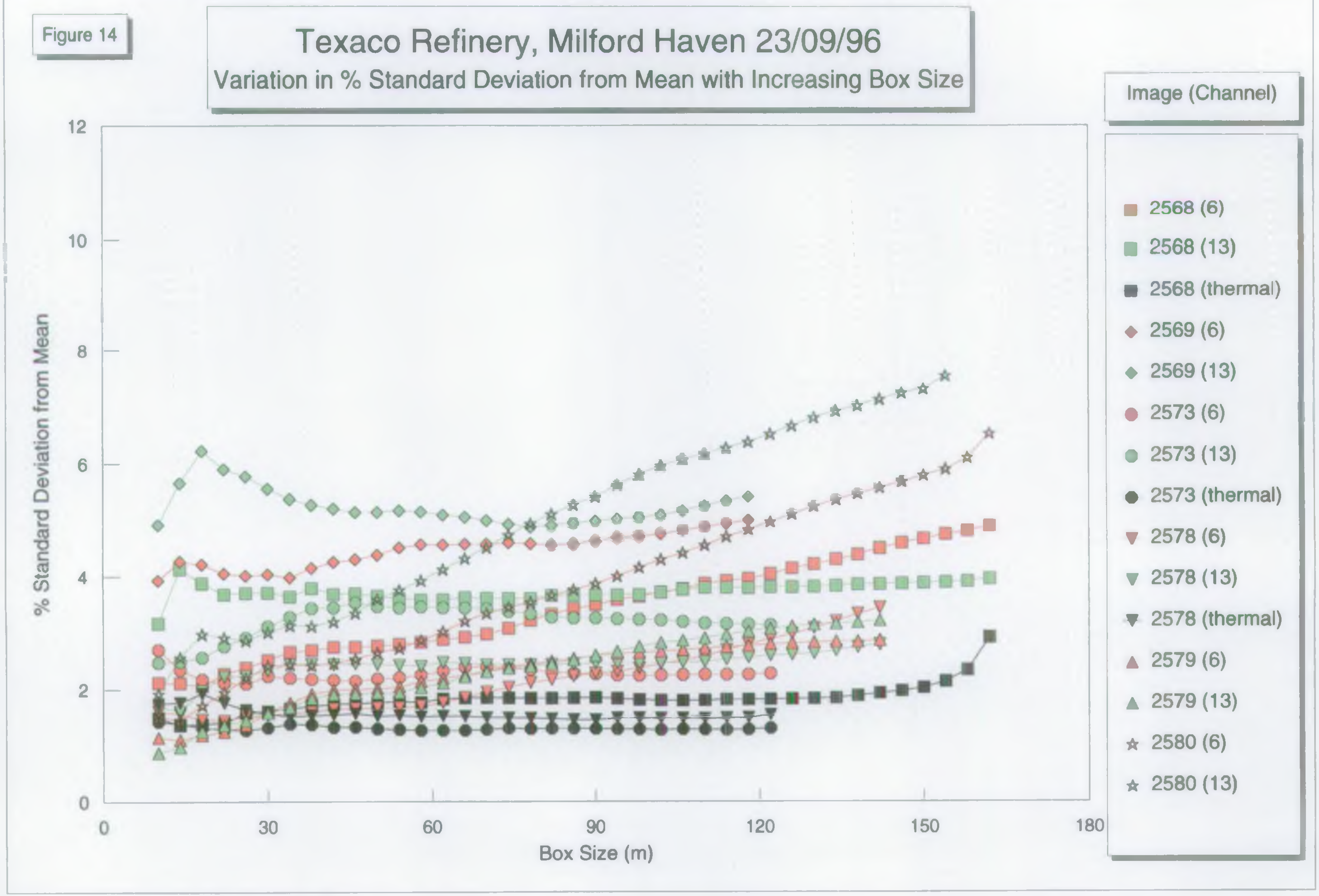
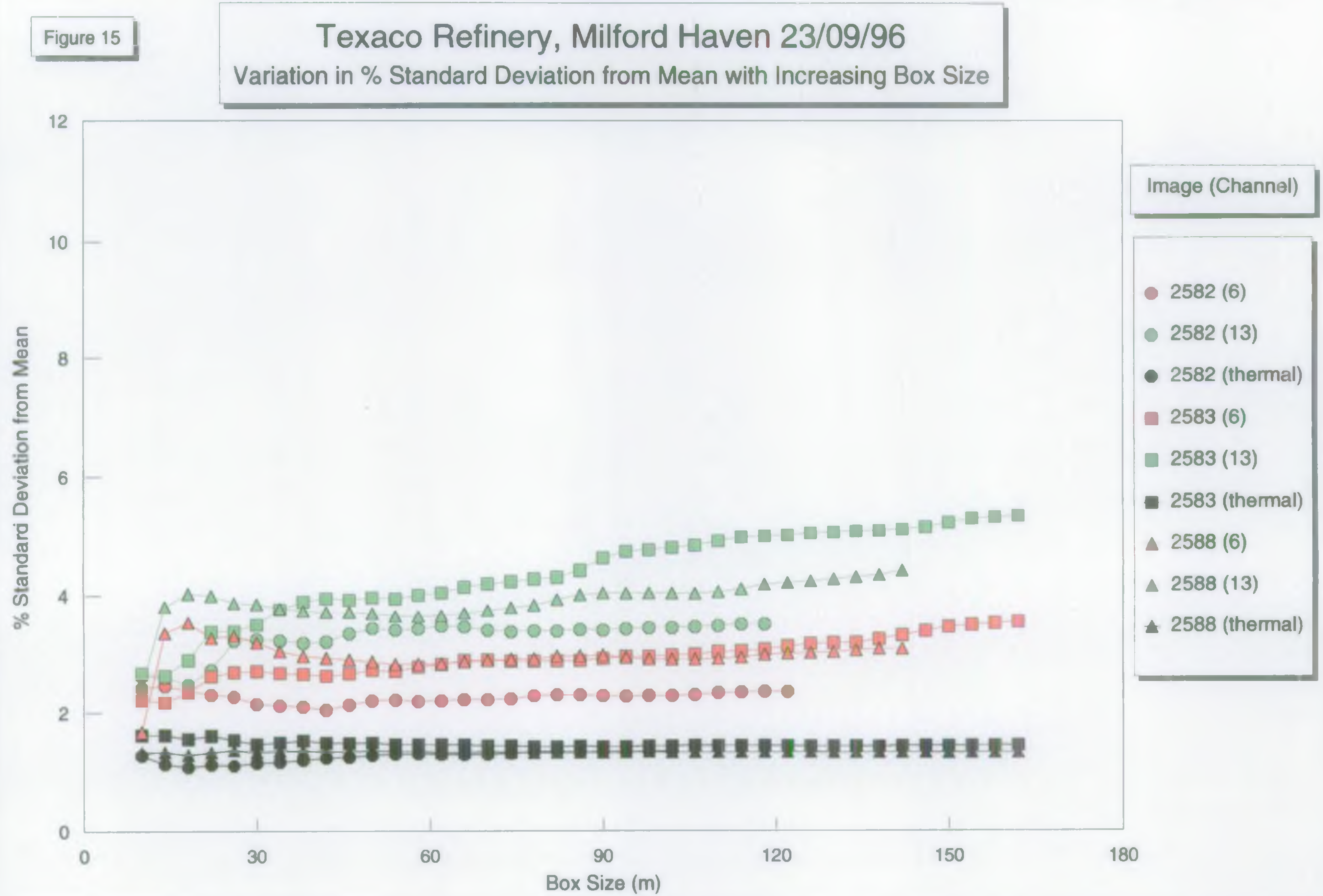

Texaco Refinery, Milford Haven 23/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
12
10
8
6
4
2
0
0
30
60
90
120
150
180
Box Size (m)
Image (Channel)
2568 (6)
2568 (13)
2568 (thermal)
2569 (6)
2569 (13)
2573 (6)
2573 (13)
2573 (thermal)
2578 (6)
2578 (13)
2578 (thermal)
2579 (6)
2579 (13)
2580 (6)
2580 (13)

Figure 15



Texaco Refinery, Milford Haven 23/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
2
4
6
8
10
12
0
30
60
90
120
150
180
Image (Channel)
2582 (6)
2582 (13)
2582 (thermal)
2583 (6)
2583 (13)
2583 (thermal)
2588 (6)
2588 (13)
2588 (thermal)

Figure 16

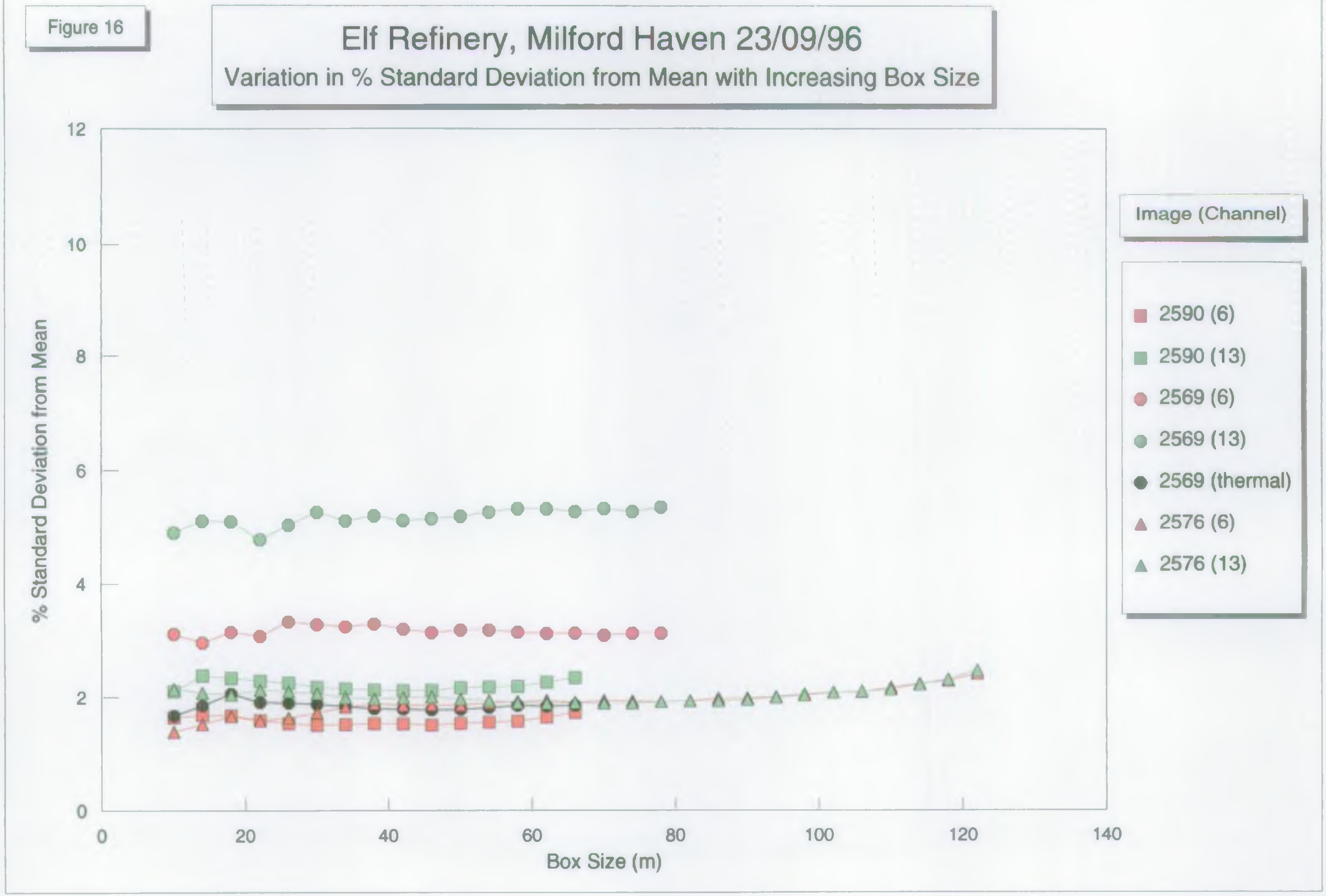
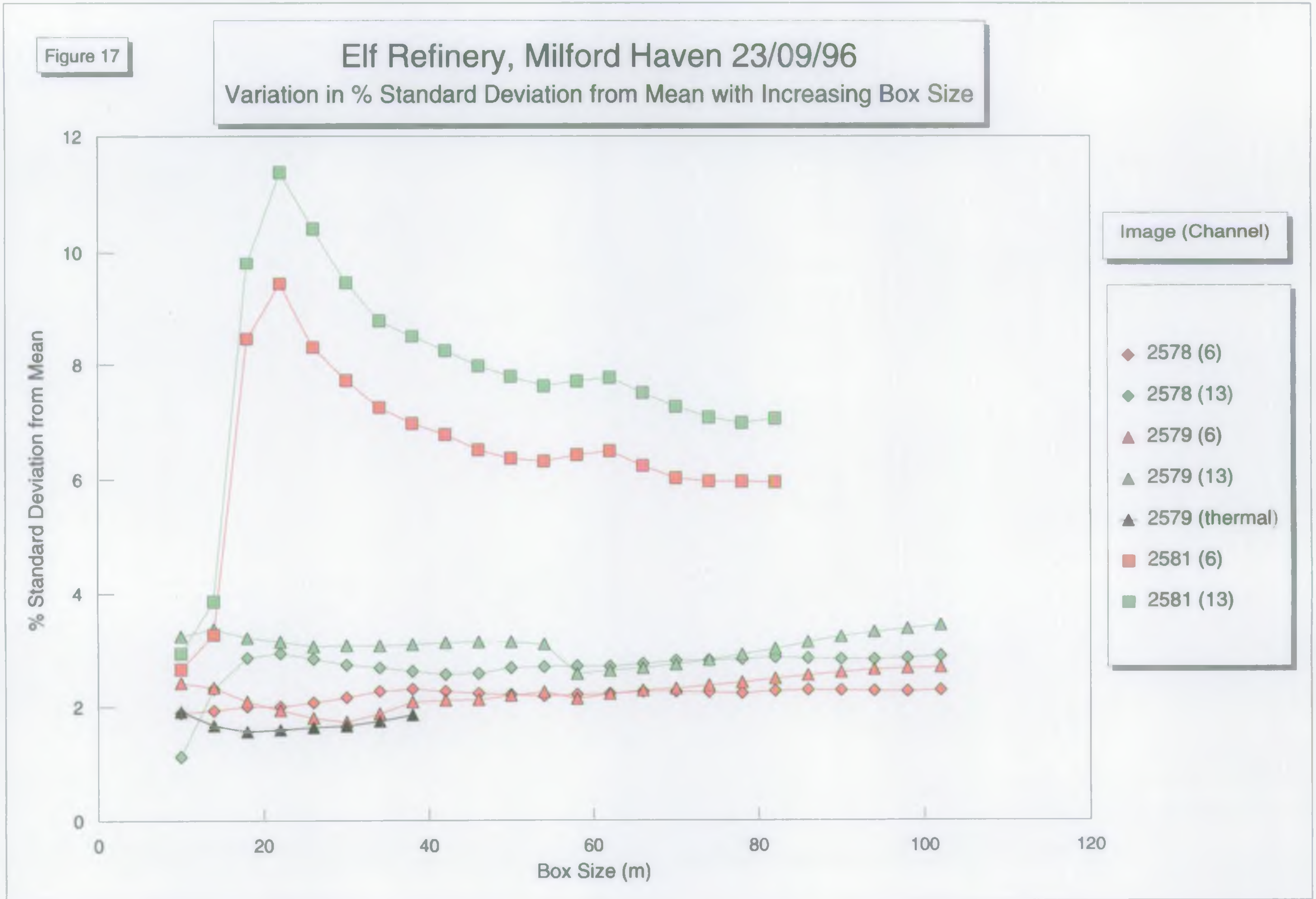

Elf Refinery, Milford Haven 23/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
2
4
6
8
10
12
20
40
60
80
100
120
140
Image (Channel)
2590 (6)
2590 (13)
2569 (6)
2569 (13)
2569 (thermal)
2576 (6)
2576 (13)

Figure 17



Elf Refinery, Milford Haven 23/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
0
2
4
6
8
10
12
Box Size (m)
0
20
40
60
80
100
120
Image (Channel)
2578 (6)
2578 (13)
2579 (6)
2579 (13)
2579 (thermal)
2581 (6)
2581 (13)

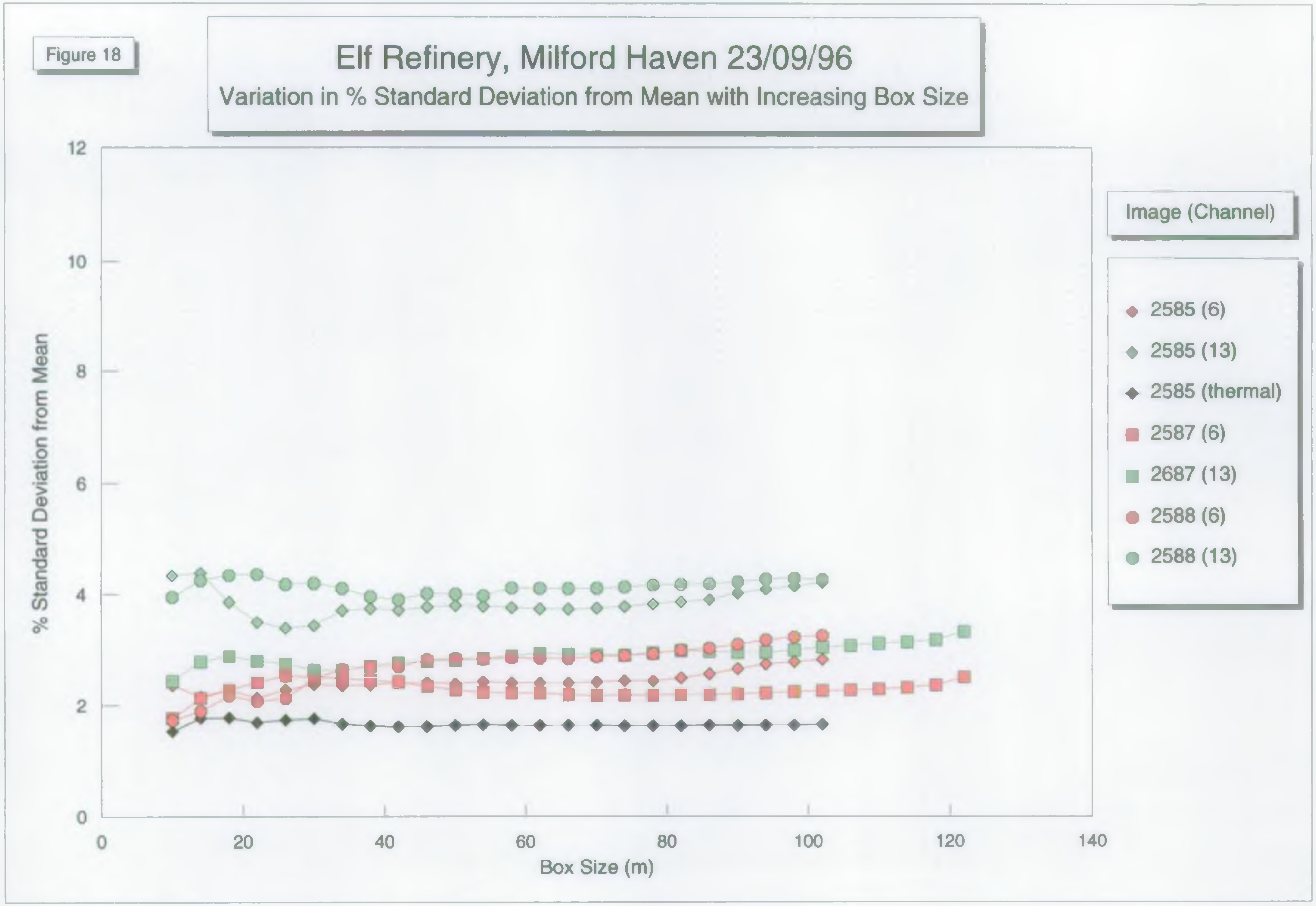


Figure 18
Elf Refinery, Milford Haven 23/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
0
2
4
6
8
10
12
Box Size (m)
0
20
40
60
80
100
120
140
Image (Channel)
2585 (6)
2585 (13)
2585 (thermal)
2587 (6)
2687 (13)
2588 (6)
2588 (13)

Figure 19. Tamar Estuary Continuous Salinity Data, 7-Sep-96, Line 3.

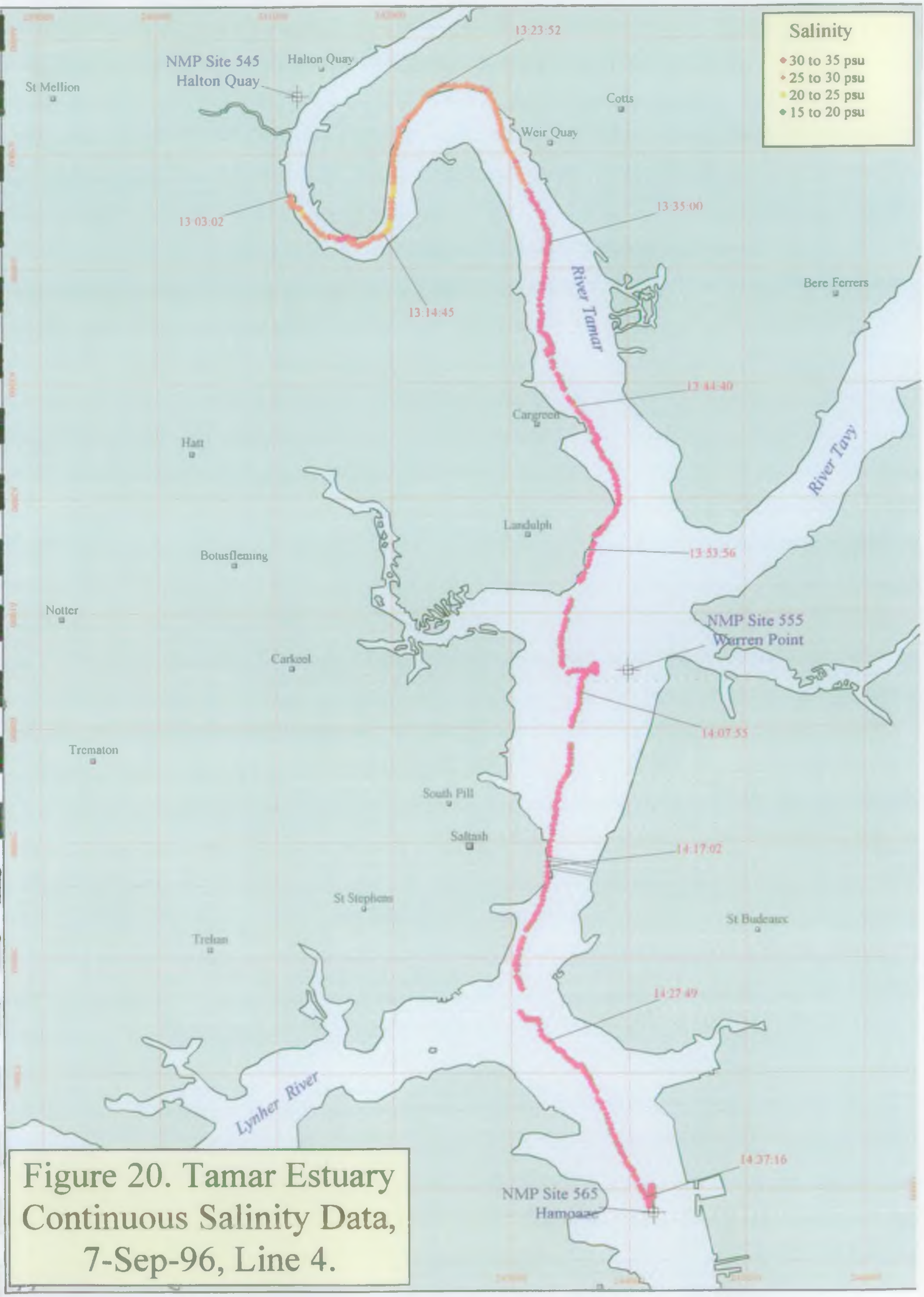
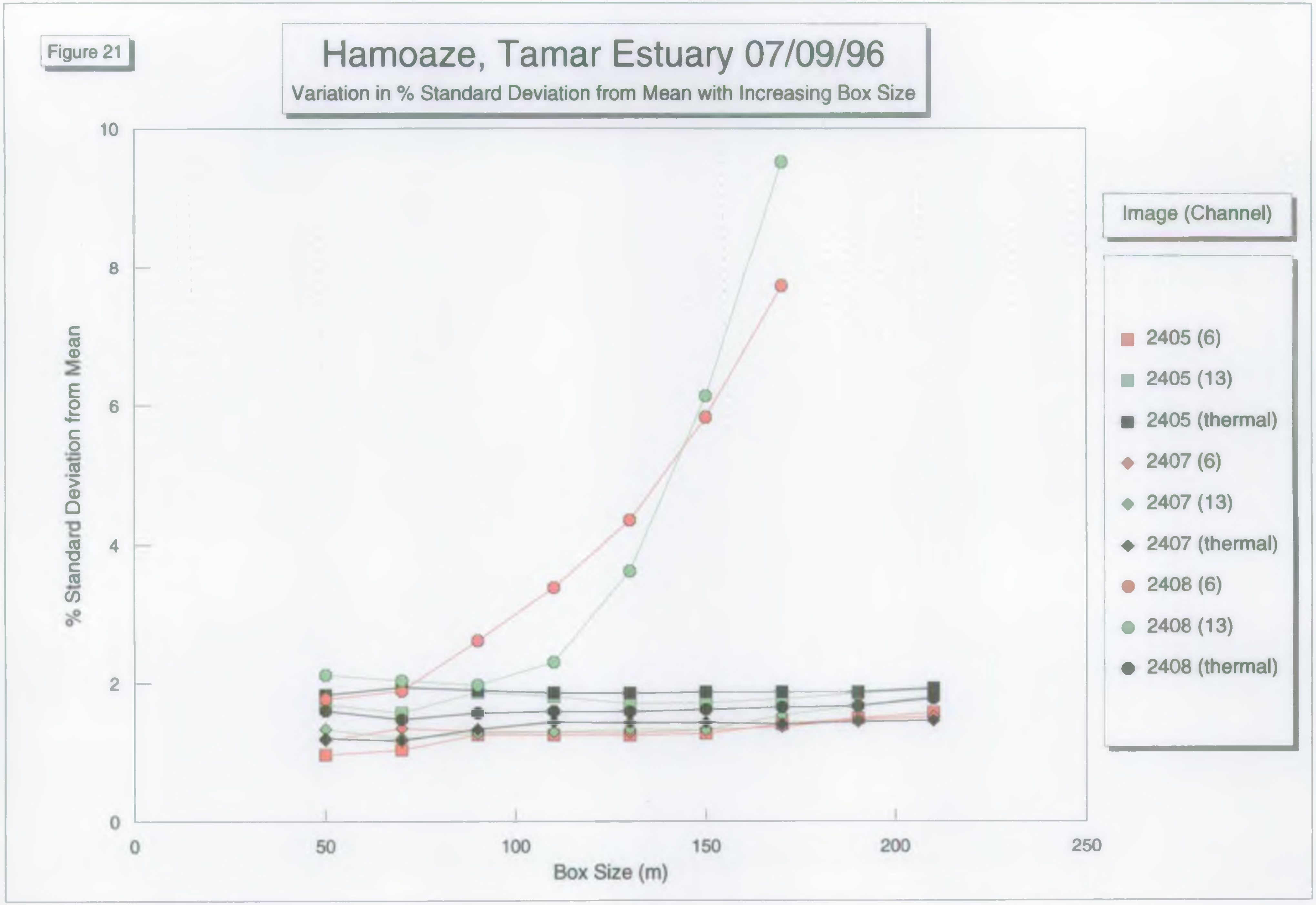


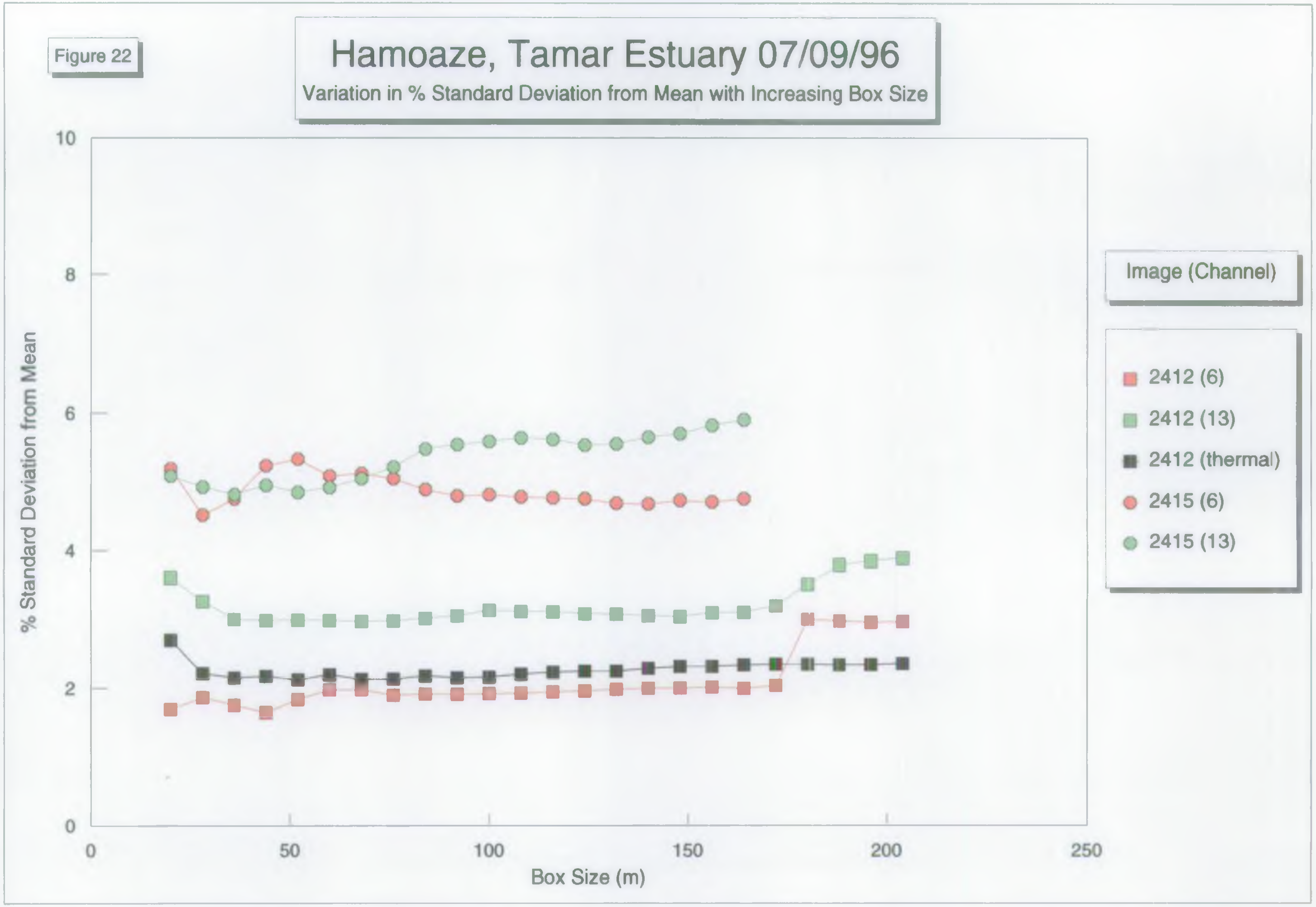
Figure 20. Tamar Estuary Continuous Salinity Data, 7-Sep-96, Line 4.

Figure 21



Hamoaze, Tamar Estuary 07/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
0
2
4
6
8
10
0
50
100
150
200
250
Box Size (m)
Image (Channel)
2405 (6)
2405 (13)
2405 (thermal)
2407 (6)
2407 (13)
2407 (thermal)
2408 (6)
2408 (13)
2408 (thermal)

Figure 22


Hamoaze, Tamar Estuary 07/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
2
4
6
8
10
0
50
100
150
200
250
Image (Channel)
2412 (6)
2412 (13)
2412 (thermal)
2415 (6)
2415 (13)

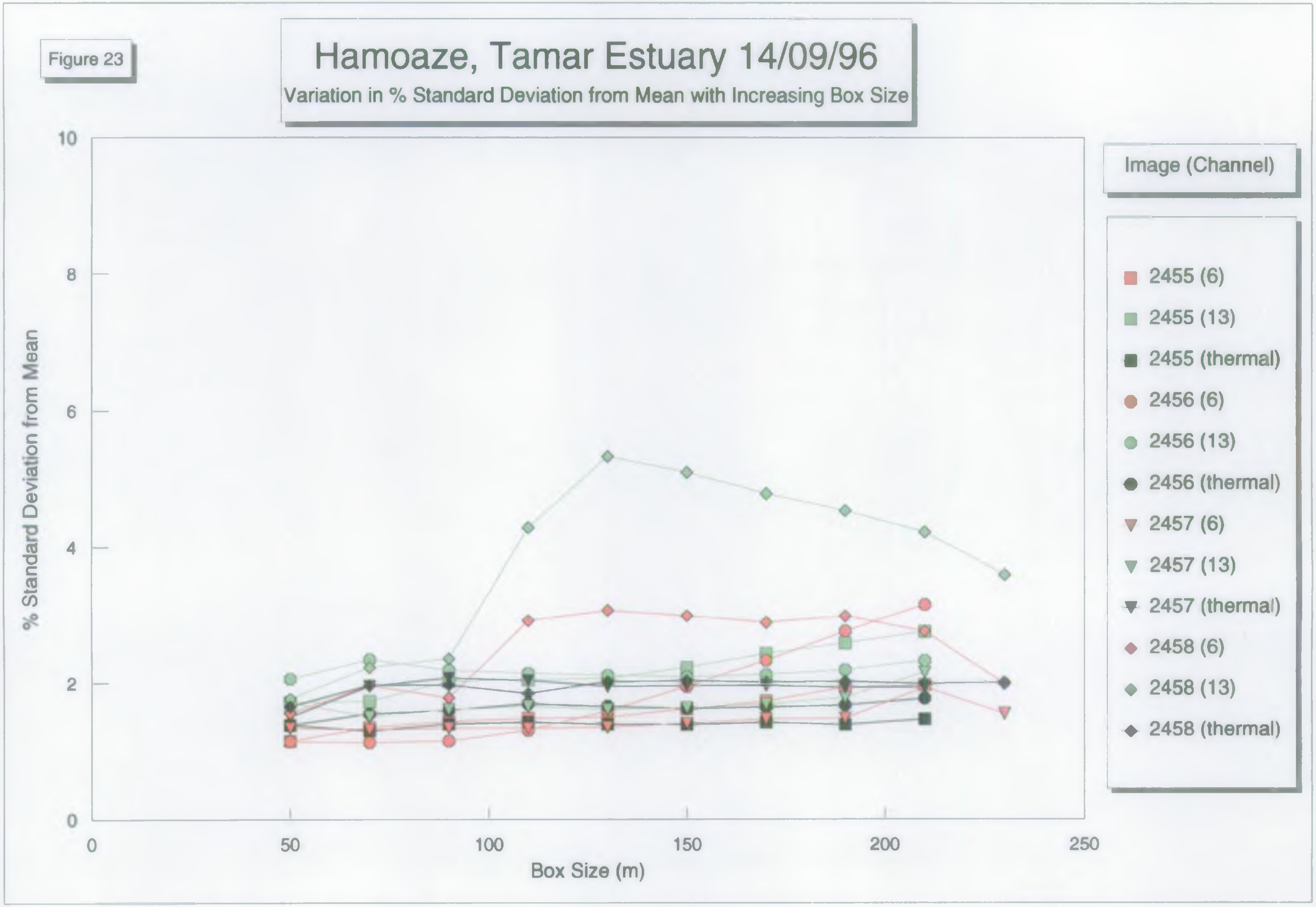


Figure 23
Hamoaze, Tamar Estuary 14/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
2
4
6
8
10
0
50
100
150
200
250
Image (Channel)
2455 (6)
2455 (13)
2455 (thermal)
2456 (6)
2456 (13)
2456 (thermal)
2457 (6)
2457 (13)
2457 (thermal)
2458 (6)
2458 (13)
2458 (thermal)

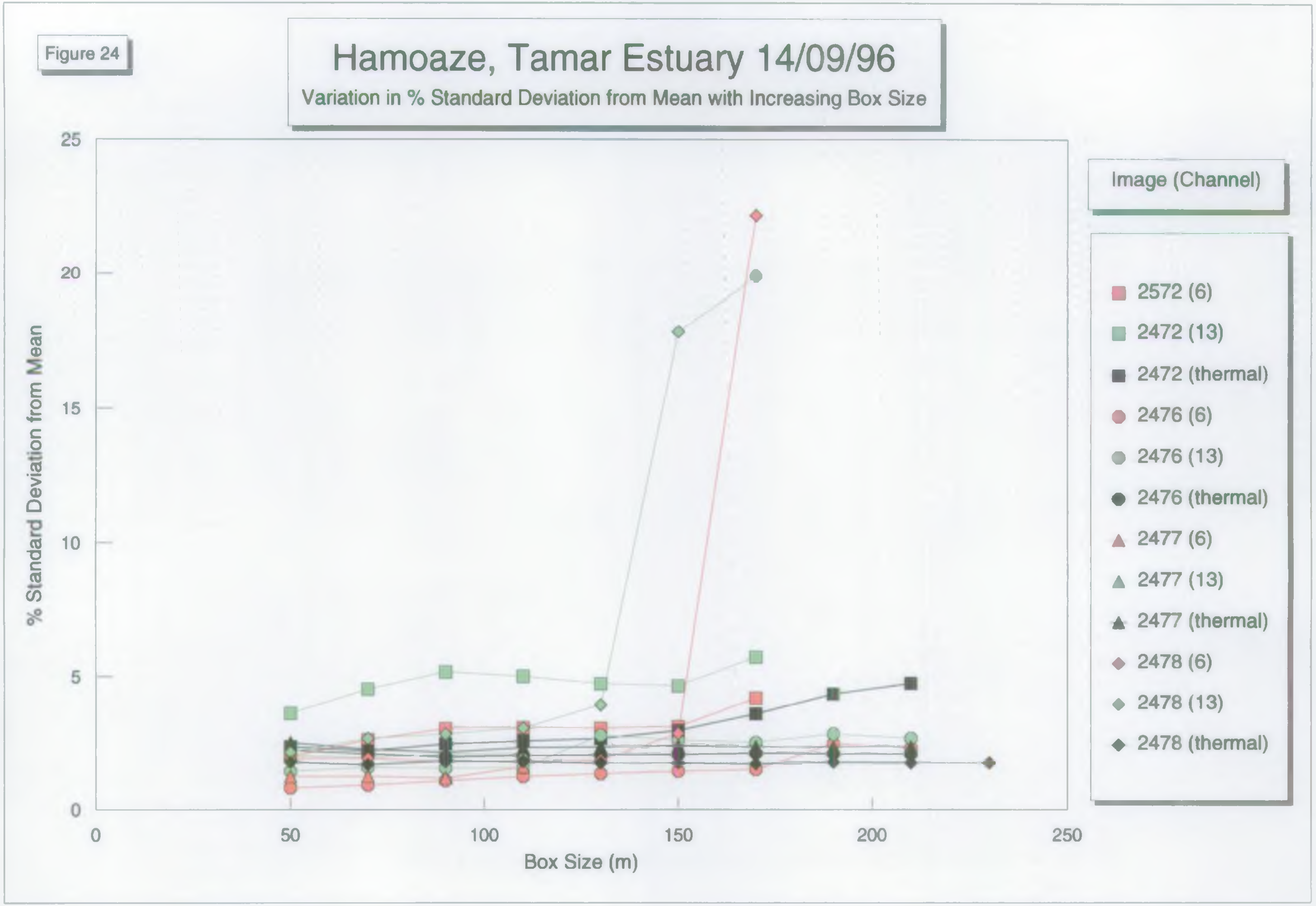


Figure 24
Hamoaze, Tamar Estuary 14/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
5
10
15
20
25
0
50
100
150
200
250
Image (Channel)
2572 (6)
2472 (13)
2472 (thermal)
2476 (6)
2476 (13)
2476 (thermal)
2477 (6)
2477 (13)
2477 (thermal)
2478 (6)
2478 (13)
2478 (thermal)

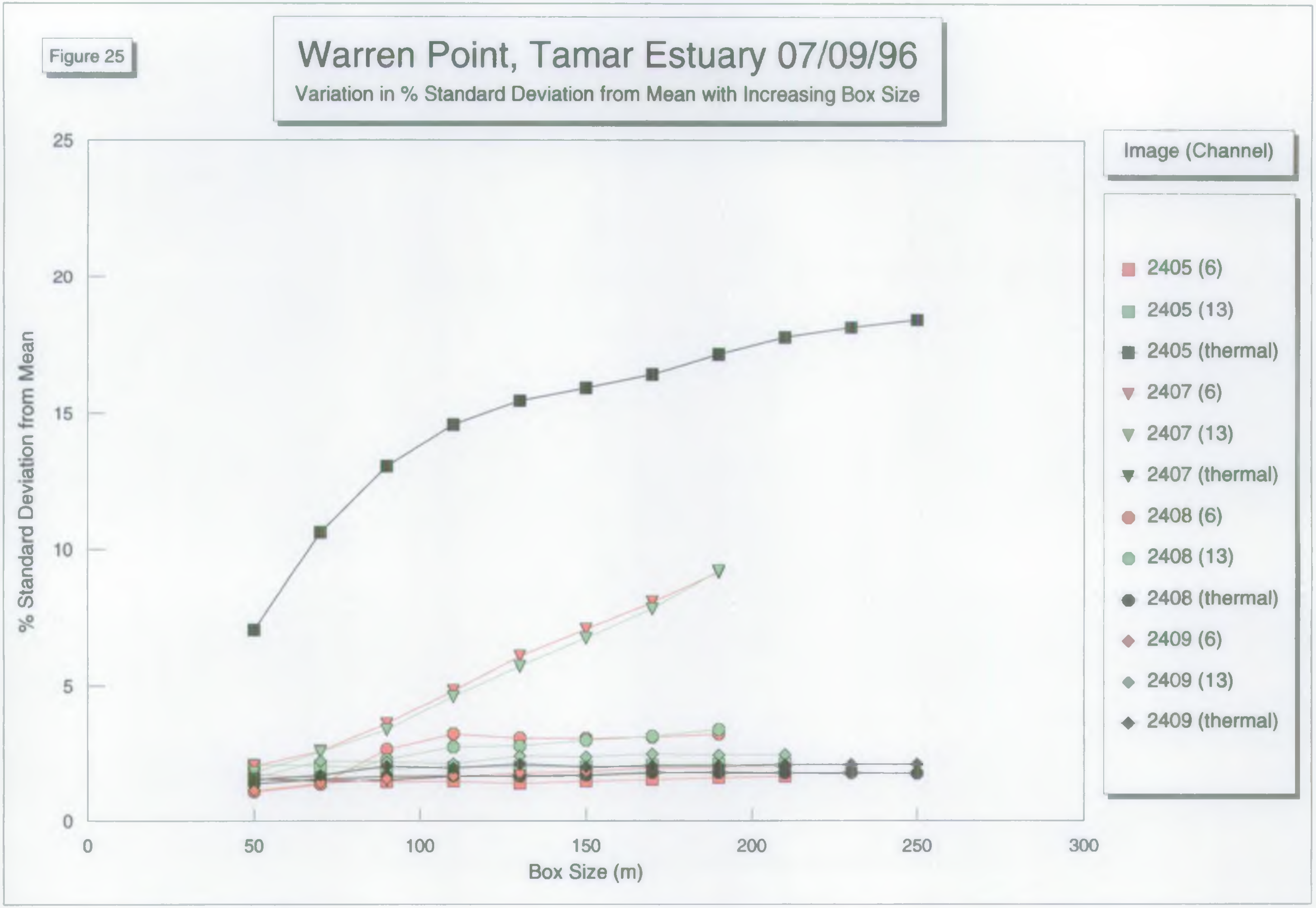
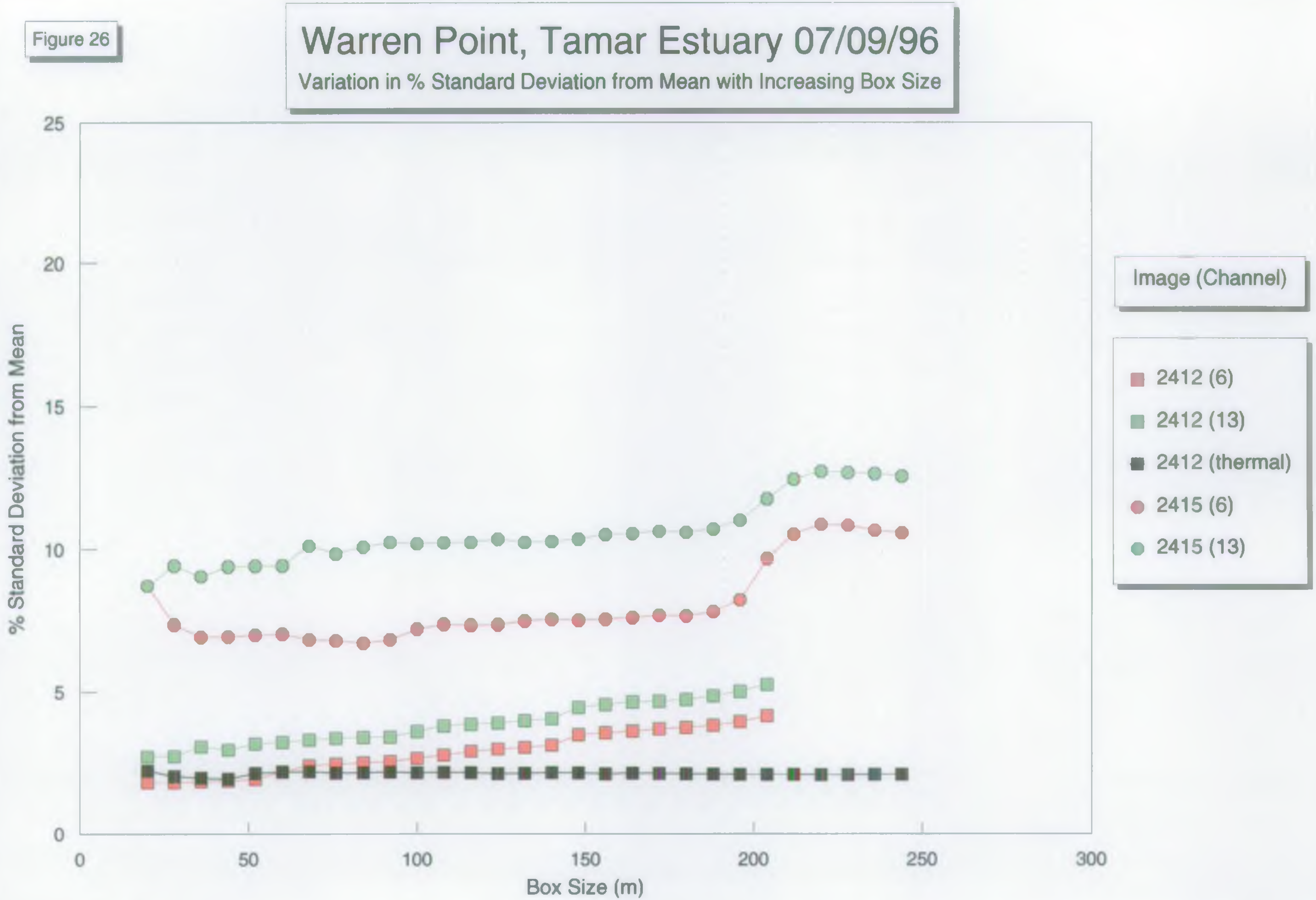


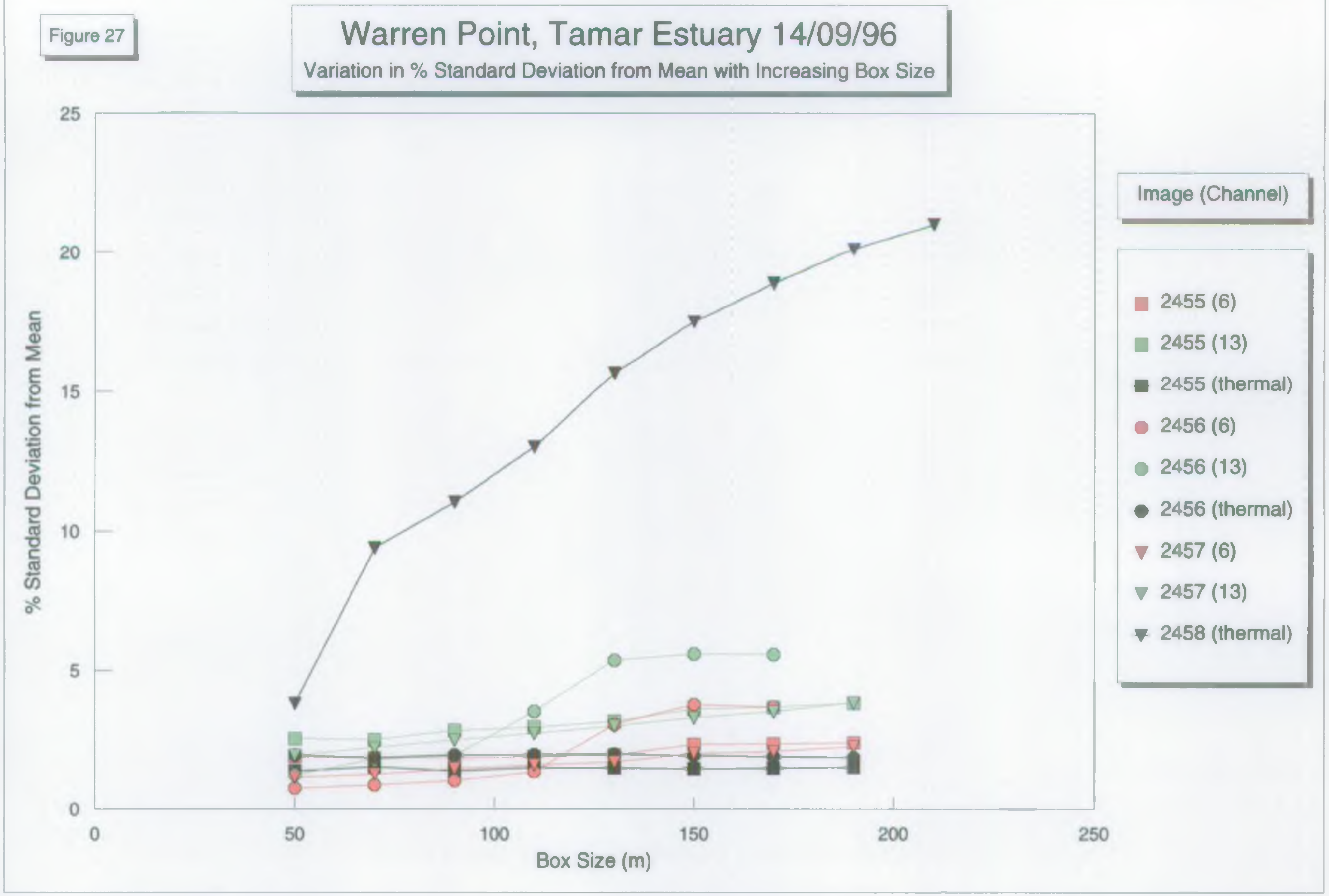
Figure 25
Warren Point, Tamar Estuary 07/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
5
10
15
20
25
0
50
100
150
200
250
300
Image (Channel)
2405 (6)
2405 (13)
2405 (thermal)
2407 (6)
2407 (13)
2407 (thermal)
2408 (6)
2408 (13)
2408 (thermal)
2409 (6)
2409 (13)
2409 (thermal)

Figure 26



Warren Point, Tamar Estuary 07/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
5
10
15
20
25
0
50
100
150
200
250
300
Image (Channel)
2412 (6)
2412 (13)
2412 (thermal)
2415 (6)
2415 (13)

Figure 27



Warren Point, Tamar Estuary 14/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
5
10
15
20
25
0
50
100
150
200
250
Image (Channel)
2455 (6)
2455 (13)
2455 (thermal)
2456 (6)
2456 (13)
2456 (thermal)
2457 (6)
2457 (13)
2458 (thermal)

Figure 28

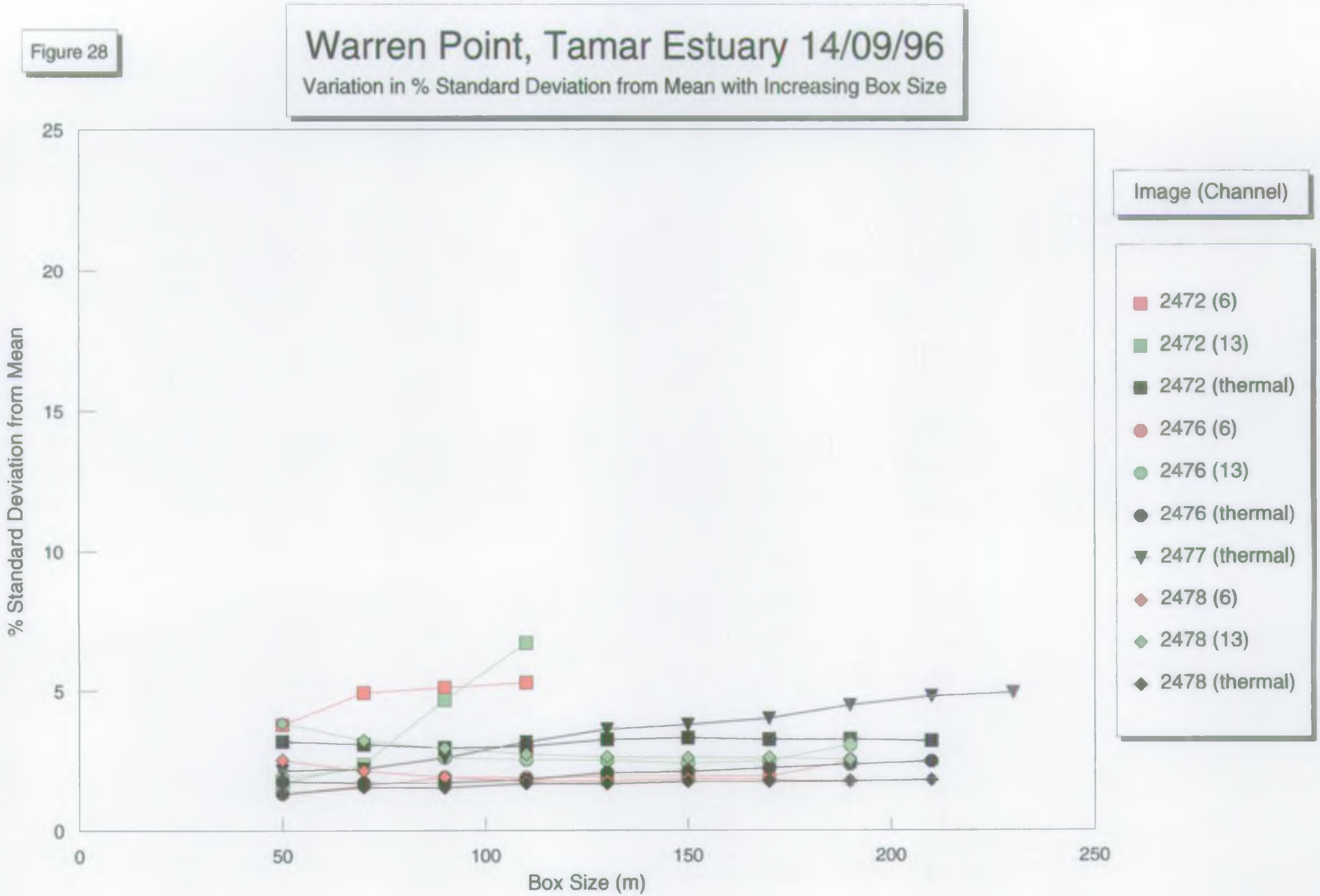
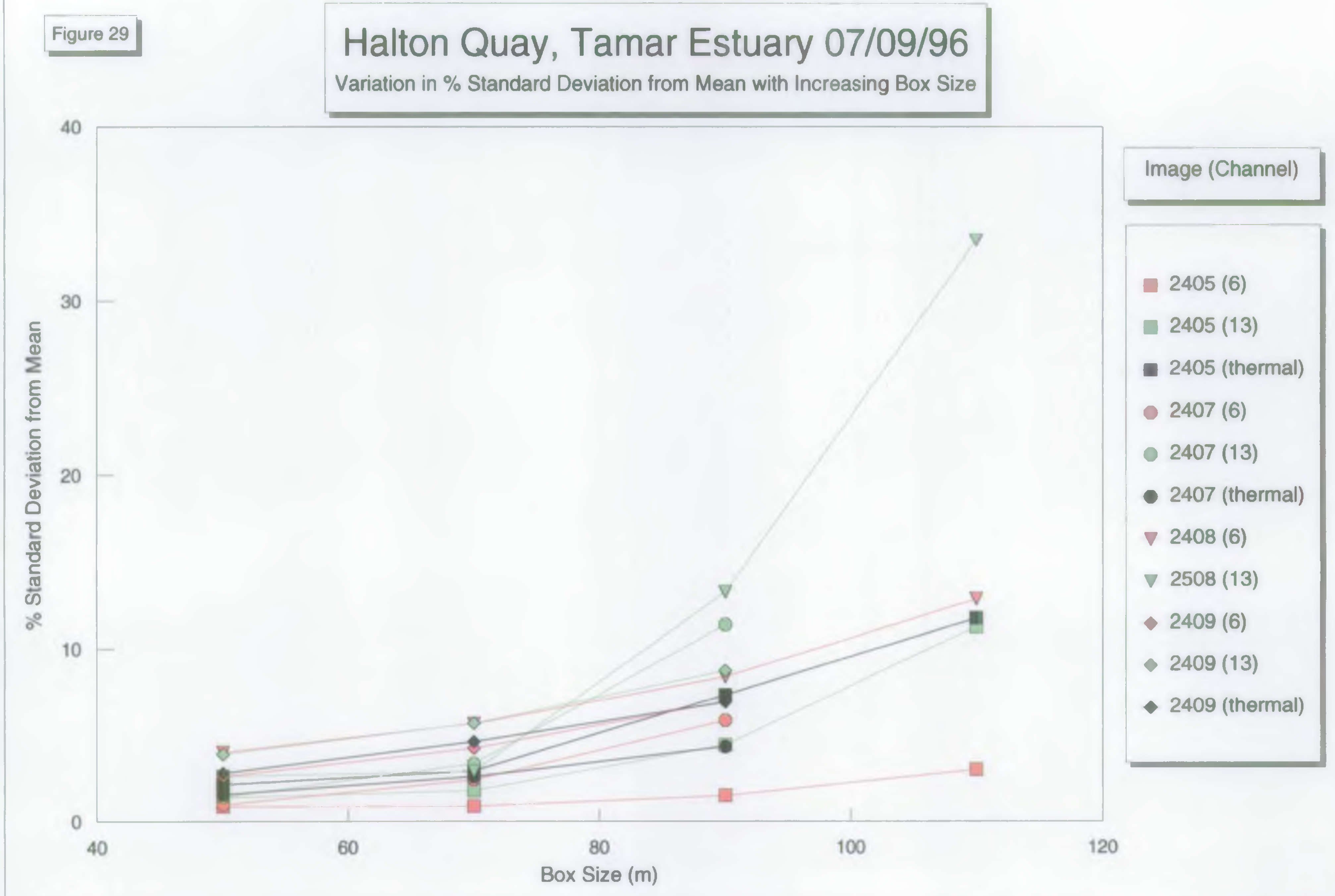

Warren Point, Tamar Estuary 14/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
5
10
15
20
25
0
50
100
150
200
250
Image (Channel)
2472 (6)
2472 (13)
2472 (thermal)
2476 (6)
2476 (13)
2476 (thermal)
2477 (thermal)
2478 (6)
2478 (13)
2478 (thermal)

Figure 29



Halton Quay, Tamar Estuary 07/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
0
10
20
30
40
40
60
80
100
120
Box Size (m)
Image (Channel)
2405 (6)
2405 (13)
2405 (thermal)
2407 (6)
2407 (13)
2407 (thermal)
2408 (6)
2508 (13)
2409 (6)
2409 (13)
2409 (thermal)

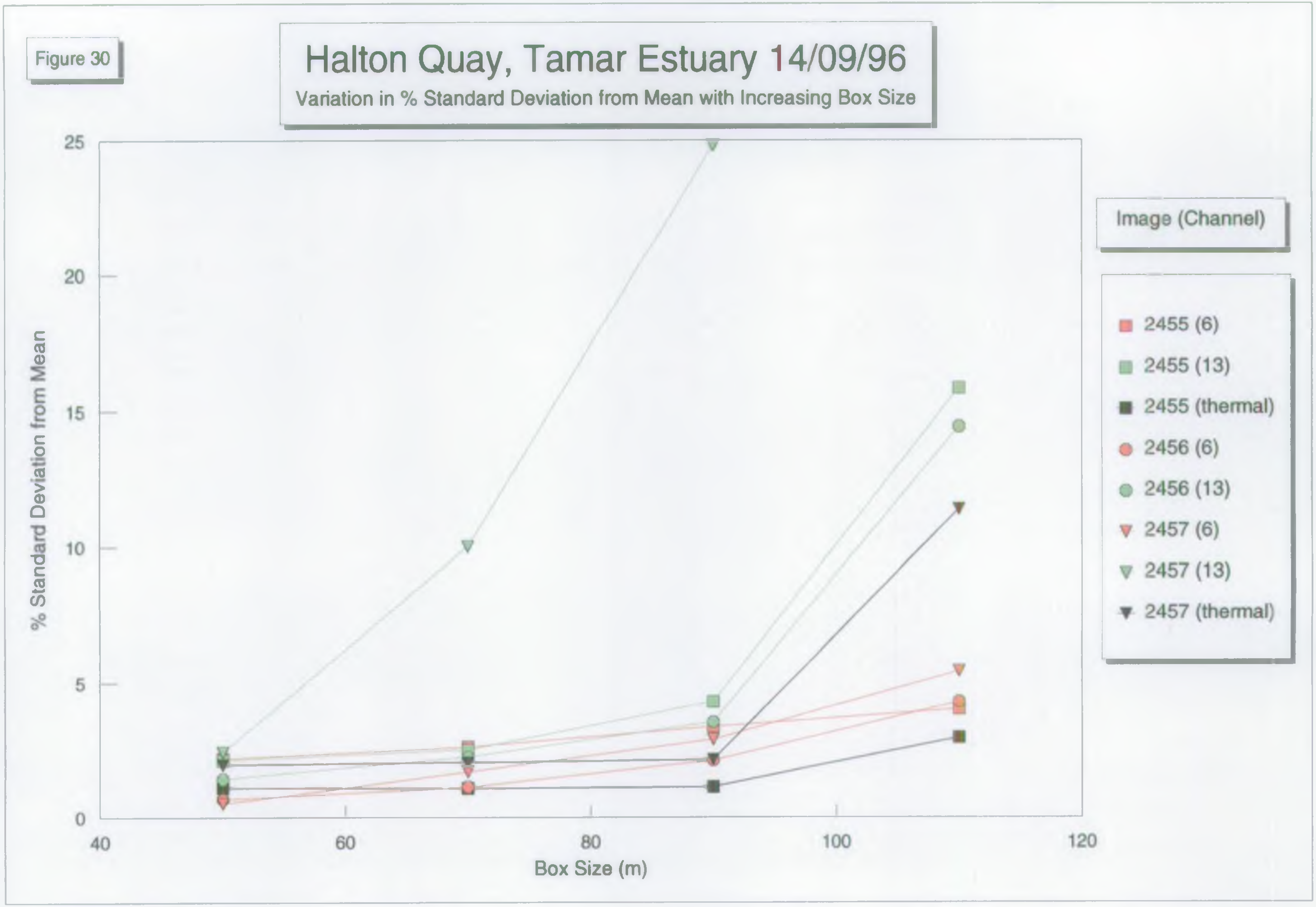


Figure 30
Halton Quay, Tamar Estuary 14/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
Box Size (m)
0
5
10
15
20
25
40
60
80
100
120
Image (Channel)
2455 (6)
2455 (13)
2455 (thermal)
2456 (6)
2456 (13)
2457 (6)
2457 (13)
2457 (thermal)

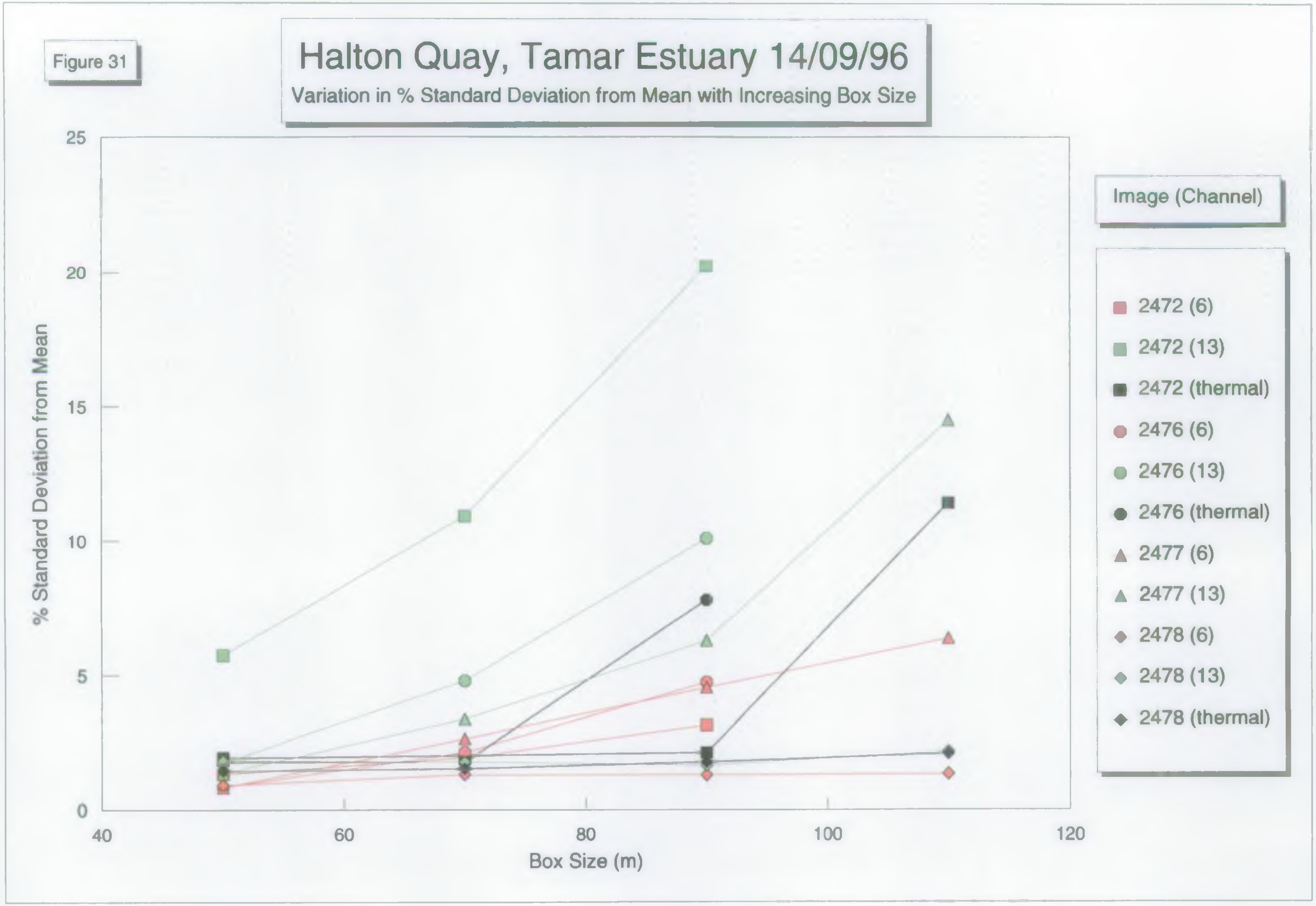


Figure 31
Halton Quay, Tamar Estuary 14/09/96
Variation in % Standard Deviation from Mean with Increasing Box Size
% Standard Deviation from Mean
0
5
10
15
20
25
40
60
80
100
120
Box Size (m)
Image (Channel)
2472 (6)
2472 (13)
2472 (thermal)
2476 (6)
2476 (13)
2476 (thermal)
2477 (6)
2477 (13)
2478 (6)
2478 (13)
2478 (thermal)

Figure 32a. Individual Frames From Suspended Solids Animation.

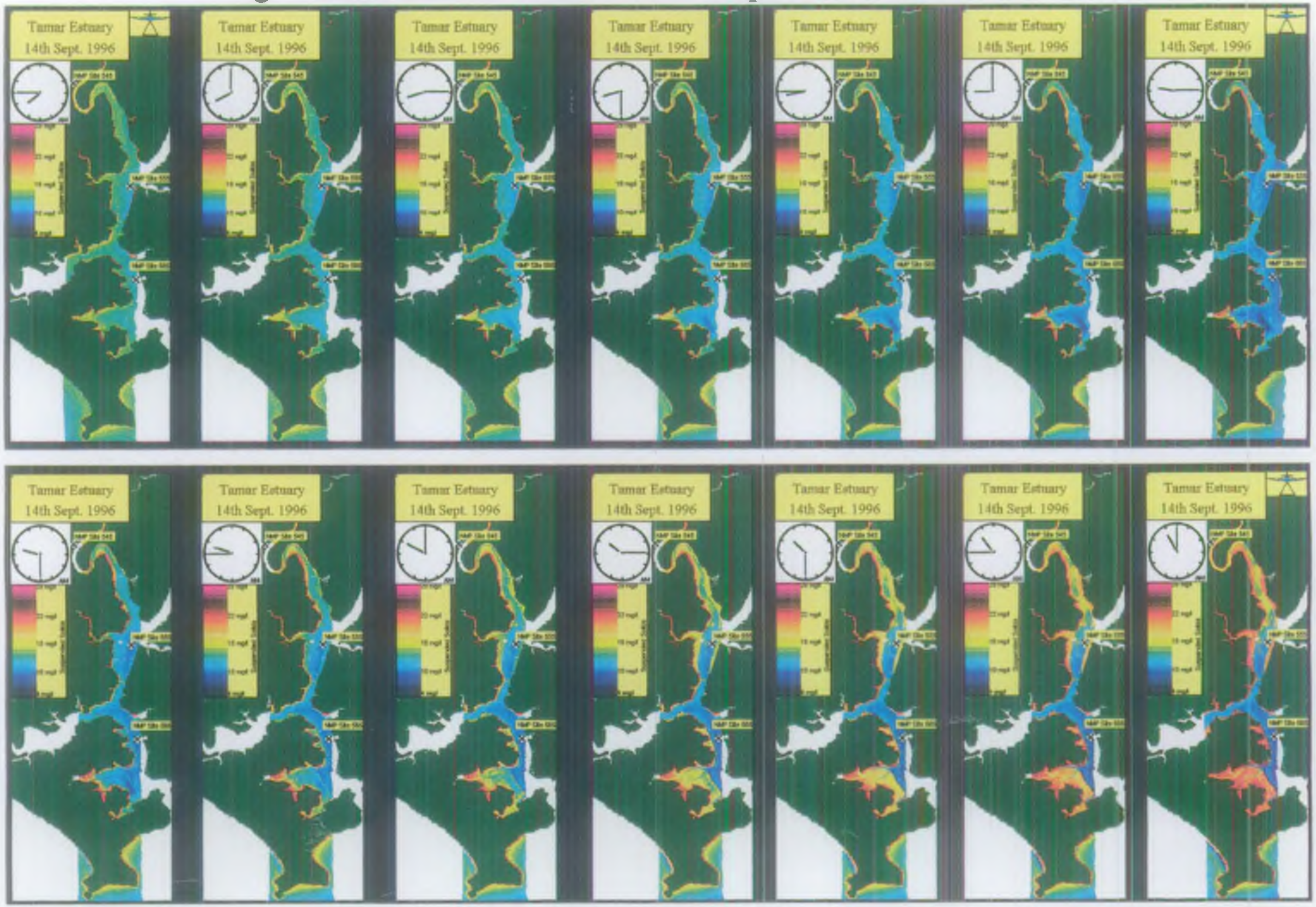


Figure 32b. Individual Frames From Suspended Solids Animation.

Figure 32c. Individual Frames From Suspended Solids Animation.