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COLOR ANALYSIS OF APPARENTLY ACHROMATIC
AUTOMOTIVE PAINTS BY VISIBLE
MICROSPECTROPHOTOMETRY

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Kristin A. Kopchick

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of the requirements for the

M.S. degree in Forensic Science

Jay Siegel
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COLOR ANALYSIS OF APPARENTLY ACHROMATIC AUTOMOTIVE PAINTS BY VISIBLE MICROSPECTROPHOTOMETRY

By

Kristin A. Kopchick

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ABSTRACT

COLOR ANALYSIS OF APPARENTLY ACHROMATIC AUTOMOTIVE PAINTS BY VISIBLE MICROSPECTROPHOTOMETRY

By

Kristin A. Kopchick

Chromatic secondary pigments are utilized in achromatic automotive paints to create unique paint systems. Achromatic paints are considered to lack color and include white, black, and shades of gray. The chromatic pigments that add an intended color effect may not be observable in reflected light; however, utilizing visible microspectrophotometry (MSP) discriminating data may be gathered. This study analyzed 160 apparently achromatic automotive paints via this technique for spectral evidence of chromatic secondary pigmentation. Positive spectral results were attained in the black and gray/silver topcoat sample set while the white topcoat and gray undercoat set yielded no spectral data. The data suggests that paint analysis schemes should incorporate visible microspectrophotometry for black and gray/silver samples.

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Introduction

Color analysis is a valuable aspect of any paint comparison performed in a forensic setting. The American Society for Testing and Materials (ASTM) and the Scientific Working Group on Materials Analysis (SWGMAT) recognize the importance of this element and outline guidelines for consistent definition and comparison of color. Different techniques have been developed to provide information on color including visible microspectrophotometry (MSP) which allows discrimination of samples by their interaction with light in the visible region of the electromagnetic spectrum. Both ASTM and SWGMAT have recommended absorption spectrophotometry as discriminating techniques for paint color (1,2). As light strikes a paint coating, some wavelengths will be absorbed based on the chemical composition of the paint and all others will be reflected resulting in the observable color of the paint. A paint which appears blue is reflecting the wavelengths of visible light in the blue region and absorbing the wavelengths of the complementary colors which comprise the remainder of the color spectrum. Variables involved with observation by the human eye include the physical state of the observer, lighting, and microscope optics. One of the primary goals of the ASTM and SWGMAT guidelines is to promote consistent analysis. Removing the subjective analysis of color is a step toward achieving this goal.

MSP eliminates the majority of these variables and produces a calibrated, objective measurement of the sample's interaction with light. MSP has been proven to be more sensitive than the human eye to differences in color (3). Early MSP was based upon reflectance which measured the amount of white light a sample would reflect. Later developments allowed for transmission spectroscopy which is preferred over reflectance due to the decrease in noise and artifacts (4). The transmitted light is dispersed by wavelength and graphically represented as a spectrum of percent light transmitted versus wavelength.

Both black and white are defined as achromatic due to their interactions with visible light as are neutral grays which are hues of black. The color perceived as white is a result of the reflection of all wavelengths of visible light. On the contrary, black objects absorb all wavelengths and the resulting lack of reflected light is perceived as the color black. Achromatic materials reflect or absorb all wavelengths approximately equally and therefore lack what is perceived as color. Because of this, achromatic forensic samples are not typically analyzed via visible MSP.

Automotive paint is a non-homogenous suspension of a binder and pigments whose purpose is two-fold: appearance and corrosion prevention. Pigments can be divided into four groups - white, color, inert, and functional. Inert and functional pigments serve as fillers and may impart some beneficial attribute to the coating such as corrosion inhibition or elasticity while white and color pigments account for the physical appearance of the layer. Rutile titanium dioxide is the predominant pigment used in white layers and as a shading agent in conjunction with other pigments. This pigment has a relatively high refractive index of 2.76 while most binders have a refractive index around 1.5, a difference of 1.26. As light travels from one material to another of a different refractive index, scattering occurs which is important for hiding in paints. Scattering is the internal reflection of light in an object and increases as the difference in refractive indices increases. Hiding prevents the darker undercoat or raw substrate layers from being observable in the finished product. Effective hiding is integral to quality paint appearance and industry demands for superior paint systems have supported the use of titanium dioxide for this beneficial attribute.

The pigments used to create black automotive coatings are the products of partial combustion of petroleum products or natural gas and are called carbon-blacks. The exact process and raw materials used to produce these pigments determine their chemical nature: however, they are essentially elemental carbon. Different groups of these carbon-black pigments exist with different particle sizes and jetness, which is a measure of blackness. Channel, furnace, and lamp blacks are examples of carbon-black pigments with increasing particle size and decreasing jetness (5).

While titanium dioxide is the preferred white pigment, it absorbs in the violet region which results in a white paint that may display a yellowish tint due to the violet wavelengths that are not reflected. To counter this, manufacturers may add a secondary pigment that will not absorb where titanium dioxide does, such as carbazole violet or even black pigments (5). This type of pigment modification is an example of secondary pigments being used to improve the final achromatic color of the coating. There is also demand on the automotive industry to develop paint systems which are unique and appealing yet still maintain high quality. The use of secondary pigments to impart a chromatic effect in an achromatic color system would be an example of this. The benefit in this instance would be subtle chromatic tinting of the achromatic shade.

Automotive paint manufacturers also often add secondary pigments to paint formulations to produce unique vehicle coatings. While the final paint coating appears achromatic, it contains pigments which are chromatic and could yield spectral data. Previous work has been done in analyzing colorless automobile topcoats via ultraviolet or near infrared MSP. No prior work on has been located regarding colorimetric analysis of achromatic color layers. This study examined a set of apparently achromatic automotive paints via MSP. The goals of this project were to determine if it is possible to obtain informative spectral data from apparently achromatic paints in the visible region and if the spectra could be of value in forensic comparisons.

Methods

One hundred twenty paint samples were obtained from damaged vehicle panels at salvage yards and local body shops. Forty samples each were obtained from vehicles with white, gray/silver, and black topcoats. An additional 40 samples of gray undercoat were obtained from the original vehicular samples resulting in a total sample set of 160. The vehicle data was recorded to track the origin of the samples (Appendix A). Sample set was not intended to be unbiased and was collected with minimal regard to manufacturer and year of production. Table 1 summarizes manufacturer and year of production for the 120 collected samples.

Samples for MSP were prepared by manually removing a thin peel of the desired layer and mounting on a microscope slide. This peel was thinned by rolling (Excel razor), immersed in 1.520 Cargille refractive index oil, and a coverslip applied. A second rolling over the coverslip was performed immediately prior to instrumental analysis. This preparation is consistent with techniques reported in published literature (6).

Examination via polarizing light microscopy (PLM) was performed with an Olympus BX41 microscope at 400x magnification. This ensured proper preparation and absence of excessive contamination by adjacent layers. Presence of metallic flake or visible pigments was also recorded (Appendix B).

Visible microspectrophotometric analysis was performed on a SEE 2100 with 15x objective. Grams 32 software was used for spectral manipulation and instrument control. NIST traceable standards were used to calibrate the instrument. Dark and reference scans were performed prior to analysis of each sample. Samples were analyzed in five locations in absorbance mode. Each location analysis result was an average of ten scans.

Manufacturer	**Number of samples**	**Year of Production**	**Number of samples**
BMW	**1**	1986	1
Chrysler	**13**	1987	1
Chrysler	2	1988	3
Dodge	7	1989	5
Plymouth	4		
Ford Motor Co.	**31**	1990	8
Ford	19	1991	9
Mazda	5	1992	9
Mercury	7	1993	11
General Motors Corporation	**56**	1994	5
Buick	7	1995	9
Chevrolet	25	1996	14
Geo	2	1997	9
GMC	2	1998	5
Oldsmobile	6	1999	10
Pontiac	10		
Saturn	4	2000	3
Honda Motor Co.	**3**	2001	7
Acura	1	2002	7
Honda	2	2003	2
Hyundai	**2**	2004	2
Kia	**2**		
Mitsubishi	**2**		
Nissan	**4**		
Subaru	**2**		
Toyota	**4**		

Table 1: Vehicle totals by manufacturer and production date.

Results and Discussion

The majority of the samples resulted in a featureless curve in the visible range. This is characteristic of the flat absorption expected with achromatic samples. Some samples showed a spectrum with an increase in absorption in the same region. This region was typically between 550nm and 700nm and the absorption varied in intensity. Any absorption that was visually distinguishable from the flat achromatic absorption samples was classified as a positive spectral result.

In the black sample set, 11 of 40 yielded spectral information. Seven of the 11 samples demonstrated a slight absorbance at 700nm. Three of the 11 had absorbances from 575nm to 680nm. One sample displayed a very strong absorbance at 620nm with a shoulder at 580nm and a second absorbance at 690nm. Review of microscopy notes revealed that this sample had a blue tinted binder and was taken from a vehicle which appeared black or dark blue-black. Chromatic pigments would then be present and strong absorbances would be expected. The three samples with absorbances at 575nm to 680nm were noted to have chromatic pigment particles visible in PLM analysis. All three were distinguishable from one another. The seven samples with slight absorbances near 700nm did not show any chromatic pigment particles during initial examination via PLM (Figure 1).

In the gray/silver sample set, 10 of 40 yielded some spectral variation. Two of the 10 gave weak absorbances at 525nm and 575nm. These samples were not distinguishable based on visible spectra. Eight of 10 resulted in stronger and more distinct absorbances through out the entire visible region (Figure 2). This larger set was found via PLM to have a tinted binder. Similar to the single black sample with strong absorbances, this type

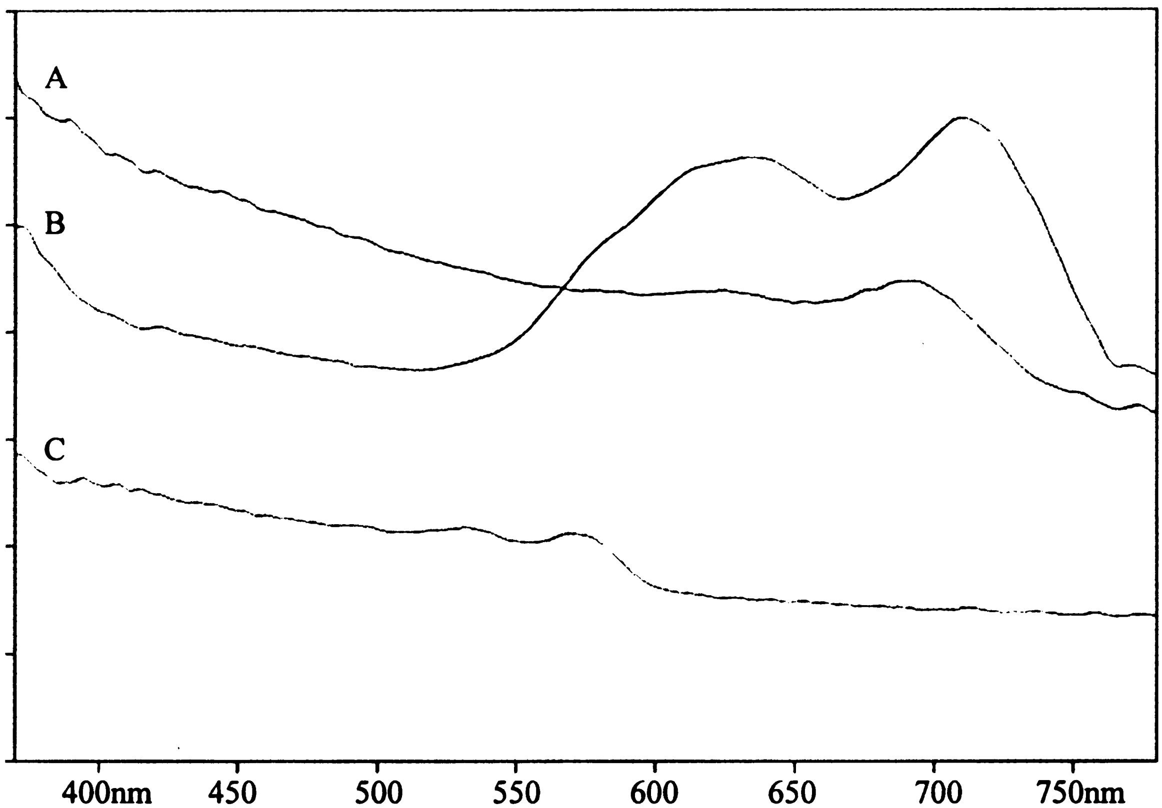

Figure 1: Absorbances in the visible spectrum may be the result of colored binders or pigments which may or may not be visible in reflected light. A: 1996 Ford Explorer where no pigments were visible via PLM, B: 1999 Mercury Sable with tinted binder, C: 1996 Oldsmobile Cutlass where pigments were visible via PLM.

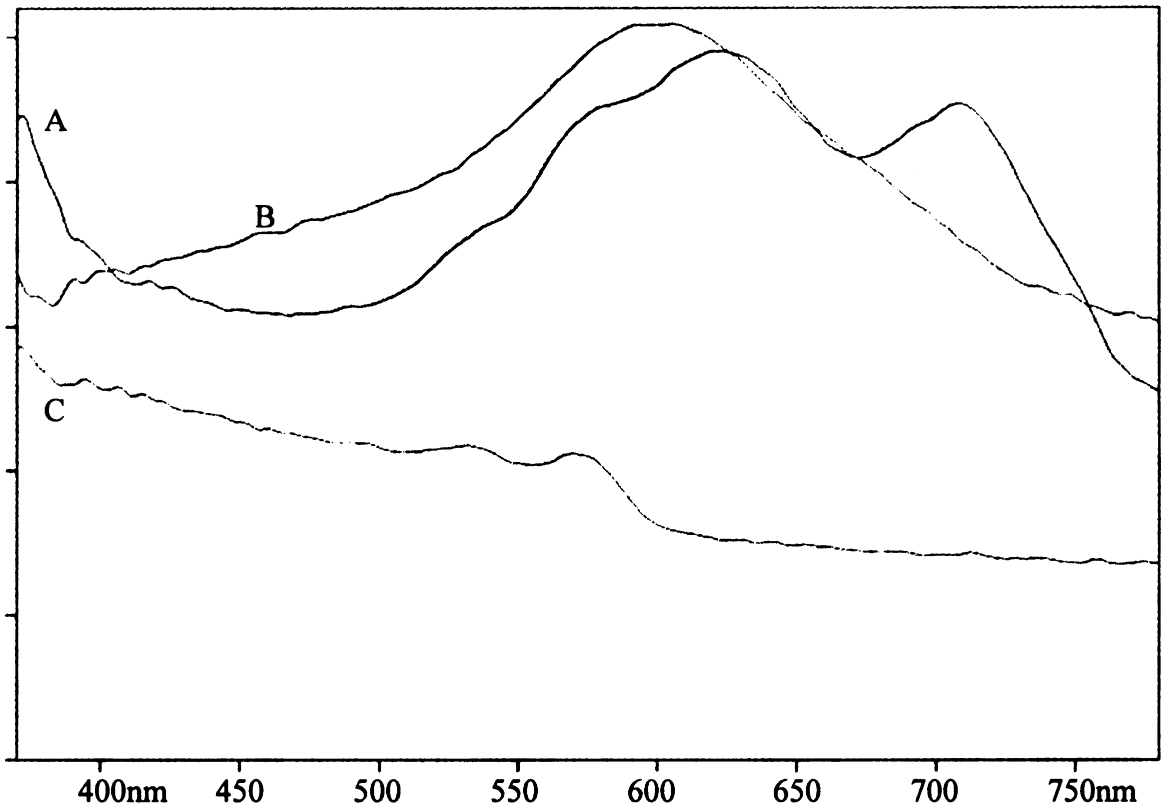

Figure 2: Spectra A and B represent gray samples which displayed strong absorbances throughout the visible region due to colored binders. Spectrum C with weaker absorbances at 525 and 575nm is consistent with grey samples with pigments visible via PLM. A: 2002 Honda Odyssey, B: 2004 Saturn Ion, C: 1996 Oldsmobile Cutlass.

of response in MSP would be expected with a colored substance. In the initial PLM exam of the set of two samples, chromatic pigment particles were identified

Within the white sample set, no informative spectra were obtained. All samples resulted in a very noisy, flat absorption. This is likely due to the prominent white pigment, rutile titanium dioxide. Its high refractive index and effective light scattering attributes prevent light from being transmitted and spectra being obtained. Similarly, the gray undercoat set also gave noisy, uninformative spectra. As undercoat layers are not typically seen in the final automotive finish, there is little need for these layers to be pigmented with a secondary pigment.

When the data gained during MSP analysis is compared to the observations made via PLM, three sources of color in the achromatic samples can be identified. In the case of the samples where a colored film or binder was identified, this is clearly the chromatic element. Whether the coloration is a result of a dye element or finely dispersed pigment particles, the effect is visible in reflected light. The MSP spectra were reproducible and were valuable in distinguishing between samples whose binders appeared similarly colored via PLM. Samples in which chromatic pigment particles were visible via PLM typically had a clear binder and while the pigments could be identified the sample did not appear colored. Concentration of the particles varied between samples as did the colors observed. Some samples only displayed one color of pigment while others displayed up to five. The spectra of these samples had greater noise and displayed weaker absorbances than that of the colored film set however; they did not vary based on analysis location within a sample. This indicates that while the heterogeneity of the sample is visible in PLM, the spectral analysis via MSP was fairly consistent within the aperture size utilized

(Figure 3).

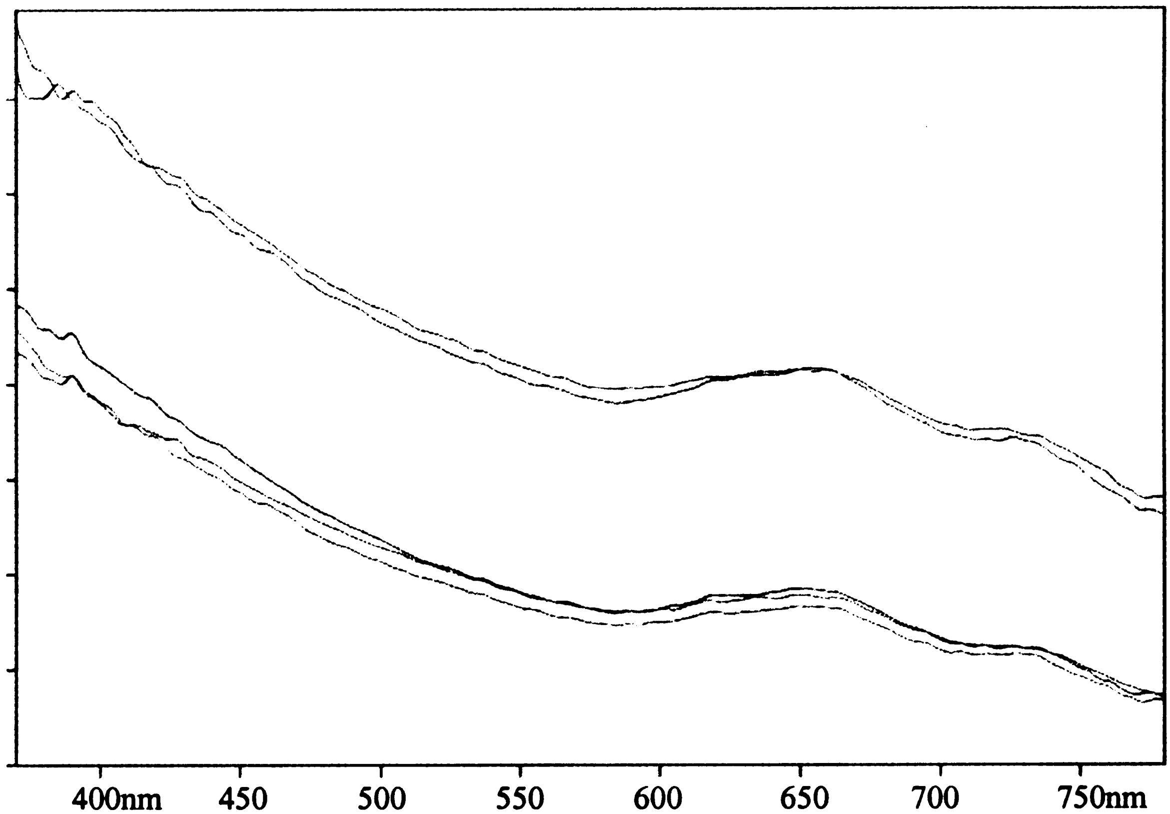

Figure 3: Five analyses from sample B34 taken from different locations. B34: 1993 BMW 318i

The final group of samples which yielded positive spectral information was not identified as having chromatic pigment particles during the initial microscopic examination. The group had very consistent spectra in MSP with slight absorbances at 700nm. Sample reproducibility within this group was also good. This set was re-examined via PLM and in some cases (3 of 7) faint pigment particles could be detected when the lamp intensity was varied. The presence of these chromatic pigments was not noted upon initial examination due to their faint color and the presence of the dark achromatic pigments.

As with any non-homogenous sample, control of preparation, and sampling is extremely important to ensure quality analysis. Sample considerations include obtaining consistent thickness and parallel planes during preparation. Microscopic techniques, including color comparisons must be made under similar conditions, e.g. same instrument and analyst, etc. Sample thinning was performed to obtain the shortest possible path length for improved MSP resolution. The analysis locations were also chosen to improve resolution. The thinnest areas of the mounted sample were scanned regardless of pigment presence or density. The only other consideration made during sampling was to avoid metallic flakes which efficiently refract light to produce their effects and would interfere with obtaining spectra.

Conclusions

This project analyzed achromatic automotive paints for the purpose of determining whether microspectrophotometric spectra were attainable in the visible region and if those spectra could have forensic value. For white and gray primer coatings, no spectra were obtained and the technique yielded no discrimating value. However, for black and gray paints, some spectra were obtained. This spectral information enabled discrimination of the positive samples from those that did not yield spectra. Additionally, some discrimination was possible within the group of positive samples. When the data obtained via PLM and MSP are used in conjunction, the level of discrimination increases.

The work of this thesis also proposes sources of chromaticity in the achromatic materials that could result in spectra. A colored binder is an apparent source and is often observable during preparation and noted via PLM. These samples often originated from vehicles that appeared to have a slightly tinted color such as greenish gray. MSP enabled discrimination between the metameric pairs. The second source of color identified was agglomerations of pigment particles that were visible via PLM. Spectra were reproducible and displayed absorbances at different wavelengths, allowing discrimination. Samples that showed neither colored binders nor visible pigments comprised the third group. It is proposed that these paints contain some secondary chromatic pigments which are not visible in reflected light but do absorb in the visible region enabling them to produce spectra. As the presence of this chromatic element is not noted in a microscopic examination, MSP analysis becomes significant.

Achromatic paints are commonly used vehicle coatings. Recent information shows silver is the most popular vehicle color with 24.1% of 2005 model sales in the fourth quarter of 2004. Black was second on the list with 16.7% of sales. (7) The possibility that achromatic coatings will then be encountered by the forensic analyst is rather high. Paint evidence may be analyzed via polarizing light microscopy and infrared spectroscopy and no discriminating data gained. The application of a microspectrophotometric technique may reveal different absorbance trends in the visible region. This may allow questioned and known samples to be discriminated. Additionally, consistent results in MSP analysis, combined with other analyses, reduces the class size of common sources and strengthens the association between questioned and known material.

As a colorimetric technique, MSP analysis can be applied early in the analyst's scheme, preferably after a PLM examination and prior to infrared spectroscopy or elemental analysis. The necessary preparation of samples for MSP analysis is in line with that for there techniques and can be easily incorporated. While this study found no valuable information with the white sample set, the data suggests that while a sample appears achromatic, a MSP spectrum may be attainable. This project advises analysis of all color layer samples which may include very subtly pigmented samples including white. Very pale chromatic samples may appear white especially considering the small sample size typically encountered in forensic settings.

In summary, the work of this thesis promotes the use of visible microspectrophotometric analysis techniques in regards to black, and grey or silver automotive paints. Increased discrimination based on the presence or absence of secondary chromatic pigments is the basis for this recommendation. This work has shown these pigments to be present with artifacts both visible and non-visible via microscopy and to yield spectra due to absorbances in the visible region. Substantial forensic information may be gained via this technique. It is therefore recommended that when MSP is regularly included in an automotive paint analysis scheme it should be included in schemes involving black and gray/silver topcoats.

Future Work

The conclusions of this thesis have raised questions that are in need of future investigation and research. Studies with a larger sample size may be able to significantly determine whether microspectrophotometric techniques offer more resolving power than polarizing light microscopy. Increased sample size with consideration paid to manufacturer during collection would also allow for increased interpretation. Determining what percentage of the automobile paint population yields positive spectral results would be valuable in analyzing the importance of this class. Also, investigatory information may be developed that would be useful when only questioned material is available.

Interesting topics to investigate include the effects of weathering and sampling location (roof, door, quarter panel, etc.) Applying the techniques used in this thesis to other apparently achromatic materials may also prove informative. Such materials include achromatic fibers which also utilize pigments and possibly contain secondary chromatic elements.

It was noted in the course of this research that certain samples contained very large agglomerations of pigments. These were often gray paints with secondary blue pigments. One sample was analyzed in four locations based on thickness, as was the established method, and the fifth analysis was taken of the secondary pigment. It was possible to place the aperture of the MSP within the border of this agglomeration and obtain a spectrum from the pigment particle alone. The first four locations yielded flat absorptions while the fifth yielded a positive spectrum. Future work into this application of selective scanning could prove beneficial in discrimination between these pigment agglomerations. Effects of size and distribution within samples that contain these pigments would first need to be studied.

References were located that recommended the use of a microtome for sectioning and thinning. While not performed in this research, microtoming could produce thinner samples that could improve spectral analysis. One of the chromatic sources identified in this project included pigment particles identified via PLM. However, there were samples that displayed these pigments but did not yield spectral data. Applying microtoming to these samples prior to MSP analysis would be an interesting project to determine if thinning would truly increase microspectrophotometric analysis. Microtoming may also reduce the sample concentration of chromatic elements by creating such thin samples that the MSP analysis loses resolution. Analysis of microtomed samples that yielded positive spectral results when manually peeled would investigate this possibility and could provide conclusions.

APPENDICES

Appendix A

Vehicle Data of all Samples Collected

Table 2: Vehicle Data of all Samples Collected

Sample Number	Make	Model	VIN	Year	Color	Area Sampled	Collection info
W1	Chevy	Cavalier	1G1JC12Y2VM147611	1997	WHITE	dr front qp	10/4 Shroyers
W2	Mazda	MX-3	JM1EC4311N0132667	1992	WHITE		10/4 Shroyers
W3	Pontiac	Grand Am	1GZNE54D1NCZ30559	1992	WHITE		10/4 Shroyers
W4	Ford	Escort	1FAPP11J9MW108715	1990	WHITE		10/4 Shroyers
W5	Chevy	Lumina APV	1GNCU06D1LT169028	1990	WHITE		10/4 Shroyers
W6	Pontiac	Grand Am SE	1GZNE5439NM058055	1992	WHITE	dr rear qp	10/4 Shroyers
W7	Geo	Storm Gsi	J81RT2354M7561361	1991	WHITE	dr front qp	10/4 Shroyers
W8	Dodge	Spirit	3B3XA46K9PT530252	1993	WHITE	pass front qp	10/4 Shroyers
W9	Pontiac	Grand Am	1GZNE1433PM590025	1993	WHITE	roof	10/4 Shroyers
W10	Chevy	Corsica	1G1LD55M7RY270683	1994	WHITE	pass front qp	10/4 Shroyers
W11	Chevy	Cavalier	1G1JC524427296314	2002	WHITE	pass front qp	10/4 Shroyers
W12	Chevy	Monte Carlo	2G1WW12E7Y9293400	2000	WHITE	hood	10/4 Shroyers
W13	Nissan	Altima	1N4BU31F2PC180775	1993	WHITE	trunk	10/13 Tenny
W14	Ford	Escort	1FASP11J6SW360283	1996	WHITE	dr rear qp	10/30 Birrells
W15	Chrysler	Concorde	2C3HD56F8TH281565	1996	WHITE	pass front qp	10/30 Birrells
W16	Pontiac	Sunfire	1G2JB1243T7561507	1996	WHITE	pass front qp	10/30 Birrells
W17	Plymouth	Breeze	1P3EJ46C0WN187604	1998	WHITE	hood	10/30 Birrells
W18	Hyundai	Elantra	KMHJF32M6PU355161	1993	WHITE	dr rear qp	10/30 Birrells
W19	Geo	Metro	2C1MR5299V6737161	1997	WHITE	pass rear qp	10/30 Birrells
W20	Chevy	Corsica	1G1LT54G0LY214333	1990	WHITE	dr rear qp	10/30 Birrells
W21	Ford	Crown Victoria	2FAFP71W11X147034	2001	WHITE		10/30 Birrells
W22	Pontiac	Grand Am	1G2NE52T3TC702476	1995	WHITE	dr front qp	10/30 Birrells

W23	Pontiac	Grand Am	1G2NE14U2LC359576	1990	WHITE	hood	10/30 Birrells
W24	Ford	Escort GT	1FAPP1287PW176656	1993	WHITE	hood	10/30 Birrells
W25	Chevy	1500 truck	1GCEC19V7YE152163	1999	WHITE	dr front qp	10/30 Birrells
W26	GMC	Sonoma	1GTCS1441TK512157	1996	WHITE	dr front qp	10/30 Birrells
W27	Buick	Century	3G4AG54N9NS611935	1991	WHITE	pass front qp	10/30 Birrells
W28	Ford	F350 truck	3FEKF3751VMA69097	1998	WHITE	hood	10/30 Birrells
W29	Chevy	Lumina	1G1LD55M1TY141913	1996	WHITE	dr front qp	10/30 Birrells
W30	Ford	Escort	1FASP10J2SW134498	1995	WHITE	pass rear qp	10/30 Birrells
W31	Buick	Le Sabre limited	1G4HR52K5WH521841	1998	WHITE		12/1 Tenny
W32	Chevy	Lumina	2G1WL52M8S1138707	1995	WHITE	pass front door	12/1 Tenny
W33	Olds	Cutlass GLS	1G3NG52M9X6313733	1999	WHITE		12/1 Tenny
W34	Plymouth	Acclaim	1P3XA463XNF231903	1992	WHITE		12/1 Tenny
W35	Chevy	S10 Pickup	1GCCS14Z4M0193412	1991	WHITE		12/1 Tenny
W36	Buick	Regal		1991	WHITE		12/1 Shroyers
W37	Ford	Contour		1997	WHITE		12/1 Shroyers
W38	Ford	van		1992	WHITE	pass front qp	12/1 Shroyers
W39	Ford	Focus		2001	WHITE		12/1 Shroyers
W40	Acura	2.2 CL	19UYA1158VL018267	1997	WHITE		12/1 Shroyers
G1	Dodge	Caravan SE	2B4FK41GXGR770985	1986	GRAY	dr rear qp	10/4 Shroyers
G2	Chevy	Cavalier	1G1JC1110KJ2733051	1989	GRAY	dr door inner	10/4 Shroyers
G3	Toyota	Tercel DX	JT2EL43A0M0060903	1991	SILVER	front bump	10/4 Shroyers
G4	Kia	Rio	KNADC123816080150	2001	GRAY	rear bump	10/4 Shroyers
G5	Subaru	Loyale	JF1AC4227MB207180	1991	SILVER	pass front door	10/4 Shroyers
G6	Chrysler	New Yorker	1C3XV66R5PD167017	1993	SILVER	trunk	10/4 Shroyers
G7	Ford	Mustang	1FACP44MZPF160441	1993	SILVER	pass door	10/4 Shroyers

G8	Buick	Skylark	1G4NV54N5PC250932	1993	SILVER	hood	10/4 Shroyers
G9	Chevy	Lumina Euro	2G1WN54T7N9248278	1992	SILVER	dr front door	10/4 Shroyers
G10	Pontiac	Grand Prix SE	1G2WP14TXKF312895	1989	SILVER	dr rear upper	10/4 Shroyers
G11	Buick	Regal Limited	2G4WD14WXJ1515849	1988	GRAY	hood	10/4 Shroyers
G12	Olds	Aurora	11G3GR62C2S4118528	1995	SILVER		10/13 Tenny
G13	Toyota	Camry SE	4T1BG22K9YU662481	2000	SILVER		10/13 Tenny
G14	Mercury	Sable	1MEFMF9S53A618394	2003	GRAY		10/13 Tenny
G15	Mazda	626	1YVGE22A0P5149131	1993	SILVER	pass front qp	10/13 Tenny
G16	Ford	Escort	1FARP15J8RW295472	1994	SILVER	dr rear qp	10/30 Birrells
G17	Mercury	Villager	4M2DV11W6SDJ77508	1995	SILVER	dr side panel	10/30 Birrells
G18	Chevy	Lumina	2G1WL52M2V1114410	1997	SILVER	hood	10/30 Birrells
G19	Hyundai	Accent	KMHVD34N3WU405459	1999	SILVER	dr front qp	10/30 Birrells
G20	Mercury	Sable G5	1MEFM50U0XA621756	1999	GRAY/GRN	dr front qp	10/30 Birrells
G21	Ford	Probe	3FAFP11392R179992	2002	SILVER	hood	10/30 Birrells
G22	Chevy	Malibu	1G3NG52J4X6312995	1999	SILVER	qp	10/30 Birrells
G23	Dodge	Stratus	1B3EJ46X5VN527560	1996	SILVER	pass front qp	10/30 Birrells
G24	Ford	Escort SE	1FAFP13P5XW28264	1999	SILVER	pass front qp	10/30 Birrells
G25	Kia	Rio	KNADC123626195296	2002	SILVER	hood	10/30 Birrells
G26	Chevy	Beretta	1G1LV15M1SY262896	1995	GRAY	hood	10/30 Birrells
G27	Pontiac	Grand Am	1G2NE5438NM025208	1992	SILVER	trunk	10/30 Birrells
G28	Mercury	Grand Marquis	2MEFM74W6XX611215	1999	SILVER	rear bump	10/30 Birrells
G30	Chevy	Lumina	2G1WL54T8N1150915	1992	GRAY	hood	10/30 Birrells
G31	Dodge	Ram 1500	2B7HB11X6VK564837	1997	GRAY	roof	10/30 Birrells
G32	Buick	LeSabre	1G4HP52L2RH401837	1994	GRAY	roof	10/30 Birrells
G33	Toyota	Camry LE	4T1BG12K2TU026661	1996	DK GRAY	pass front qp	10/30 Birrells

G34	Toyota	Camry	JT2VV22W9J0005020	1988	GRAY	dr front qp	10/30 Birrells
G35	Saturn	Vue	5GZCZ63B22832111	2002	SILVER	rear hatch	12/1 Tenny
G36	Subaru	Forrester		2004	SILVER	hood	11/27 Kopchick
G37	Dodge	Neon	1B3AS46F41D134510	2001	SILVER	dr front qp	12/1 Tenny
G38	Mercury	Sable		2001	SILVER	hood	12/1 Tenny
G39	Olds	Cutlass		1996	SILVER	hood	12/1 Tenny
G40	Saturn	Ion	1G8AJ52F04Z209458	2004	GRAY	hood	12/1 Tenny
G45	Honda	Odyssey EX	5FNRL18682B041820	2002	GRAY	door panel	12/1 Tenny
B1	Chevy	Astro	1GNDM15Z5LB152052	1990	BLACK		10/4 Shroyers
B2	Mazda	MX-3	JM1EC4355R0304059	1994	BLACK		10/4 Shroyers
B3	Mitsubishi	Eclipse GS	4A3CS44R7ME111478	1991	BLACK	pass front door	10/4 Shroyers
B4	Plymouth	Laser LS	4P3CS44U1LE085030	1990	BLACK	dr front qp	10/4 Shroyers
B5	Plymouth	Colt	JP3CU34X4KU041253	1989	BLACK	dr read qp	10/4 Shroyers
B6	Dodge	Intrepid	2B3HD46R6XH677484	1999	BLACK		10/4 Shroyers
B7	Mercury	Grand Marquis	ZMECM75F6LX640256	1990	BLACK ?	pass front door	10/4 Shroyers
B8	Pontiac	Grand Am	1G2NE1JM2SM546775	1995	BLACK	pass rear qp	10/4 Shroyers
B9	Buick	Park Avenue	1G4CW53L0M1630210	1991	BLACK	pass rear qp	10/4 Shroyers
B10	Ford	Taurus CX 4d	1FALP53S8VG181162	1997	BLACK	pass front qp	10/4 Shroyers
B11	Pontiac	Grand Prix SE	1G2WJ14T5MF216287	1991	BLACK	dr front qp	10/4 Shroyers
B12	Olds	Cutlass Supreme	1G3WR14W2KD305192	1989	BLACK	dr front door	10/4 Shroyers
B13	Olds	Royale 88	1G3HY54CZLH335554	1990	BLACK	dr front qp	10/4 Shroyers
B14	Chevy	Z26	1G1LW15M6RY278731	1994	BLACK	pass front qp	10/4 Shroyers
B15	Mercury	Tracer	3MAP10J9NR616983	1992	BLACK	dr front door	10/4 Shroyers
B16	Mazda	RX7	JM1FC3312K0706509	1989	BLACK	dr qp	10/4 Shroyers

B17	Nissan	Maxima	JN1EJ01F8PT417125	1993	BLACK	dr door	10/13 Tenny
B18	Nissan	Altima	1N4DL01D61C182528	2001	BLACK	dr front qp	10/13 Tenny
B19	Ford	Mustang	1FAFP4ZX4WF179310	1998	BLACK		10/13 Tenny
B20	Nissan	Pulsar NX	JN1PN34S1JW401104	1988	BLACK	dr front qp	10/30 Birrells
B21	Saturn	SC1	1G8ZP12851Z229745	2001	BLACK	door	10/30 Birrells
B22	Chevy	Cavalier	1G1JC1244X7198335	1999	BLACK	pass rear	10/30 Birrells
B23	Ford	Escort	1FALP13P7VW396431	1997	BLACK	hood	10/30 Birrells
B24	Chevy	S10 truck	1GCCS19W428215664	2002	BLACK	pass cab	10/30 Birrells
B25	Mazda	Millenia	JM1TA2227Y1601030	2000	BLACK		10/30 Birrells
B26	Ford	Escort	1FALP10P6VW274198	1997	BLACK	roof	10/30 Birrells
B27	Dodge	Caravan LE	2B4FK5139HR386314	1987	BLACK	dr door	10/30 Birrells
B28	Olds	Cutlass		1996	BLACK		12/1 Tenny
B29	Honda	Civic	1HGES26822L064620	2002	BLACK	hood	12/1 Tenny
B30	Ford	Explorer XLT		1996	BLACK	dr front qp	12/1 Tenny
B31	Mitsubishi	Eclipse	4A3AK54F1TE249275	1996	BLACK	hood	12/1 Tenny
B32	Chevy	Cavalier	1G1JC1244X7147241	1999	BLACK	dr front qp	12/1 Tenny
B33	Ford	Escort ZX2		1998	BLACK	dr rear door	11/28 McKinney
B34	BMW	318i	WBACA5317PFG07743	1993	BLACK		12/1 Tenny
B35	Chevy	s10 Blazer		1995	BLACK		12/1 Shroyers
B36	GMC	Yukon XL		2003	BLACK	pass front qp	12/1 Kouts
B37	Chevy	Lumina		1996	BLACK		12/1 Shroyers
B38	Chevy	Cavalier		1996	BLACK	dr front qp	12/1 Shroyers
B39	Saturn	ion		1996	BLACK		12/1 Shroyers
B40	Chevy	Cavalier		1995	BLACK		12/1 Shroyers
W6GP	Pontiac	Grand Am	1GZNE5439NM058055	1992	WHITE	dr rear qp	10/4 Shroyers
W7GP	Geo	Storm Gsi	J81RT2354M7561361	1991	WHITE	dr front qp	10/4 Shroyers

W8GP	Dodge	Spirit	3B3XA46K9PT530252	1993	WHITE	pass front qp	10/4 Shroyers
W10GP	Chevy	Corsica	1G1LD55M7RY270683	1994	WHITE	pass front qp	10/4 Shroyers
W12GP	Chevy	Monte Carlo	2G1WW12E7Y9293400	2000	WHITE	hood	10/4 Shroyers
W13GP	Nissan	Altima	1N4BU31F2PC180775	1993	WHITE	trunk	10/13 Tenny
W14GP	Ford	Escort	1FASP11J6SW360283	1996	WHITE	dr rear qp	10/30 Birrells
W15GP	Chrysler	Concorde	2C3HD56F8TH281565	1996	WHITE	pass front qp	10/30 Birrells
W16GP	Pontiac	Sunfire	1G2JB1243T7561507	1996	WHITE	pass front qp	10/30 Birrells
W17GP	Plymouth	Breeze	1P3EJ46C0WN187604	1998	WHITE	hood	10/30 Birrells
W20GP	Chevy	Corsica	1G1LT54G0LY214333	1990	WHITE	dr rear qp	10/30 Birrells
W22GP	Pontiac	Grand Am	1G2NE52T3TC702476	1995	WHITE	dr front qp	10/30 Birrells
W24GP	Ford	Escort GT	1FAPP1287PW176656	1993	WHITE	hood	10/30 Birrells
W25GP	Chevy	1500 truck	1GCEC19V7YE152163	1999	WHITE	dr front qp	10/30 Birrells
W26GP	GMC	Sonoma	1GTCS1441TK512157	1996	WHITE	dr front qp	10/30 Birrells
W27GP	Buick	Century	3G4AG54N9NS611935	1991	WHITE	pass front qp	10/30 Birrells
W28GP	Ford	F350	3FEKF3751VMA69097	1998	WHITE	hood	10/30 Birrells
G2GP	Chevy	Cavalier	1G1JC1110KJ2733051	1989	GRAY	dr door inner	10/4 Shroyers
G3GP	Toyota	Tercel DX	JT2EL43A0M0060903	1991	SILVER	front bump	10/4 Shroyers
G4GP	Kia	Rio	KNADC123816080150	2001	GRAY	rear bump	10/4 Shroyers
G5GP	Subaru	Loyale	JF1AC4227MB207180	1991	SILVER	pass front door	10/4 Shroyers
G6GP	Chrysler	New Yorker	1C3XV66R5PD167017	1993	SILVER	trunk	10/4 Shroyers
G7GP	Ford	Mustang	1FACP44MZPF160441	1993	SILVER	pass door	10/4 Shroyers
G8GP	Buick	Skylark	1G4NV54N5PC250932	1993	SILVER	hood	10/4 Shroyers
G9GP	Chevy	Lumina Euro	2G1WN54T7N9248278	1992	SILVER	dr front door	10/4 Shroyers
G15GP	Mazda	626	1YVGE22AOP5149131	1993	SILVER	pass front qp	10/13 Tenny
G16GP	Ford	Escort	1FARP15J8RW295472	1994	SILVER	dr rear qp	10/30 Birrells
G18GP	Chevy	Lumina	2G1WL52M2V1114410	1997	SILVER	hood	10/30 Birrells

G19GP	Hyundai	Accent	KMHVD34N3WU405459	1999	SILVER	dr front qp	10/30 Birrells
G20GP	Mercury	Sable G5	1MEFM50U0XA621756	1999	GRAY/GRN	dr front qp	10/30 Birrells
G21GP	Ford	Probe	3FAFP11392R179992	2002	SILVER	hood	10/30 Birrells
G22GP	Chevy	Malibu	1G3NG52J4X6312995	1999	SILVER	qp	10/30 Birrells
G23GP	Dodge	Stratus	1B3EJ46X5VN527560	1996	SILVER	pass front qp	10/30 Birrells
G33GP	Toyota	Camry LE	4T1BG12K2TU026661	1996	DK GRAY	pass front qp	10/30 Birrells
B1GP	Chevy	Astro	1GNDM15Z5LB152052	1990	BLACK		10/4 Shroyers
B3GP	Mitsubishi	Eclipse GS	4A3CS44R7ME111478	1991	BLACK	pass front door	10/4 Shroyers
B4GP	Plymouth	Laser LS	4P3CS4401LE085030	1990	BLACK	dr front qp	10/4 Shroyers
B13GP	Olds	Royale 88	1G3HY54CZLH335554	1990	BLACK	dr front qp	10/4 Shroyers
B14GP	Chevy	Z26	1G1LW15M6RY278731	1994	BLACK	pass front qp	10/4 Shroyers
B16GP	Mazda	RX7	JM1FC3312K0706509	1989	BLACK	dr qp	10/4 Shroyers
B17GP	Nissan	Maxima	JN1EJ01F8PT417125	1993	BLACK	dr door	10/13 Tenny
B19GP	Ford	Mustang	1FAFP4ZX4WF179310	1998	BLACK		10/13 Tenny

Appendix B

Table 3: Polarizing Light Microscopy Data

Sample Number	Make	Model	Color	PLM Notes
W1	Chevy	Cavalier	WHITE	No flake, properly mounted
W2	Mazda	MX-3	WHITE	"
W3	Pontiac	Grand Am	WHITE	"
W4	Ford	Escort	WHITE	"
W5	Chevy	Lumina APV van	WHITE	"
W6	Pontiac	Grand Am SE	WHITE	some rust present
W7	Geo	Storm Gsi	WHITE	No flake, properly mounted
W8	Dodge	Spirit	WHITE	"
W9	Pontiac	Grand Am	WHITE	"
W10	Chevy	Corsica	WHITE	"
W11	Chevy	Cavalier	WHITE	"
W12	Chevy	Monte Carlo	WHITE	"
W13	Nissan	Altima	WHITE	"
W14	Ford	Escort	WHITE	"
W15	Chrysler	Concorde	WHITE	"
W16	Pontiac	Sunfire	WHITE	"
W17	Plymouth	Breeze	WHITE	"
W18	Hyundai	Elantra	WHITE	"
W19	Geo	Metro	WHITE	"
W20	Chevy	Corsica	WHITE	"
W21	Ford	Crown Victoria	WHITE	some primer cont.
W22	Pontiac	Grand Am	WHITE	No flake, properly mounted
W23	Pontiac	Grand Am	WHITE	"
W24	Ford	Escort GT	WHITE	"
W25	Chevy	1500 truck	WHITE	"
W26	GMC	Sonoma	WHITE	small amount of primer contamination
W27	Buick	Century	WHITE	flake, properly mounted
W28	Ford	F350 truck	WHITE	No flake, properly mounted
W29	Chevy	Lumina	WHITE	"

W30	Ford	Escort	WHITE	"
W31	Buick	Le Sabre limited	WHITE	"
W32	Chevy	Lumina	WHITE	"
W33	Olds	Cutlass GLS	WHITE	"
W34	Plymouth	Acclaim	WHITE	No flake, properly mounted
W35	Chevy	S10 Pickup	WHITE	"
W36	Buick	Regal	WHITE	"
W37	Ford	Contour	WHITE	little contamination
W38	Ford	van	WHITE	No flake, properly Mounted
W39	Ford	Focus	WHITE	"
W40	Acura	2.2 CL	WHITE	"
G1	Dodge	Caravan SE	GRAY	Transparent with flake, properly mounted
G2	Chevy	Cavalier	GRAY	transparent with flake, properly mounted
G3	Toyota	Tercel DX	SILVER	Heavy flake
G4	Kia	Rio	GRAY	Transparent blue with Flake
G5	Subaru	Loyale	SILVER	Transparent with flake, pigments visible, some rust and primer cont.
G6	Chrysler	New Yorker	SILVER	heavy flake, little pigment
G7	Ford	Mustang	SILVER	little blue pigment, flake, some rust cont.
G8	Buick	Skylark	SILVER	Transparent with flake, properly mounted
G9	Chevy	Lumina Euro 4d	SILVER	"
G10	Pontiac	Grand Prix SE	SILVER	"
G11	Buick	Regal Limited	GRAY	"
G12	Olds	Aurora	SILVER	Faintly blue with flake
G13	Toyota	Camry SE	SILVER	Transparent with flake, properly mounted
G14	Mercury	Sable	GRAY	greenish tint
G15	Mazda	626	SILVER	some rust present
G16	Ford	Escort Wagon	SILVER	Transparent with flake, some primer cont.
G17	Mercury	Villager	SILVER	Transparent with flake, properly mounted
G18	Chevy	Lumina	SILVER	some primer cont.
G19	Hyundai	Accent	SILVER	some pigments visible

G20	Mercury	Sable G5	GRAY/GRN	green with flake and mica
G21	Ford	Probe	SILVER	mica flake
G22	Chevy	Malibu	SILVER	Transparent with flake, properly mounted
G23	Dodge	Stratus	SILVER	yellow with flake
G24	Ford	Escort SE	SILVER	Transparent with flake, properly mounted
G25	Kia	Rio	SILVER	heavy flake, little primer cont.
G26	Chevy	Beretta	GRAY	Transparent with flake and mica, properly mounted
G27	Pontiac	Grand Am	SILVER	Transparent with flake, properly mounted
G28	Mercury	Grand Marquis	SILVER	little primer cont.
G30	Chevy	Lumina	GRAY	Heavy flake
G31	Dodge	Ram 1500 van	GRAY	No flake, properly Mounted
G32	Buick	LeSabre	GRAY	red with mica
G33	Toyota	Camry LE	DK GRAY	pinkish with flake
G34	Toyota	Camry	GRAY	dense with red, blue pigs
G35	Saturn	Vue	SILVER	Transparent with flake, properly mounted
G36	Subaru	Forrester	SILVER	fragmented, Transparent with flake
G37	Dodge	Neon	SILVER	Transparent with flake, properly mounted
G38	Mercury	Sable	SILVER	pigments present
G39	Olds	Cutlass	SILVER	some pigments visible
G40	Saturn	Ion	GRAY	blue with flake, and blue pigments
G45	Honda	Odyssey EX van	GRAY	Transparent blue with some rust
B1	Chevy	Astro	BLACK	Properly mounted
B2	Mazda	MX-3	BLACK	"
B3	Mitsubishi	Eclipse GS	BLACK	"
B4	Plymouth	Laser LS	BLACK	"
B5	Plymouth	Colt	BLACK	"
B6	Dodge	Intrepid	BLACK	Metallic flake, large blue pigments
B7	Mercury	Grand Marquis LS	BLACK ?	Transparent blue, Flake

B8	Pontiac	Grand Am	BLACK	Properly mounted
B9	Buick	Park Avenue	BLACK	"
B10	Ford	Taurus CX 4d	BLACK	round flake visible
B11	Pontiac	Grand Prix SE	BLACK	Properly mounted
B12	Olds	Cutlass Supreme	BLACK	"
B13	Olds	Royale 88	BLACK	"
B14	Chevy	Z26	BLACK	"
B15	Mercury	Tracer	BLACK	Properly mounted
B16	Mazda	RX7	BLACK	"
B17	Nissan	Maxima	BLACK	"
B18	Nissan	Altima	BLACK	appears more grey than others
B19	Ford	Mustang	BLACK	Properly mounted
B20	Nissan	Pulsar NX	BLACK	"
B21	Saturn	SC1	BLACK	some primer cont.
B22	Chevy	Cavalier	BLACK	Properly mounted
B23	Ford	Escort	BLACK	"
B24	Chevy	S10 truck	BLACK	Some primer cont. and blue pigments
B25	Mazda	Millenia	BLACK	Properly mounted
B26	Ford	Escort	BLACK	"
B27	Dodge	Caravan LE	BLACK	"
B28	Olds	Cutlass	BLACK	"
B29	Honda	Civic	BLACK	"
B30	Ford	Explorer XLT	BLACK	some contamination
B31	Mitsubishi	Eclipse	BLACK	some primer cont.
B32	Chevy	Cavalier	BLACK	Properly mounted
B33	Ford	Escort ZX2	BLACK	"
B34	BMW	318i	BLACK	blue pigments
B35	Chevy	s10 Blazer	BLACK	Properly mounted
B36	GMC	Yukon XL	BLACK	"
B37	Chevy	Lumina	BLACK	"
B38	Chevy	Cavalier	BLACK	"
B39	Saturn	ion	BLACK	mica flake
B40	Chevy	Cavalier	BLACK	Properly mounted
W6GP	Pontiac	Grand Am SE	WHITE	some rust present
W7GP	Geo	Storm Gsi	WHITE	Properly mounted
W8GP	Dodge	Spirit	WHITE	"
W10GP	Chevy	Corsica	WHITE	some rust cont.
W12GP	Chevy	Monte Carlo	WHITE	Properly mounted
W13 GP	Nissan	Altima	WHITE	"
W14GP	Ford	Escort	WHITE	"

W15GP	Chrysler	Concorde	WHITE	"
W16GP	Pontiac	Sunfire	WHITE	"
W17GP	Plymouth	Breeze	WHITE	"
W20GP	Chevy	Corsica	WHITE	"
W22GP	Pontiac	Grand Am	WHITE	"
W24GP	Ford	Escort GT	WHITE	"
W25GP	Chevy	1500 truck	WHITE	"
W26GP	GMC	Sonoma truck	WHITE	"
W27GP	Buick	Century	WHITE	"
W28GP	Ford	F350 truck	WHITE	"
G2GP	Chevy	Cavalier	GRAY	some rust contamination
G3GP	Toyota	Tercel DX	SILVER	some metal cont.
G4GP	Kia	Rio	GRAY	some rust present
G5GP	Subaru	Loyale	SILVER	Properly mounted
G6GP	Chrysler	New Yorker	SILVER	some rust contamination
G7GP	Ford	Mustang convertible	SILVER	some rust/flake cont.
G8GP	Buick	Skylark	SILVER	Properly mounted
G9GP	Chevy	Lumina Euro 4d	SILVER	"
G15GP	Mazda	626	SILVER	"
G16GP	Ford	Escort Wagon	SILVER	some color layer cont.
G18GP	Chevy	Lumina	SILVER	Properly mounted
G19GP	Hyundai	Accent	SILVER	"
G20GP	Mercury	Sable G5	GRAY/GRN	mottled black with white and gray
G21GP	Ford	Probe	SILVER	Properly mounted
G22GP	Chevy	Malibu	SILVER	"
G23GP	Dodge	Stratus	SILVER	"
G33GP	Toyota	Camry LE	DK GRAY	"
B1GP	Chevy	Astro	BLACK	"
B3GP	Mitsubishi	Eclipse GS	BLACK	"
B4GP	Plymouth	Laser LS	BLACK	"
B13GP	Olds	Royale 88	BLACK	"
B14GP	Chevy	Z26	BLACK	"
B16GP	Mazda	RX7	BLACK	"
B17GP	Nissan	Maxima	BLACK	"
B19GP	Ford	Mustang	BLACK	"

Appendix C

Visible Microspectrophotometry Spectra for all Positive Samples

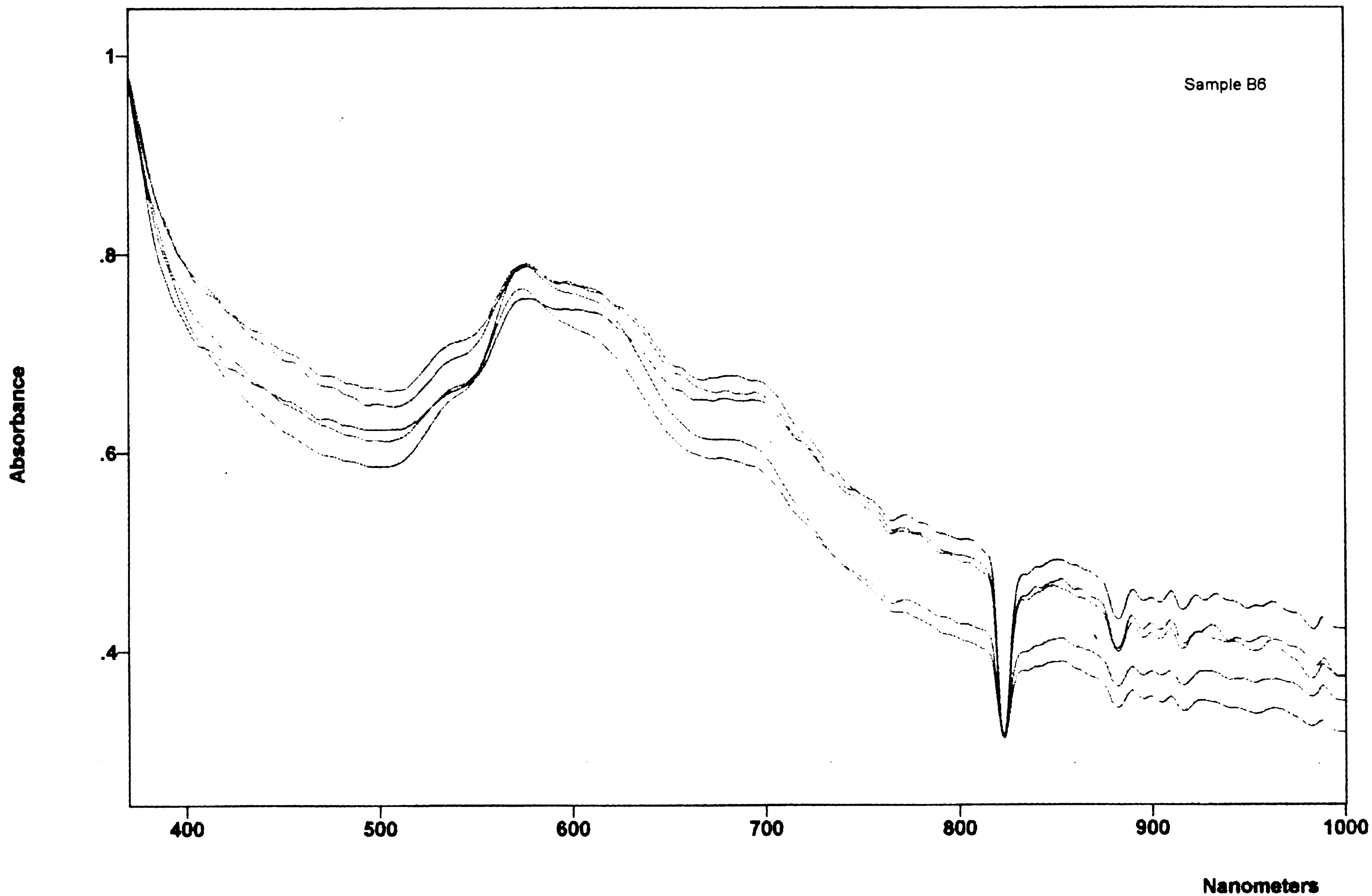

Figure 4: Visible Microspectrophotometry spectrum of sample B6

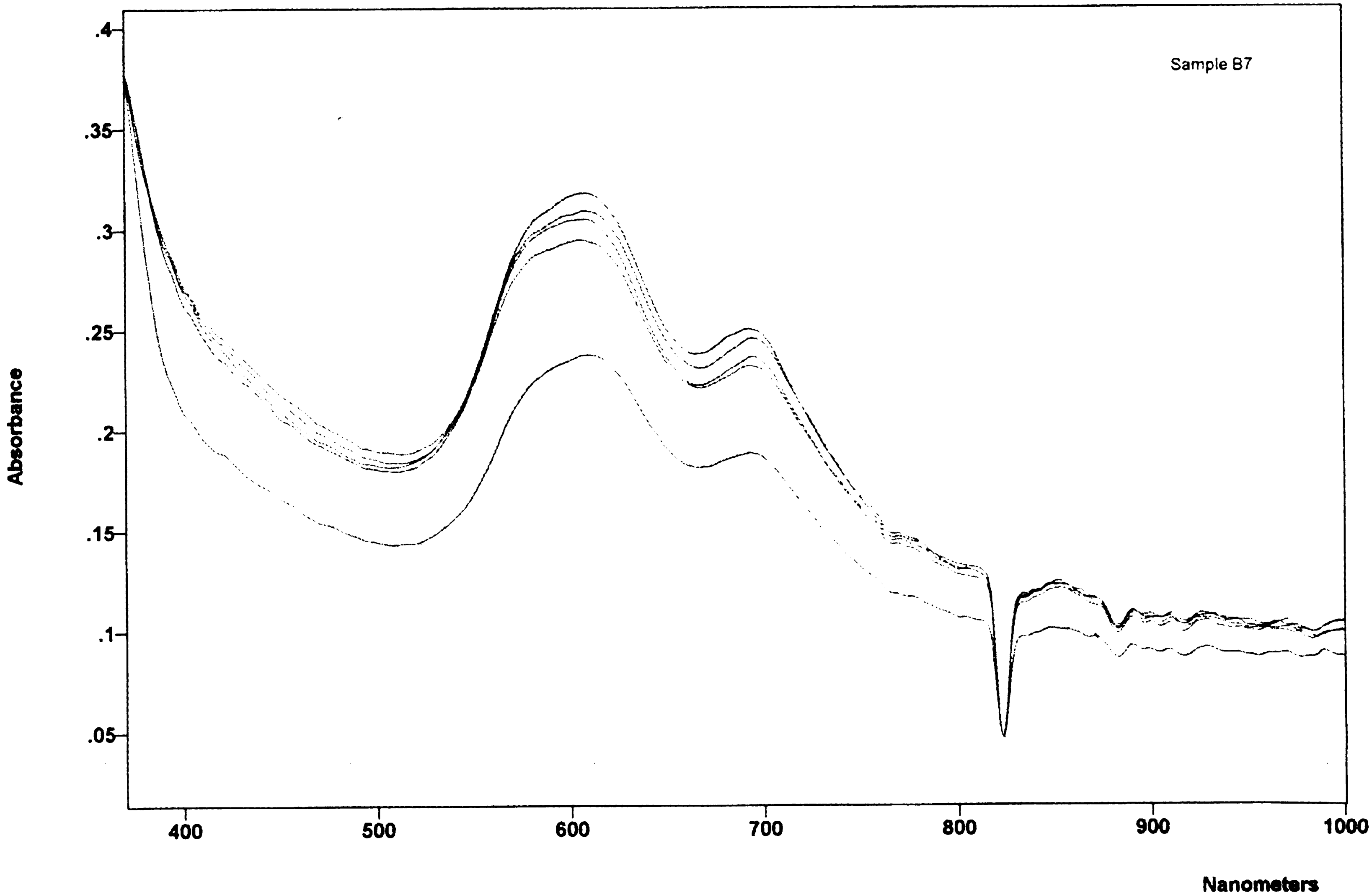

Figure 5: Visible Microspectrophotometry spectrum of sample B7

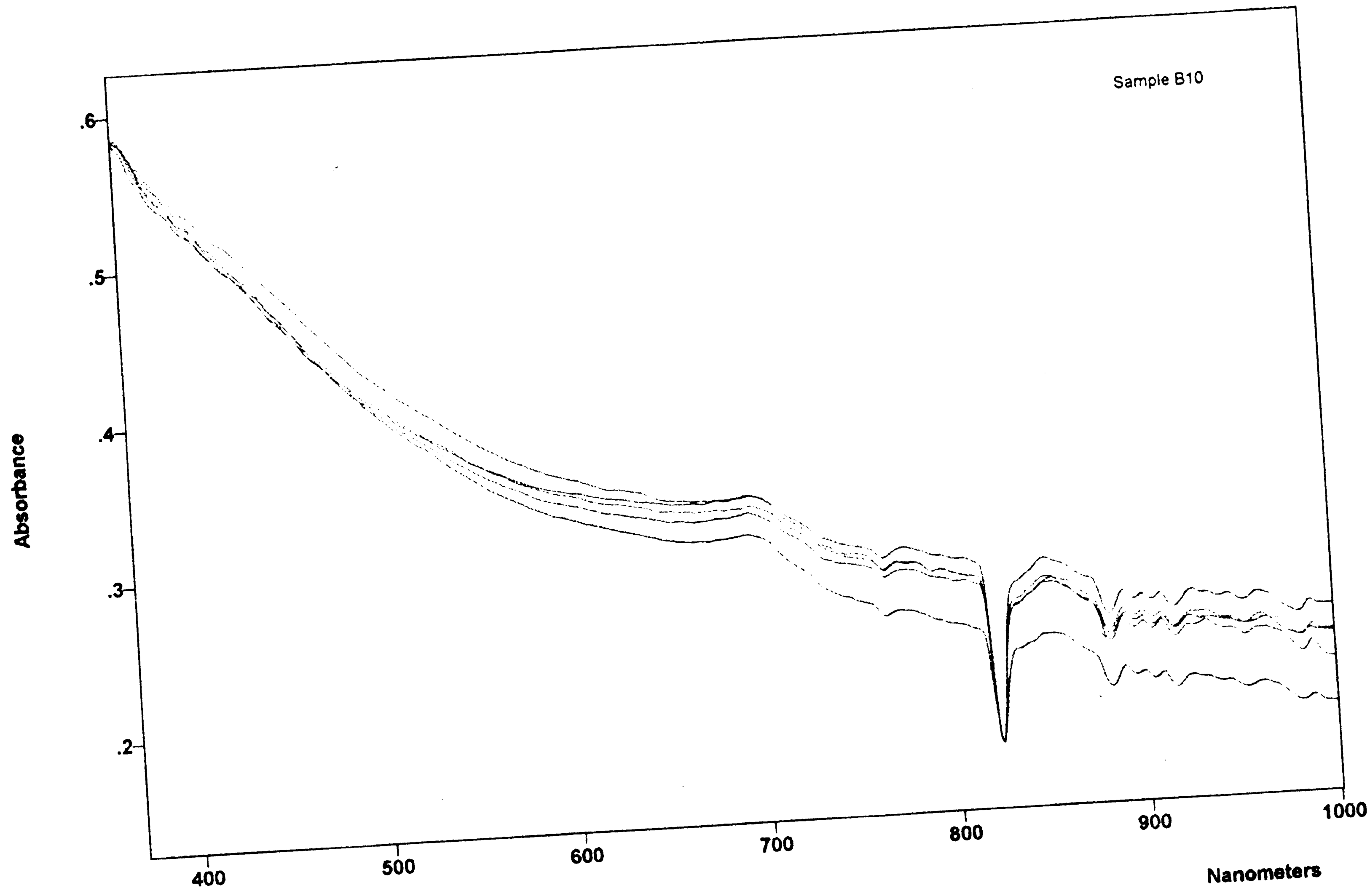

Figure 6: Visible Microspectrophotometry spectrum of sample B10

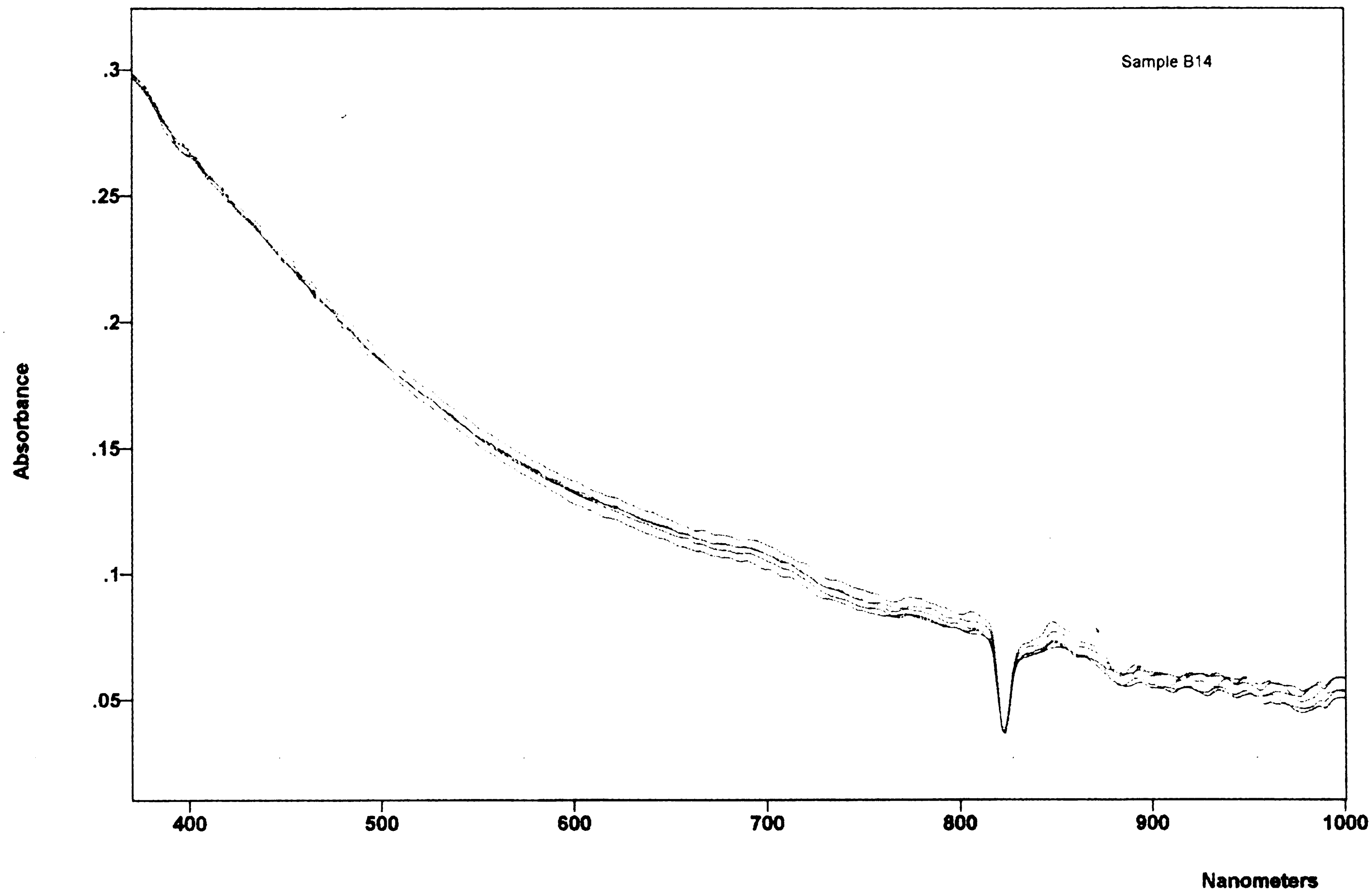

Figure 7: Visible Microspectrophotometry spectrum of sample B14

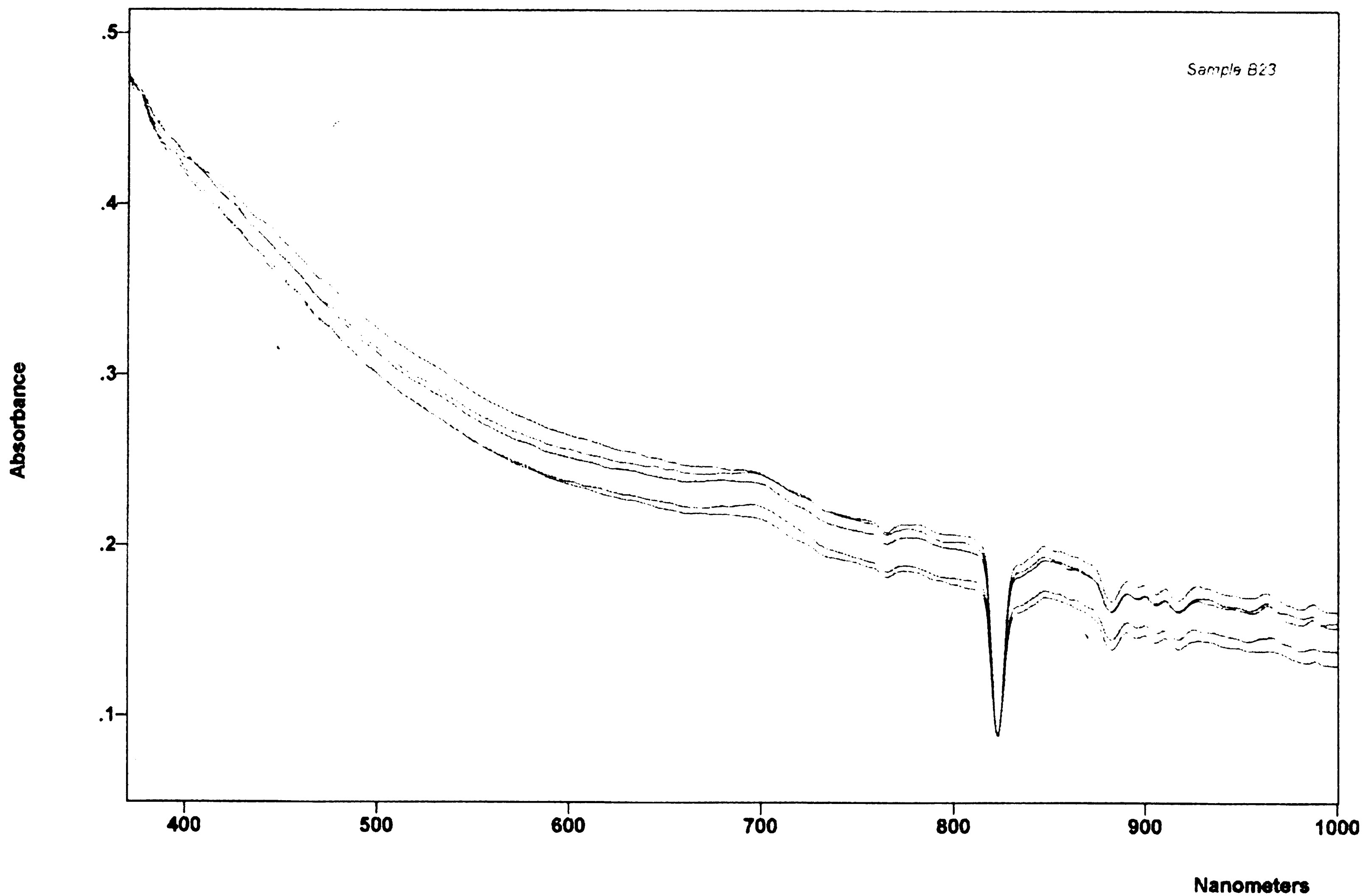

Figure 8: Visible Microspectrophotometry spectrum of sample B23

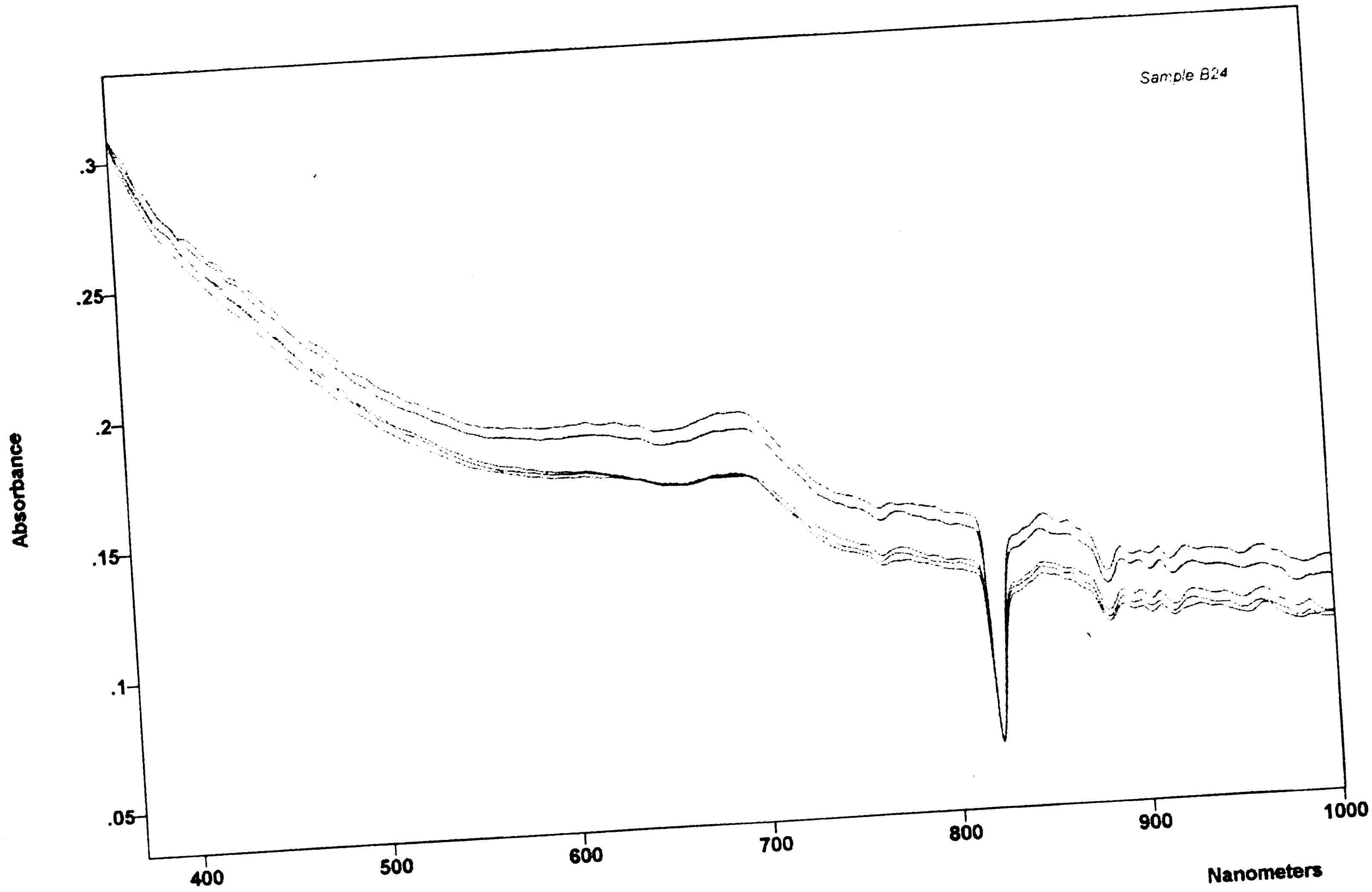

Figure 9: Visible Microspectrophotometry spectrum of sample B24

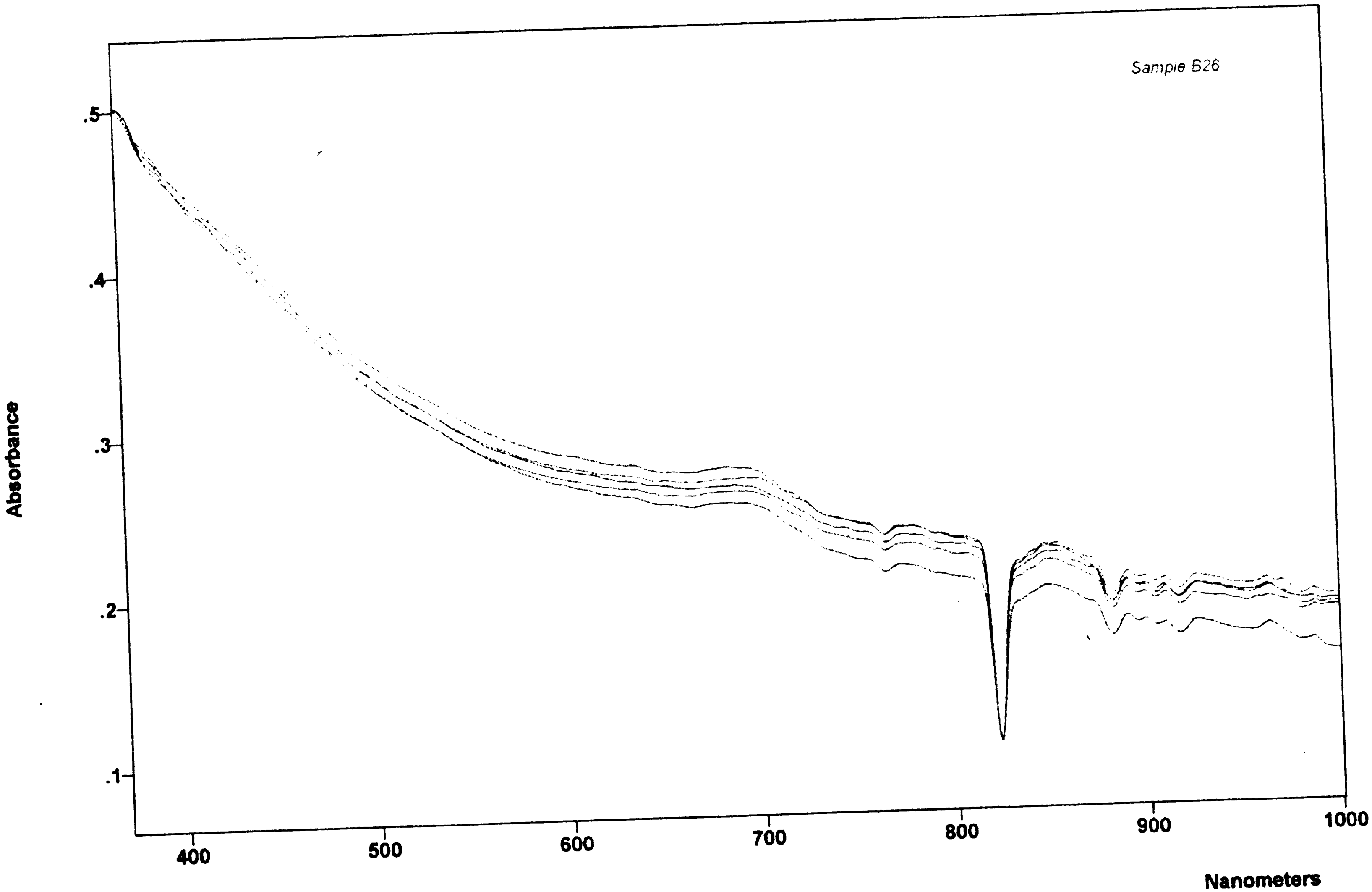

Figure 10: Visible Microspectrophotometry spectrum of sample B26

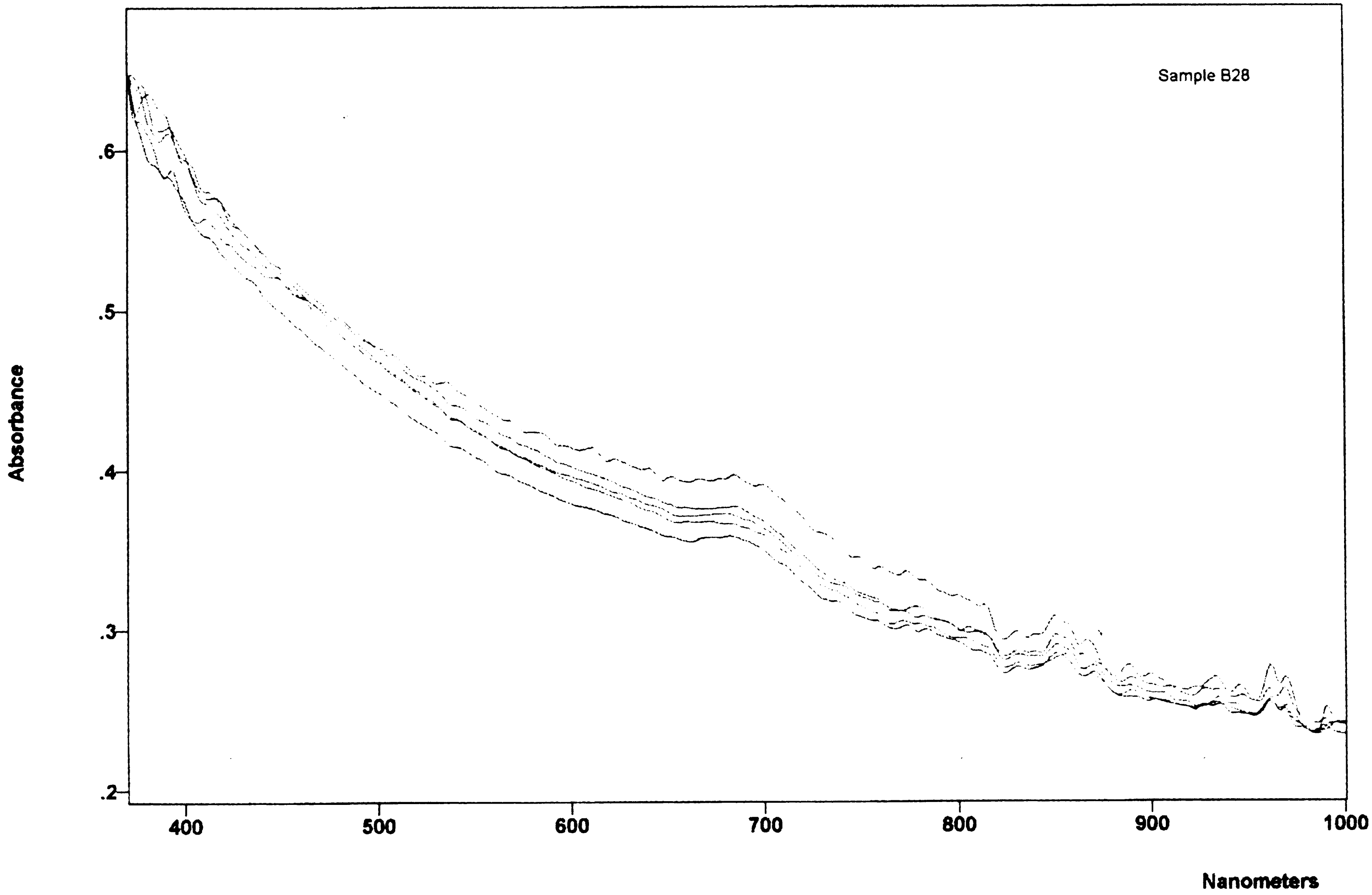

Figure 11: Visible Microspectrophotometry spectrum of sample B28

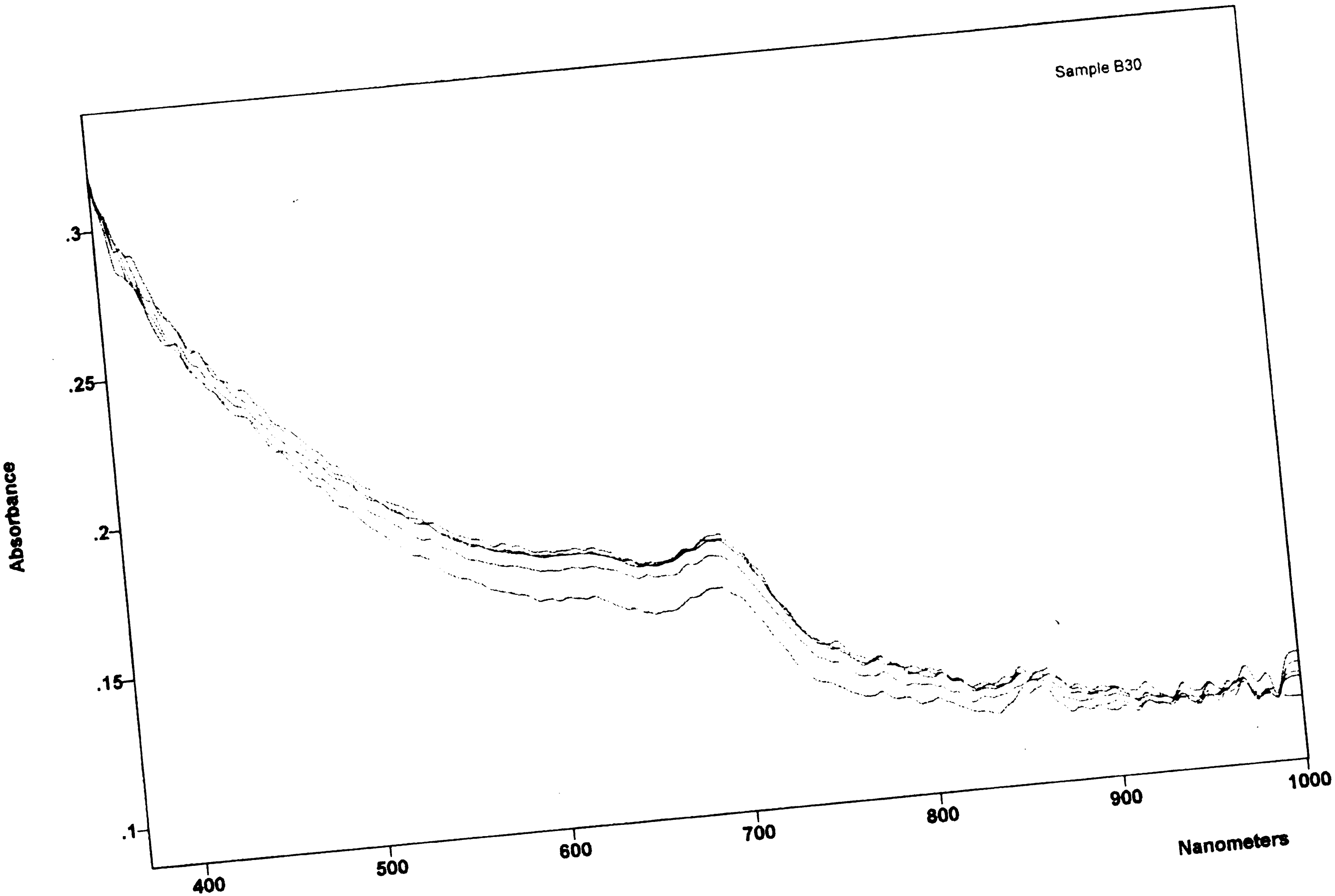

Figure 12: Visible Microspectrophotometry spectrum of sample B30

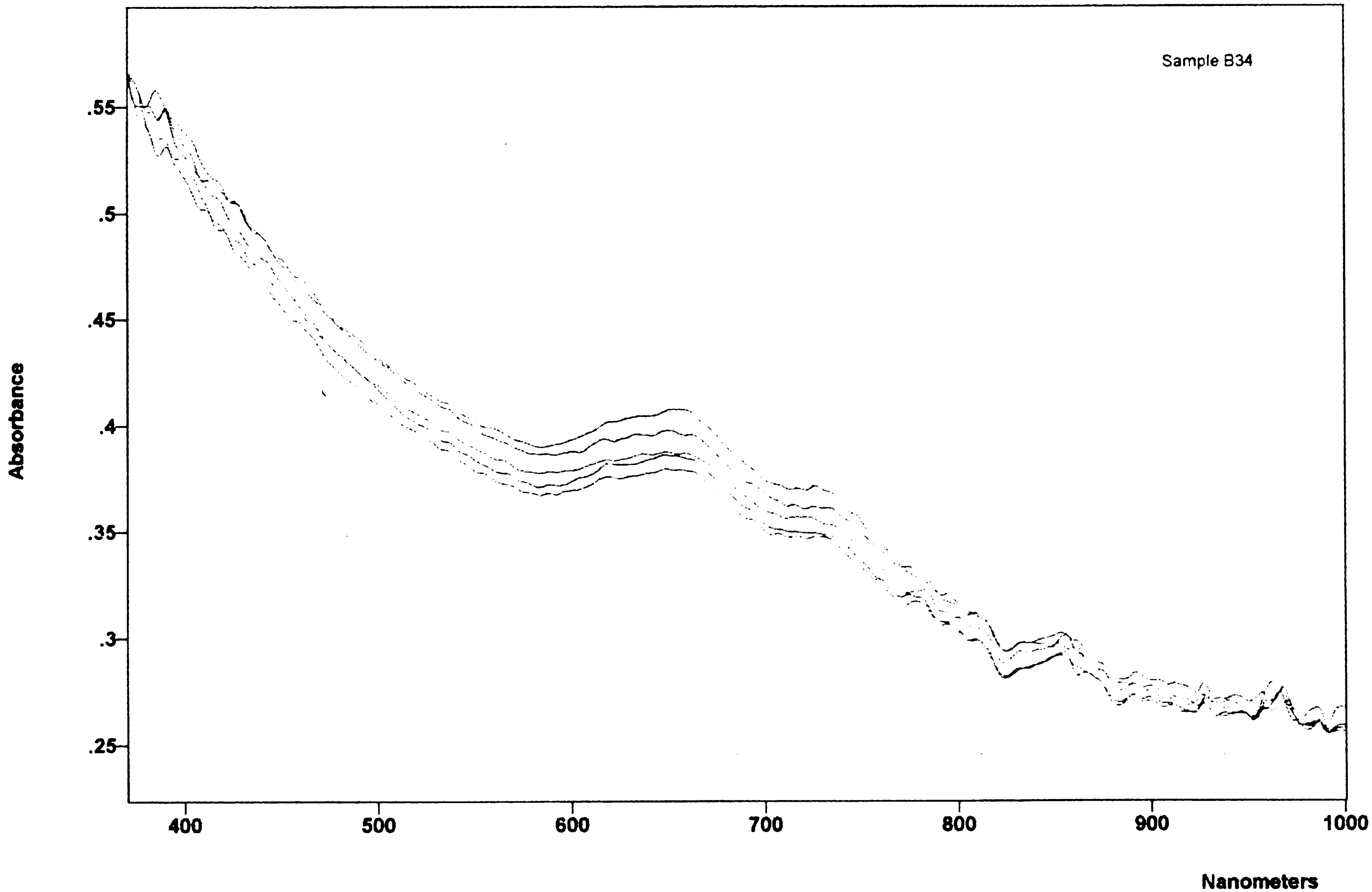

Figure 13: Visible Microspectrophotometry spectrum of sample B34

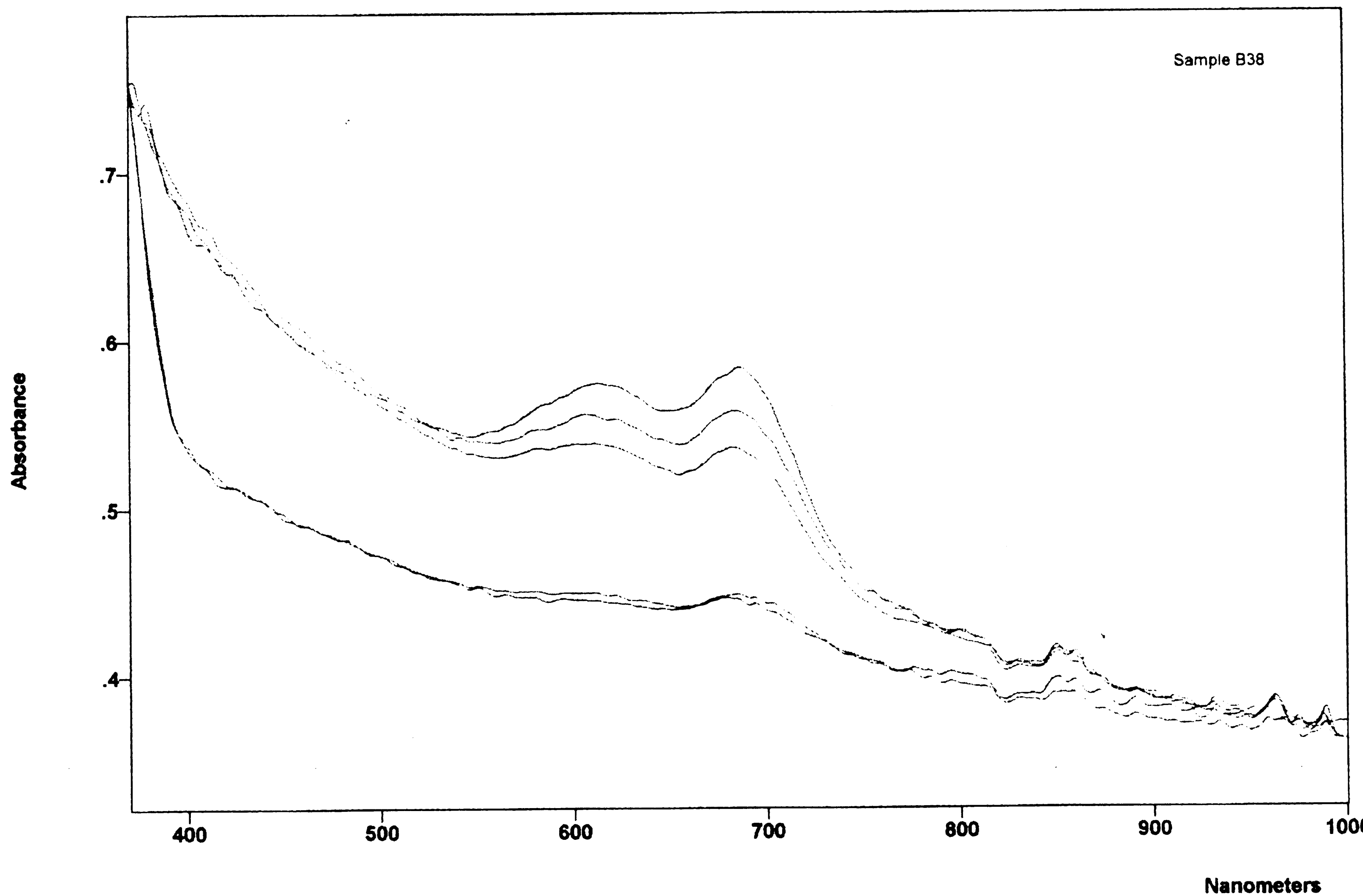

Figure 14: Visible Microspectrophotometry spectrum of sample B38

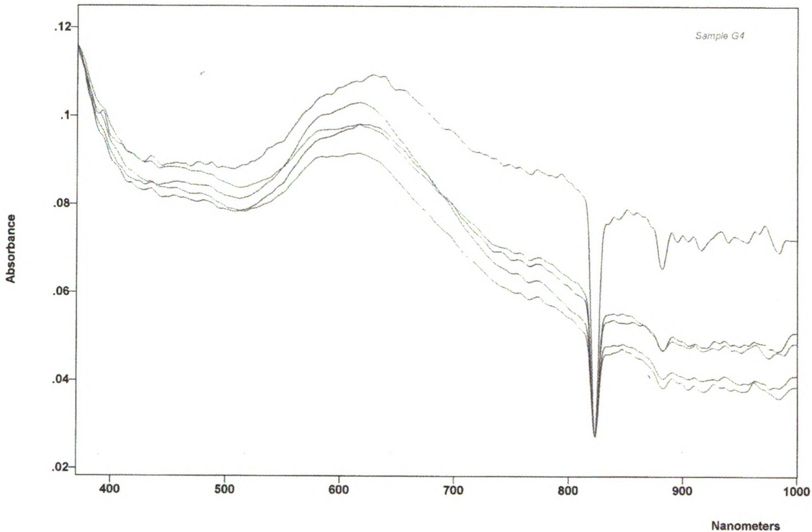

Figure 15: Visible Microspectrophotometry spectrum of sample G4

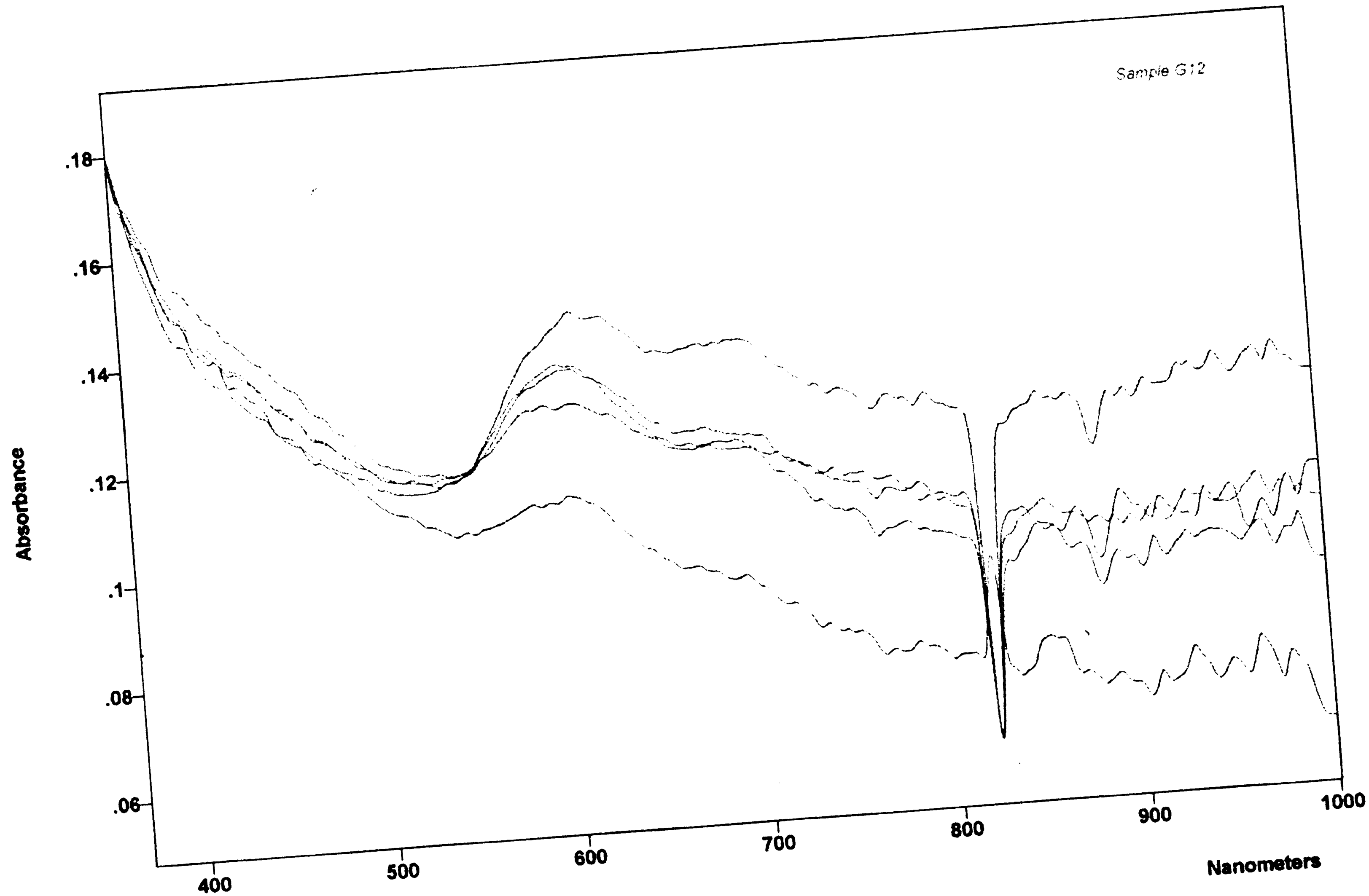

Figure 16: Visible Microspectrophotometry spectrum of sample G12

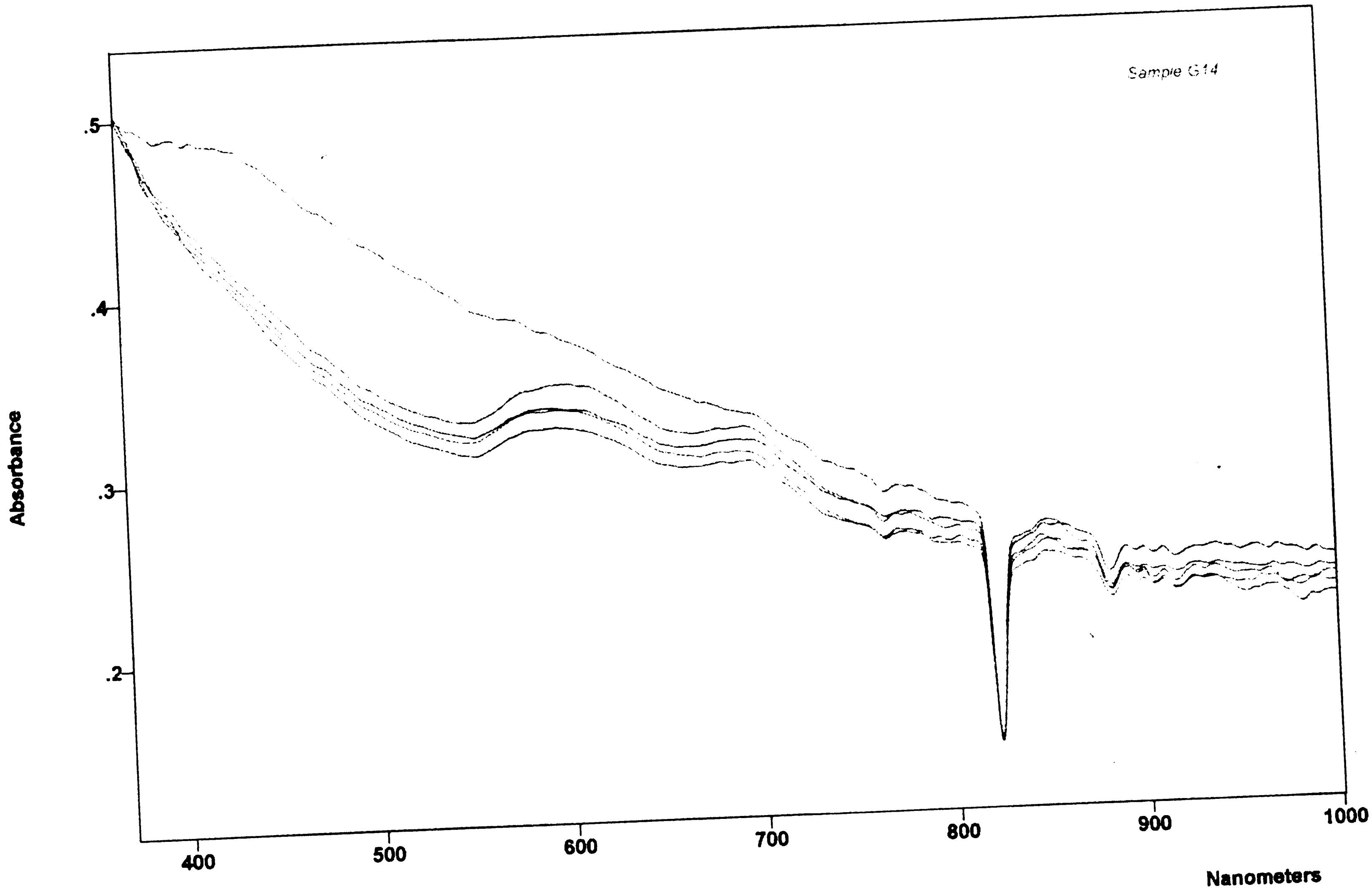

Figure 17: Visible Microspectrophotometry spectrum of sample G14

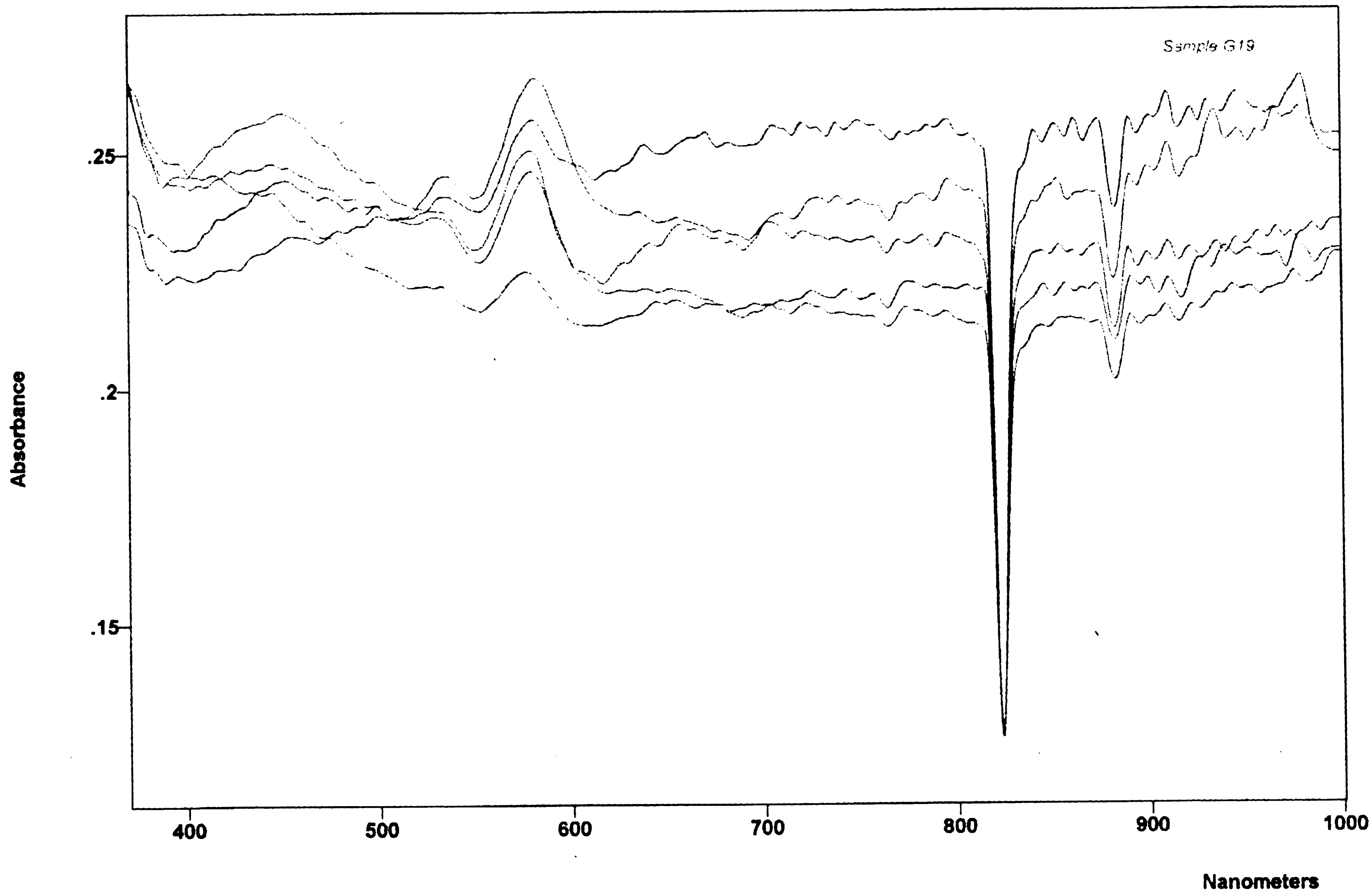

Figure 18: Visible Microspectrophotometry spectrum of sample G19

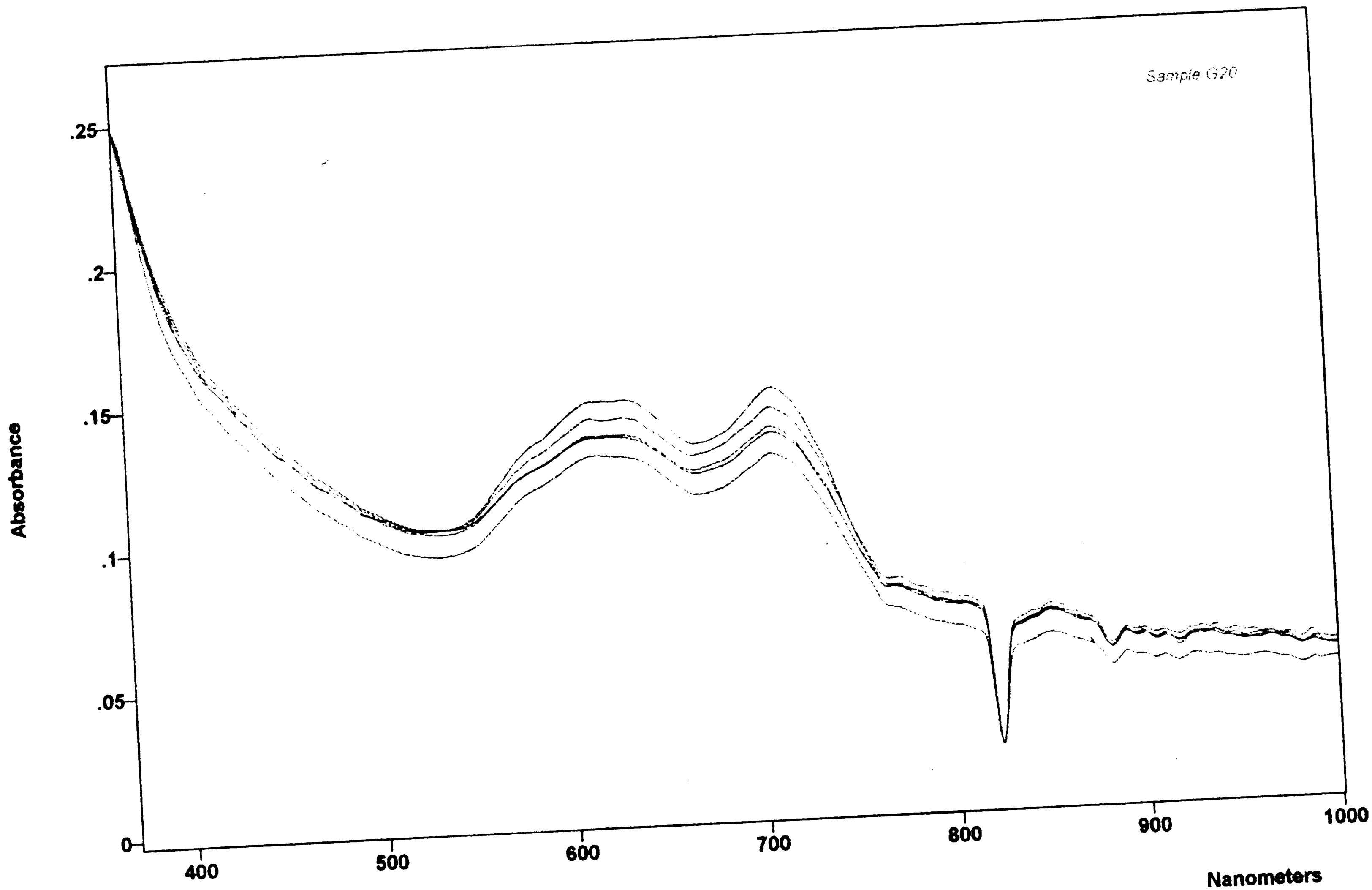

Figure 19: Visible Microspectrophotometry spectrum of sample G20

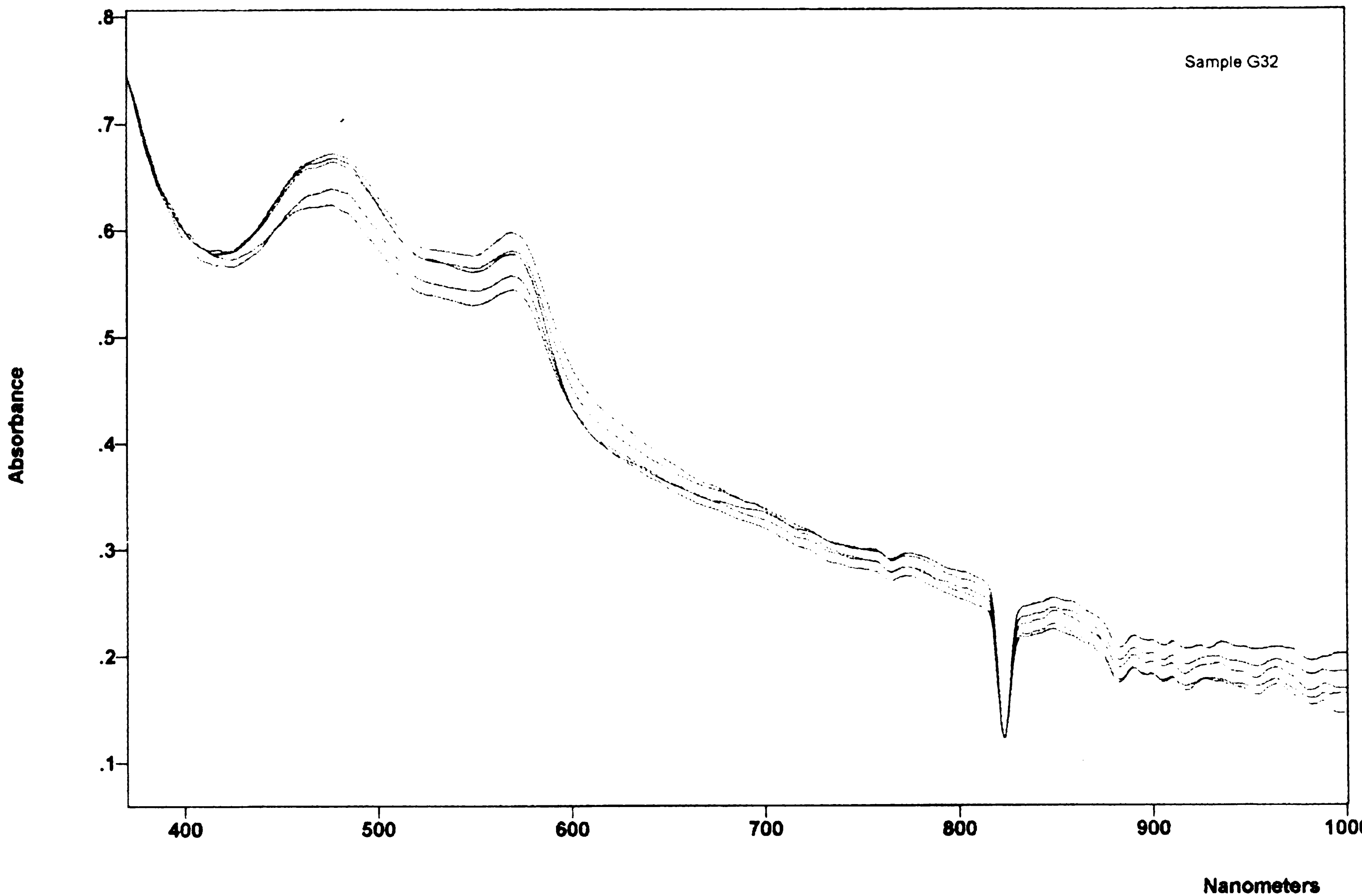

Figure 20: Visible Microspectrophotometry spectrum of sample G32

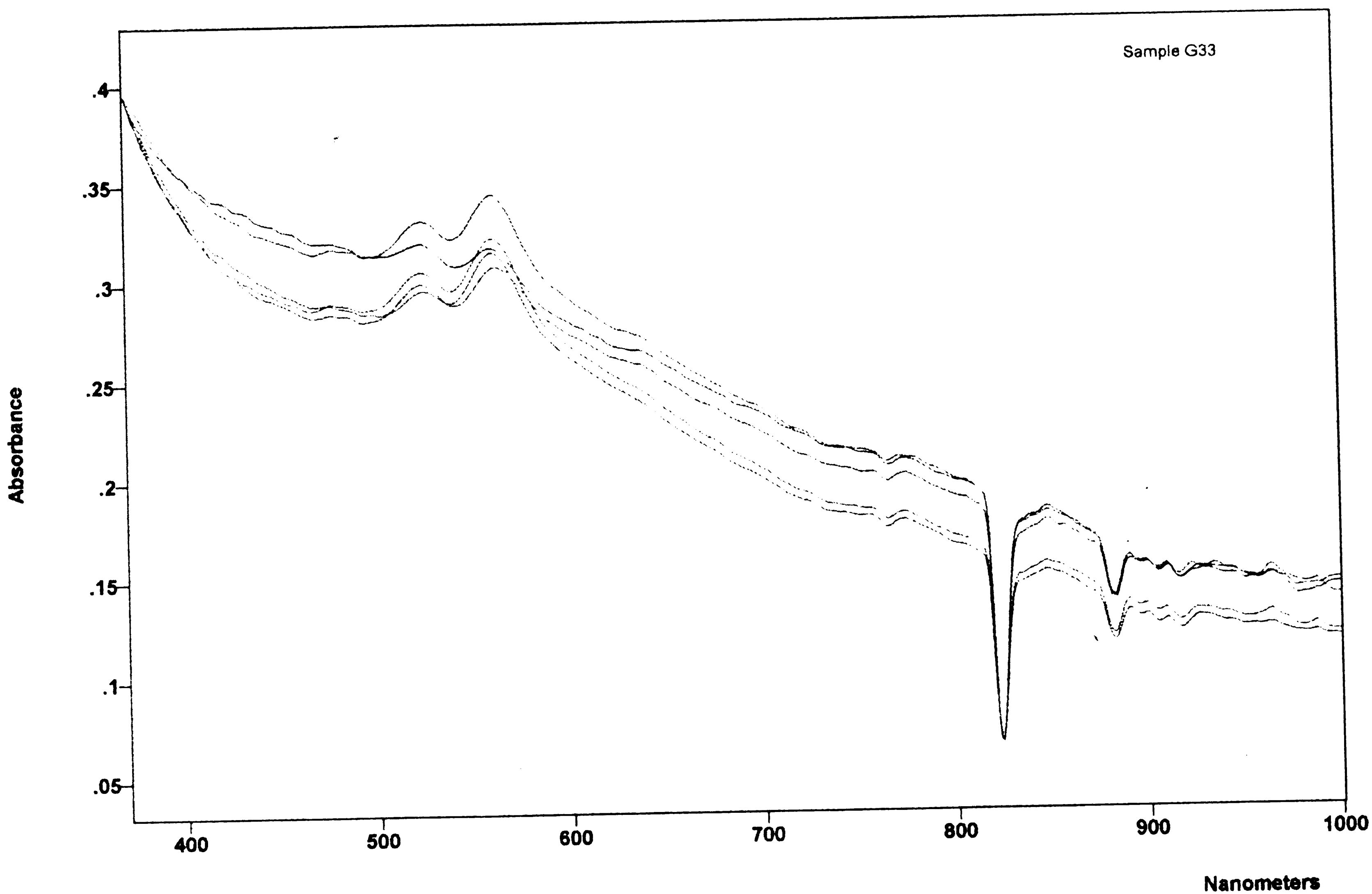

Figure 21: Visible Microspectrophotometry spectrum of sample G33

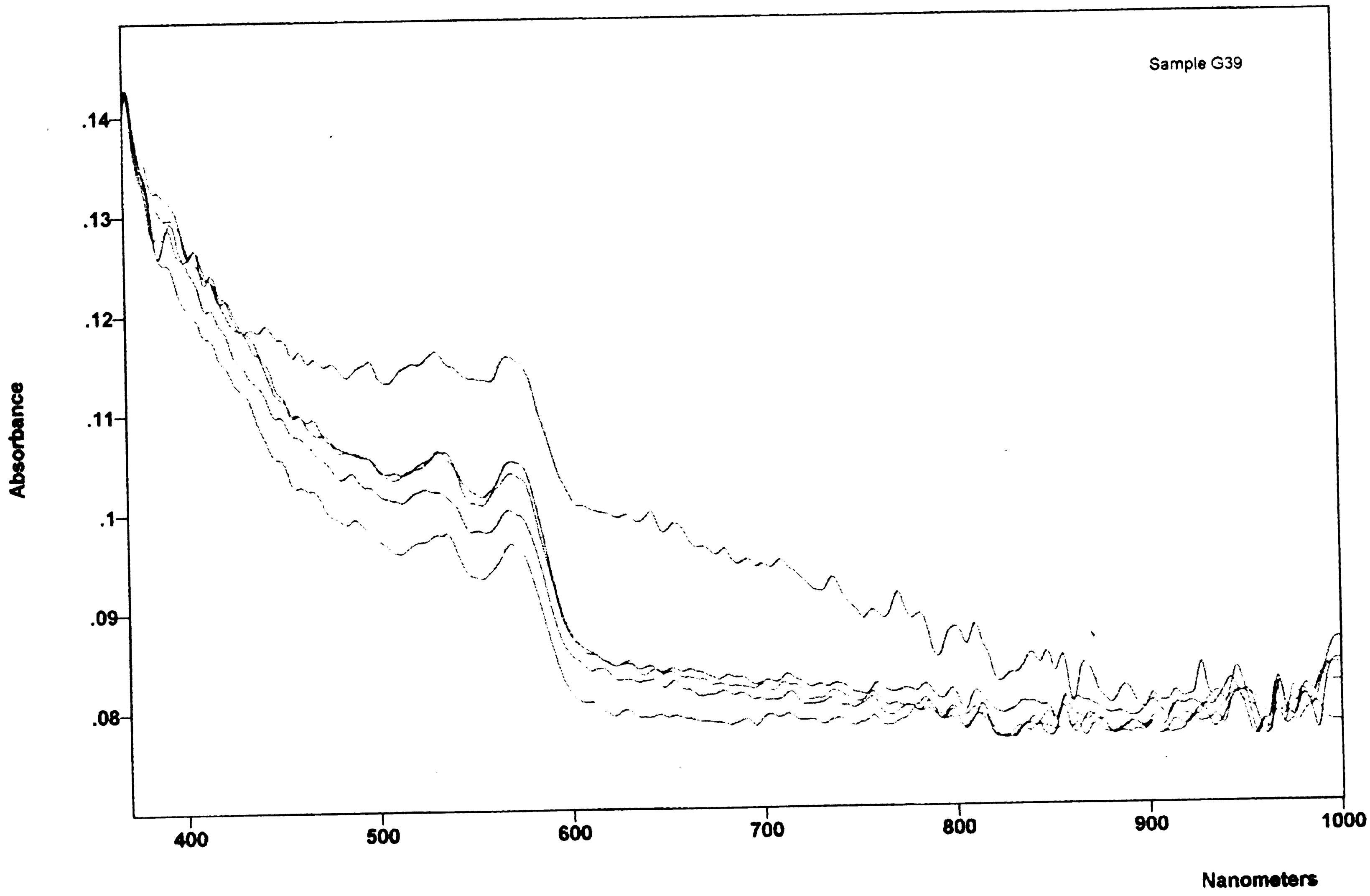

Figure 22: Visible Microspectrophotometry spectrum of sample G39

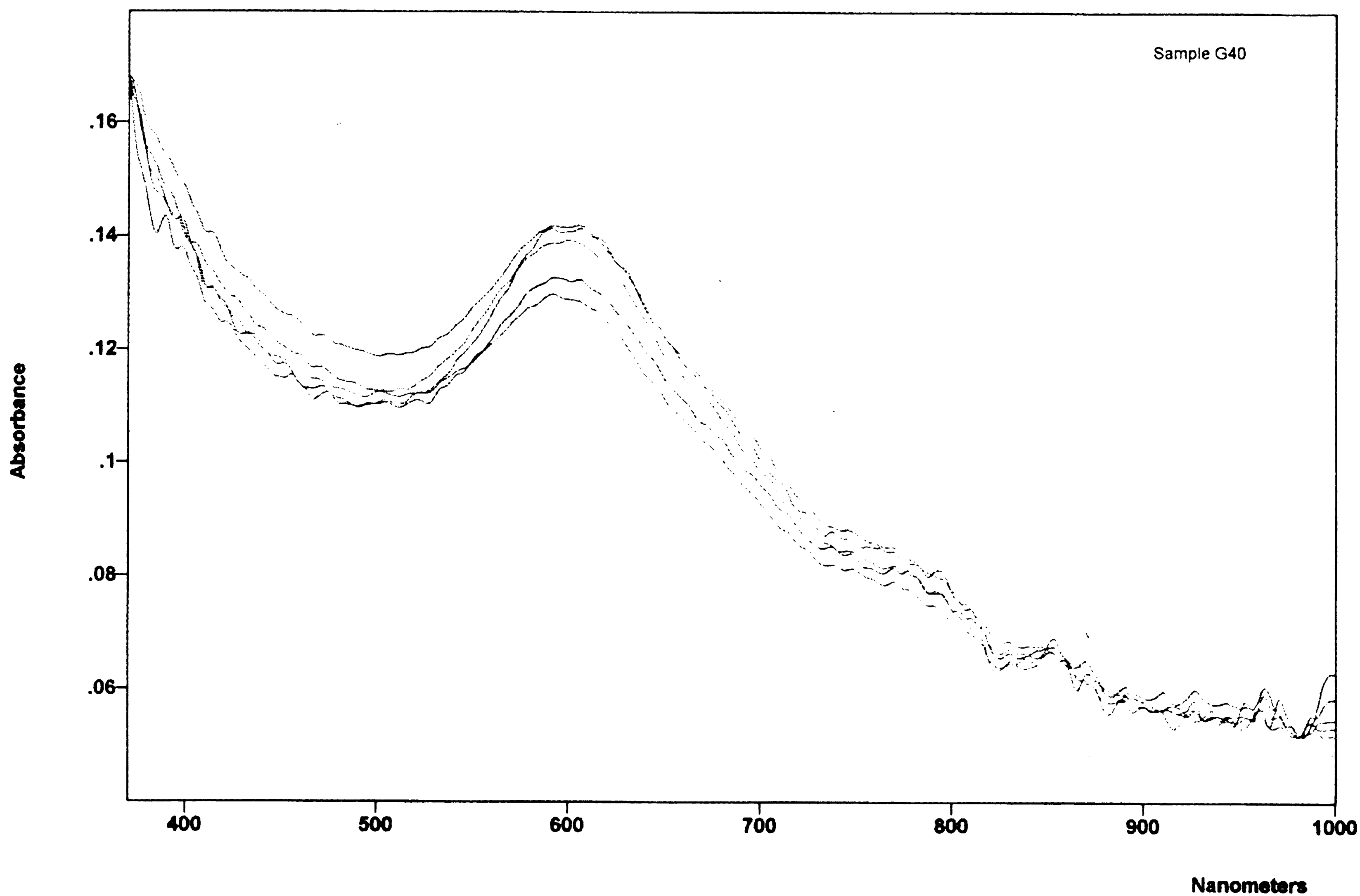

Figure 23: Visible Microspectrophotometry spectrum of sample G40

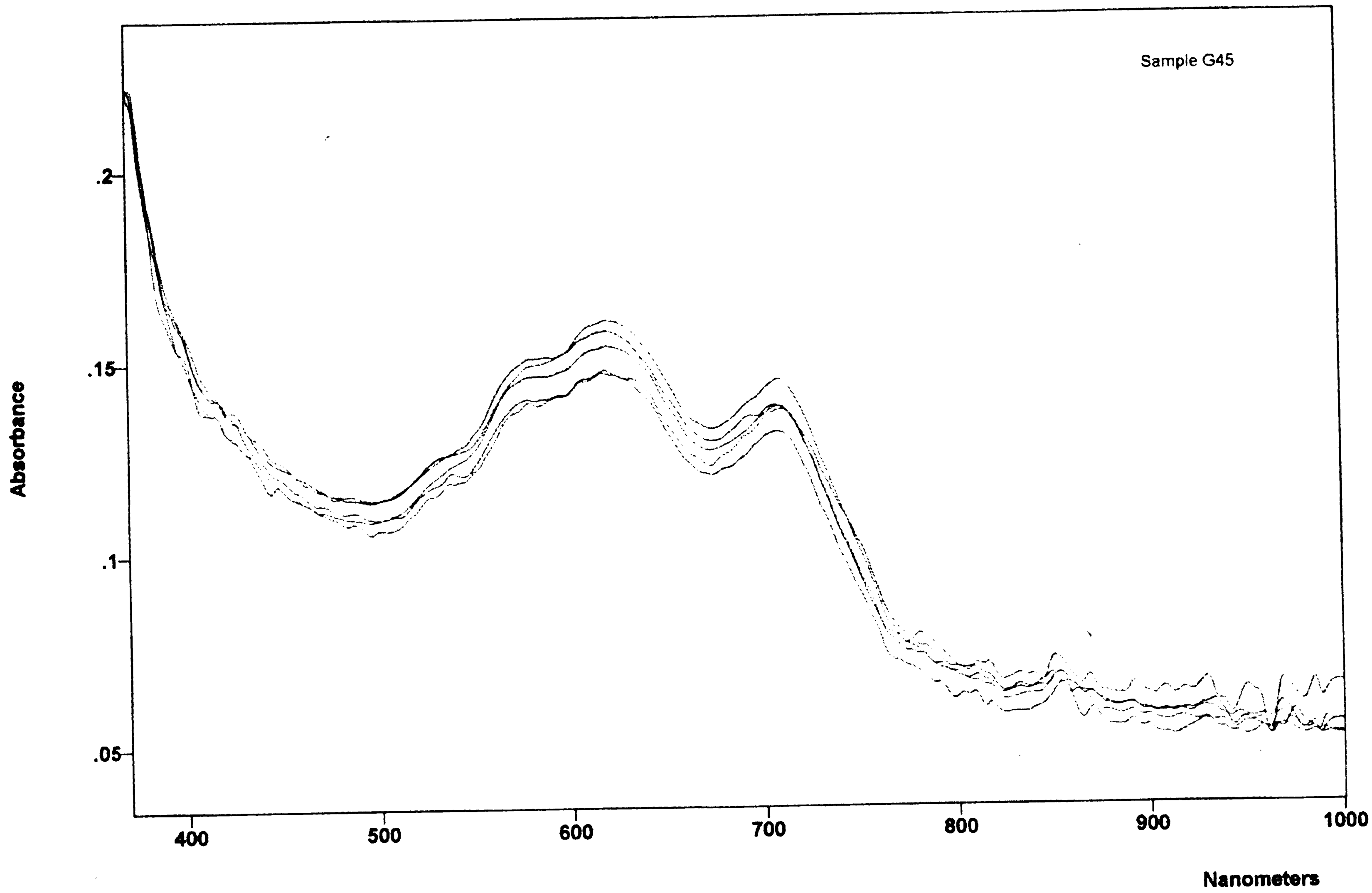

Figure 24: Visible Microspectrophotometry spectrum of sample G45

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