

# Geostatistical Evaluation of the Hazm Al-Jalamid Phosphate Deposit, Northwestern Saudi Arabia

by

Abdul-Rahman Mohammad Jarad

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the  
Requirements for the Degree of

**MASTER OF SCIENCE**

In

**GEOLOGY**

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**GEOSTATISTICAL EVALUATION OF THE  
HAZM AL-JALAMID PHOSPHORITE DEPOSIT,  
NORTHWESTERN SAUDI ARABIA**

**BY**

**ABDUL-RAHMAN MOHAMMAD JARAD**

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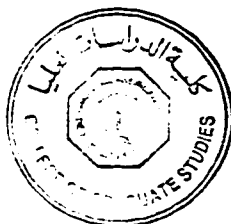
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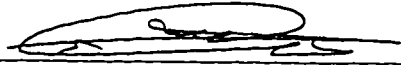
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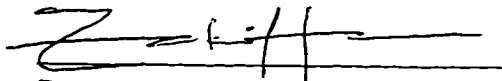
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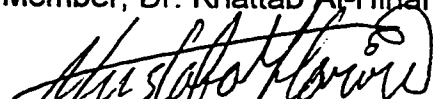
  
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**In the Name of Allah, the Most Gracious, the Most Merciful**

## *Dedication*

*This thesis is dedicated to  
my beloved late parents*



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# TABLE OF CONTENTS

| <u>Subject</u>                                                                                               | <u>Page #</u> |
|--------------------------------------------------------------------------------------------------------------|---------------|
|                                                                                                              | VII           |
| LIST OF FIGURES                                                                                              | VIII          |
| LIST OF APPENDICES                                                                                           | XII           |
| ABSTRACT IN ARABIC                                                                                           | XIII          |
| ABSTRACT IN ENGLISH                                                                                          | XIV           |
| <br><b>CHAPTER 1: INTRODUCTION</b>                                                                           | <br>1         |
| 1.1 Location and Geologic Setting                                                                            | 1             |
| 1.2 Economic Importance of Phosphorite                                                                       | 5             |
| 1.3 Previous Studies                                                                                         | 7             |
| 1.4 Objectives of the Present Work                                                                           | 10            |
| 1.5 Tools of the Study                                                                                       | 11            |
| <br><b>CHAPTER 2: GEOLOGY OF THE PHOSPHORITE DEPOSITS IN<br/>                  NORTHWESTERN SAUDI ARABIA</b> | <br>12        |
| 2.1 Geology of the Sirhan-Turayf Sedimentary Sub-basin                                                       | 12            |
| 2.2 Geology of the Hazm Al-Jalamid Phosphorite Deposit                                                       | 17            |
| 2.2.1 Stratigraphy                                                                                           | 17            |
| 2.2.2 Structural Setting                                                                                     | 25            |
| 2.2.3 Mineralogy of Deposit                                                                                  | 26            |
| 2.2.4 Economic Potential of Deposit                                                                          | 29            |
| 2.2.5 Origin of Deposit                                                                                      | 30            |
| <br><b>CHAPTER 3: DATA SETS DESCRIPTION</b>                                                                  | <br>34        |
| 3.1 Drilling Programs                                                                                        | 34            |
| 3.2 Chemical Composition of the Phosphorite Samples                                                          | 35            |
| 3.3 Preparation of Data Sets                                                                                 | 37            |

| <b>Subject</b>                                                               | <b>Page #</b> |
|------------------------------------------------------------------------------|---------------|
| <b>CHAPTER 4: SUB-SET AREA SELECTION AND DESCRIPTION OF DEPOSIT</b>          | <b>39</b>     |
| 4.1 Sub-set Area Selection                                                   | 39            |
| 4.1.1 Phosphorite Grade ( $P_2O_5$ %)                                        | 40            |
| 4.1.2 Stripping Ratio                                                        | 41            |
| 4.1.3 $Al_2O_3 + Fe_2O_3$ , $SiO_2$ and MgO Contents and CaO/ $P_2O_5$ Ratio | 41            |
| 4.1.4 Drill-hole spacing                                                     | 43            |
| 4.3 Description of Deposit                                                   | 47            |
| 4.2.1 Isotenor maps                                                          | 47            |
| 4.2.2 Isopach maps                                                           | 50            |
| 4.2.3 3D surface diagrams                                                    | 50            |
| 4.2.4 Cross-sections                                                         | 58            |
| <b>CHAPTER 5: STATISTICAL ANALYSIS</b>                                       | <b>61</b>     |
| 5.1 Introduction                                                             | 61            |
| 5.2 Statistical Parameters                                                   | 61            |
| 5.3 Histograms and Frequency Distributions                                   | 62            |
| 5.4 Cumulative Frequency Plots                                               | 66            |
| <b>CHAPTER 6: SPATIAL ANALYSIS</b>                                           | <b>77</b>     |
| 6.1 Introduction                                                             | 77            |
| 6.2 Semivariogram                                                            | 78            |
| 6.2.1 Definition                                                             | 78            |
| 6.2.2 Theoretical Models                                                     | 78            |
| 6.2.3 Choice of Model                                                        | 84            |
| 6.2.4 Semivariogram and Geologic Characteristics                             | 87            |
| 6.3 Spatial Analysis for the Hazm Al-Jalamid Deposit                         | 91            |
| 6.3.1 Semivariograms for Horizon 1                                           | 91            |
| 6.3.2 Semivariograms for Horizon 3                                           | 97            |
| <b>CHAPTER 7: LOCAL ESTIMATION AND GRADE-TONNAGE RELATIONSHIP</b>            | <b>102</b>    |
| 7.1 Introduction                                                             | 102           |

| <b><u>Subject</u></b>                                        | <b><u>Page #</u></b> |
|--------------------------------------------------------------|----------------------|
| 7.2 Local Estimation                                         | 103                  |
| 7.2.1 Block Kriging                                          | 103                  |
| 7.2.2 Application to the Hazm Al-Jalamid Deposit             | 108                  |
| 7.3 Grade-Tonnage Relationship                               | 114                  |
| 7.3.1 General introduction                                   | 115                  |
| 7.3.2 Grade-Tonnage Relationship for Hazm Al-Jalamid Deposit | 115                  |
| <br><b>CHAPTER 8: CONDITIONAL SIMULATION</b>                 | <br>121              |
| 8.1 Introduction                                             | 121                  |
| 8.2 Review of Conditional Simulation Techniques              | 121                  |
| 8.3 Turning Band Method                                      | 122                  |
| 8.4 Application to the Hazm Al-Jalamid Deposit               | 130                  |
| <br><b>CHAPTER 9: SUMMARY AND CONCLUSIONS</b>                | <br>134              |
| <br><b>REFERENCES</b>                                        | <br>138              |
| <br><b>APPENDICES</b>                                        | <br>144              |

## LIST OF TABLES

| <b>Table #</b>                                                                                   | <b>Page #</b> |
|--------------------------------------------------------------------------------------------------|---------------|
| 4.1 Stripping ratio based on some drill-holes in the study area                                  | 42            |
| 4.2 Various chemical components of the phosphorite ore in Horizon 1                              | 44            |
| 4.3 Various chemical components of the phosphorite ore in Horizon 3                              | 45            |
| 4.4 Average percentages of the main chemical components of the phosphorite ore in the study area | 46            |
| 5.1 Statistical parameters for $P_2O_5$ % within the three horizons                              | 63            |
| 5.2 Statistical parameters for the thickness representing the three horizons                     | 64            |
| 5.3 Statistical parameters for the accumulation representing the three horizons                  | 65            |
| 6.1 Parameters of horizontal semivariogram for $P_2O_5$ % in Horizon 1                           | 96            |
| 6.2 Parameters of horizontal semivariogram for $P_2O_5$ % in Horizon 3                           | 101           |
| 7.1 Grade-tonnage relationship for Horizon 1                                                     | 116           |
| 7.2 Grade-tonnage relationship for Horizon 3                                                     | 117           |

## LIST OF FIGURES

| <b>Figure #</b>                                                                                                                                                      | <b>Page #</b> |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|
| 1.1 Location map of the Sirhan-Turayf Basin                                                                                                                          | 2             |
| 1.2 Main phosphorite areas and deposits in Saudi Arabia and neighboring countries                                                                                    | 3             |
| 1.3 Satellite image showing the location of the study area in the Hazm Al-Jalamid region                                                                             | 4             |
| 1.4 NE-SW cross-section in the Hazm Al-Jalamid area                                                                                                                  | 6             |
| 1.5 World distribution of identified phosphorite resources                                                                                                           | 8             |
| 2.1 Geologic map showing different lithologies and graben systems in the Sirhan-Turayf Basin                                                                         | 14            |
| 2.2 NW-SE cross-section through the northwestern part of Saudi Arabia showing the Ha'il Arch separating the Sirhan -Turayf Sub-basin from the Main Arabian Sub-basin | 15            |
| 2.3 Generalized lithostratigraphic section for the Sirhan-Turayf basin                                                                                               | 18            |
| 2.4 Stratigraphic column for the Sirhan-Turayf Basin                                                                                                                 | 20            |
| 2.5 Stratigraphic column for the Hibr Group in the Sirhan-Turayf Basin                                                                                               | 22            |
| 2.6 Model for sedimentary phosphorite deposition and accumulation                                                                                                    | 32            |
| 3.1 The selected area for the present study in the Hazm Al-Jalamid region                                                                                            | 36            |
| 4.1 Isotenor map for $P_2O_5$ % within Horizon 1 in the selected area                                                                                                | 48            |
| 4.2 Isotenor map for $P_2O_5$ % within Horizon 2 in the selected area                                                                                                | 49            |
| 4.3 Isotenor map for $P_2O_5$ % within Horizon 3 in the selected area                                                                                                | 51            |
| 4.4 Isopach map of phosphorite for Horizon 1                                                                                                                         | 52            |

| <b>Figure #</b> |                                                                                                                           | <b>Page #</b> |
|-----------------|---------------------------------------------------------------------------------------------------------------------------|---------------|
| 4.5             | Isopach map of phosphorite for Horizon 2                                                                                  | 53            |
| 4.6             | Isopach map of phosphorite for Horizon 3                                                                                  | 54            |
| 4.7             | 3D surface diagram illustrating the distribution of P <sub>2</sub> O <sub>5</sub> % within Horizon 1 in the selected area | 55            |
| 4.8             | 3D surface diagram illustrating the distribution of P <sub>2</sub> O <sub>5</sub> % within Horizon 2 in the selected area | 56            |
| 4.9             | 3D surface diagram illustrating the distribution of P <sub>2</sub> O <sub>5</sub> % within Horizon 3 in the selected area | 57            |
| 4.10            | NE-SW cross-section parallel to the dip direction showing phosphorite horizons                                            | 59            |
| 4.11            | NW-SE cross-section along the strike direction showing phosphorite horizons                                               | 60            |
| 5.1             | Histogram and cumulative frequency plots for P <sub>2</sub> O <sub>5</sub> % within Horizon 1                             | 67            |
| 5.2             | Histogram and cumulative frequency plots for P <sub>2</sub> O <sub>5</sub> % within Horizon 2                             | 68            |
| 5.3             | Histogram and cumulative frequency plots for P <sub>2</sub> O <sub>5</sub> % within Horizon 3                             | 69            |
| 5.4             | Histogram and cumulative frequency plots for the thickness representing Horizon 1                                         | 70            |
| 5.5             | Histogram and cumulative frequency plots for the thickness representing Horizon 2                                         | 71            |
| 5.6             | Histogram and cumulative frequency plots for the thickness representing Horizon 3                                         | 72            |
| 5.7             | Histogram and cumulative frequency plots of the accumulation representing Horizon 1                                       | 73            |
| 5.8             | Histogram and cumulative frequency plots of the accumulation representing Horizon 2                                       | 74            |

| <b>Figure #</b> |                                                                                                                    | <b>Page #</b> |
|-----------------|--------------------------------------------------------------------------------------------------------------------|---------------|
| 5.9             | Histogram and cumulative frequency plots of the accumulation representing Horizon 3                                | 75            |
| 6.1             | Spherical model of semivariogram                                                                                   | 80            |
| 6.2             | Exponential model of semivariogram                                                                                 | 82            |
| 6.3             | Gaussian model of semivariogram                                                                                    | 82            |
| 6.4             | Model of semivariograms with sills                                                                                 | 83            |
| 6.5             | Linear semivariogram                                                                                               | 85            |
| 6.6             | De Wijsian semivariogram                                                                                           | 85            |
| 6.7             | Types of continuity                                                                                                | 88            |
| 6.8             | Types of anisotropies                                                                                              | 90            |
| 6.9             | Vertical semivariogram for $P_2O_5$ % in Horizon 1                                                                 | 92            |
| 6.10            | Horizontal semivariogram for $P_2O_5$ % in Horizon 1 along $N45^{\circ}E$ direction and the fitted spherical model | 94            |
| 6.11            | Horizontal semivariogram for $P_2O_5$ % in Horizon 1 along $N45^{\circ}W$ direction and the fitted spherical model | 95            |
| 6.12            | Vertical semivariogram for $P_2O_5$ % in Horizon 3                                                                 | 98            |
| 6.13            | Horizontal semivariogram for $P_2O_5$ % in Horizon 3 along $N45^{\circ}E$ direction and the fitted spherical model | 99            |
| 6.14            | Horizontal semivariogram for $P_2O_5$ % in Horizon 3 along $N45^{\circ}W$ direction and the fitted spherical model | 100           |
| 7.1             | Kriging plan used for both horizons in the study area                                                              | 109           |
| 7.2             | Kriging output for Level 1 in Horizon 1                                                                            | 111           |
| 7.3             | Kriging output for Level 1 in Horizon 3                                                                            | 113           |



| <b>Figure #</b> |                                                                             | <b>Page #</b> |
|-----------------|-----------------------------------------------------------------------------|---------------|
| 7.4             | Grade-tonnage curve for Horizon 1                                           | 118           |
| 7.5             | Grade-tonnage curve for Horizon 3                                           | 119           |
| 8.1             | Line $l$ in the three-dimensional space $R^3$                               | 124           |
| 8.2             | The projection of points $x$ on line $l$                                    | 124           |
| 8.3             | Diagram illustrating the Turning Band Simulation method in two dimensions   | 125           |
| 8.4             | Diagram illustrating the Turning Band Simulation method in three dimensions | 125           |
| 8.5             | Icosahedron.                                                                | 128           |
| 8.6             | Conditionally simulated $P_2O_5$ % map for Level 45 in Horizon 1            | 132           |
| 8.7             | Conditionally simulated $P_2O_5$ % map for Level 40 in Horizon 3            | 133           |

## LIST OF APPENDICES

| <b>Appendix</b>                                                                     | <b>Page #</b> |
|-------------------------------------------------------------------------------------|---------------|
| <b>A</b> An excerpt from the original data file                                     | 144           |
| <b>B</b> An excerpt from the master data file                                       | 146           |
| <b>C</b> An excerpt from the master data file used in the statistical analysis      | 148           |
| <b>D</b> Statistical parameters of $P_2O_5$ % in individual drill-holes             | 150           |
| <b>E</b> Experimental semivariograms for the original drill-holes data in Horizon 1 | 161           |
| <b>F</b> Experimental semivariograms for the original drill-holes data in Horizon 3 | 166           |
| <b>G</b> An excerpt from the kriging output file                                    | 171           |
| <b>H</b> Kriging output maps for Horizon 1                                          | 173           |
| <b>I</b> Kriging output maps for Horizon 3                                          | 240           |
| <b>J</b> An excerpt from the simulation output file                                 | 297           |
| <b>K</b> Simulation output maps for Horizon 1                                       | 299           |
| <b>L</b> Simulation output maps for Horizon 3                                       | 314           |

## الخلاصة

الإسم : عبدالرحمن محمد غرم الله جراد

عنوان الرسالة : تقييم جيواحصائي لخام الفوسفات في منطقة حزم الجلاميد

شمال غرب المملكة العربية السعودية

التخصص : جيولوجيا

تاريخ الشهادة : شعبان ١٤١٧هـ

يحتوي الحوض الترسيبي لمنطقة وادي السرحان - طريف على عدة مواقع لخام الفوسفات التابع لعهد الباليوجين المبكر مثل : ثنية طريف ، العمود ، القريميز - السنام ، خور أم وعال و حزم الجلاميد. وتعتبر المنطقة الأخيرة أكثرها جذباً وذلك للتركيز العالي وللمسك المقبول للخام الذي يتواجد في طبقتين متميزتين بفناهما في خامس أكسيد الفوسفور، مفصولتين بطبقة من الصخور الجيرية الفوسفاتية.

و تركز هذه الدراسة على تقييم الخام في هاتين الطبقتين بواسطة الطرق الإحصائية المستخدمة في دراسات علوم الأرض وذلك ضمن مساحة تبلغ ٨٠ كم<sup>٢</sup> من منطقة حزم الجلاميد. وقد اعتمدت الدراسة الحالية على عينات من الخام مستخرجة من ١٧٠ بئر اختبارية. هذا وقد تم تحديد نوعية التوزيع الإحصائي لكل من خامس أكسيد الفوسفور و سمك الطبقات و التراكم المعياري. أثبت التحليل الإحصائي أن درجة التركيز تتبع تقريباً دالة التوزيع الطبيعي. بينما يلاحظ وجود توزيع لا تماثلي و حيود إيجابي لكل من سمك الطبقات والتراكم المعياري.

كذلك أجريت دراسة التوزيع الفراغي على العينات لكل طبقة على حدة باستخدام دالة التباين (السيميفاريوغرام) في اتجاهات مختلفة ومن ثم تم اختيار النموذج الكروي لدوال التباين واستخدمت النتائج المستخلصة فيما بعد في حساب كمية الخام ودراسة التغيير في التركيز.

كذلك طبقت طريقة المحاكاة المشروطة ( Conditional Simulation ) على كل من الطبقتين لقياس درجة التغيير في تركيز خامس أكسيد الفوسفور من مكان إلى آخر في المنطقة المدروسة.

استخدمت طريقة كريغينغ البسيطة (Simple Kriging) لتقدير كمية الخام في كل من الطبقتين باستخدام كتل ذات أبعاد ١٠٠٠ × ٥٠٠ × ١/٢ متر. دلت نتائج الدراسة على وجود ١٠٠٨ مليون طن فوسفات في الطبقة العليا بمتوسط ٢٠ ٪ من خامس أكسيد الفوسفور و ٥٥٣ مليون طن في الطبقة السفلى بمتوسط تركيز يصل إلى ١٨ ٪ من خامس أكسيد الفوسفور.

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران ، المملكة العربية السعودية

ديسمبر ١٩٩٦م

## **ABSTRACT**

The Sirhan-Turayf Basin contains several phosphorite localities of Late Paleogene age including: the Thaniyat Turayf, Al-Amud, Al-Quraymiz, As-Sanam, Khor Umm Wu'al and Hazm Al-Jalamid areas. The Hazm Al-Jalamid deposit is apparently the most attractive one due to its exceptionally high grade and thickness. This deposit is found in two, distinctive, phosphorite horizons (Horizon 1 and Horizon 3) separated by phosphatic limestone (Horizon 2). The focus of this study is the evaluation of the two phosphorite horizons in an area covering about 80 km<sup>2</sup> using geostatistical techniques.

The study was based on a number of samples derived from 170 drill-holes. Statistical analysis was performed to determine the sampling distributions of the variables: P<sub>2</sub>O<sub>5</sub> %, thickness and accumulation. The results indicate that P<sub>2</sub>O<sub>5</sub> % values are approximately normally distributed. The distributions for both thickness and accumulation are asymmetrical with positive skewness. Semivariogram in different directions were constructed leading to the determination of spherical models used in subsequent kriging and conditional simulation.

The simple kriging technique was employed to estimate the P<sub>2</sub>O<sub>5</sub> % in blocks with 1000 m x 500 m x 0.5 m dimensions. The study shows that Horizon 1 contains approximately 1008 x 10<sup>6</sup> tonnes at an average P<sub>2</sub>O<sub>5</sub> grade of 20%, while, Horizon 3 contains approximately 553 x 10<sup>6</sup> tonnes at an average P<sub>2</sub>O<sub>5</sub> grade of 18%. Conditional simulation was also carried out to derive simulated values of P<sub>2</sub>O<sub>5</sub>% in the two horizons. The results indicate the fluctuation pattern of P<sub>2</sub>O<sub>5</sub>% within the deposit.

**MASTER OF SCIENCES DEGREE**  
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# **CHAPTER 1**

## **INTRODUCTION**

Phosphorite deposits were discovered in commercial quantities in the Sirhan-Turayf Basin within the northwestern corner of Saudi Arabia (Figure 1.1). This basin covers an area of more than 100,000 km<sup>2</sup>. So far, at least 6 phosphorite localities have been identified within this basin: the Thaniyat Turayf, Al-Amud, Al-Quraymiz, Umm Wu'al, Al-Sanam, and the Hazm Al-Jalamid areas as shown in Figure 1.2. These deposits are part of the Late Cretaceous- Early Paleogene, Mediterranean, Phosphogenic Province which extends from Morocco to Iraq. This study focuses only on the Hazm Al-Jalamid area because of its huge reserves of economic phosphorite deposit.

### **1.1 Location and Geologic Setting**

The study area is located along the Trans-Arabian pipeline (TAPLINE), 25 km north of the Hazm Al-Jalamid village and about 120 km to the southeast of the Turayf city (Figure 1.3). The area is easily accessible by the Ar'ar -Turayf road, and lies in a featureless plateau that has an elevation of about 800 m above the sea level.

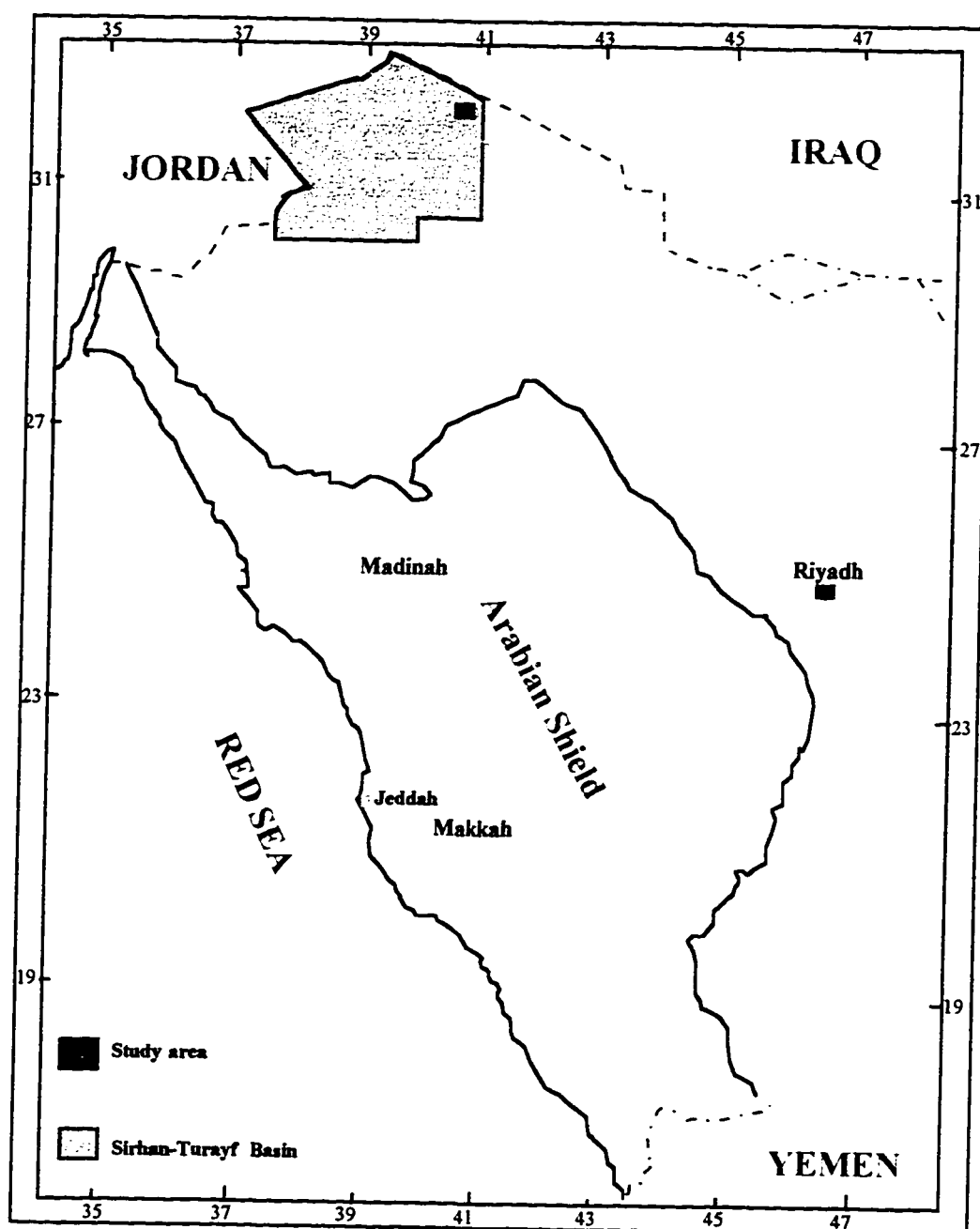


Figure 1.1 Location map for the Sirhan-Turayf Basin

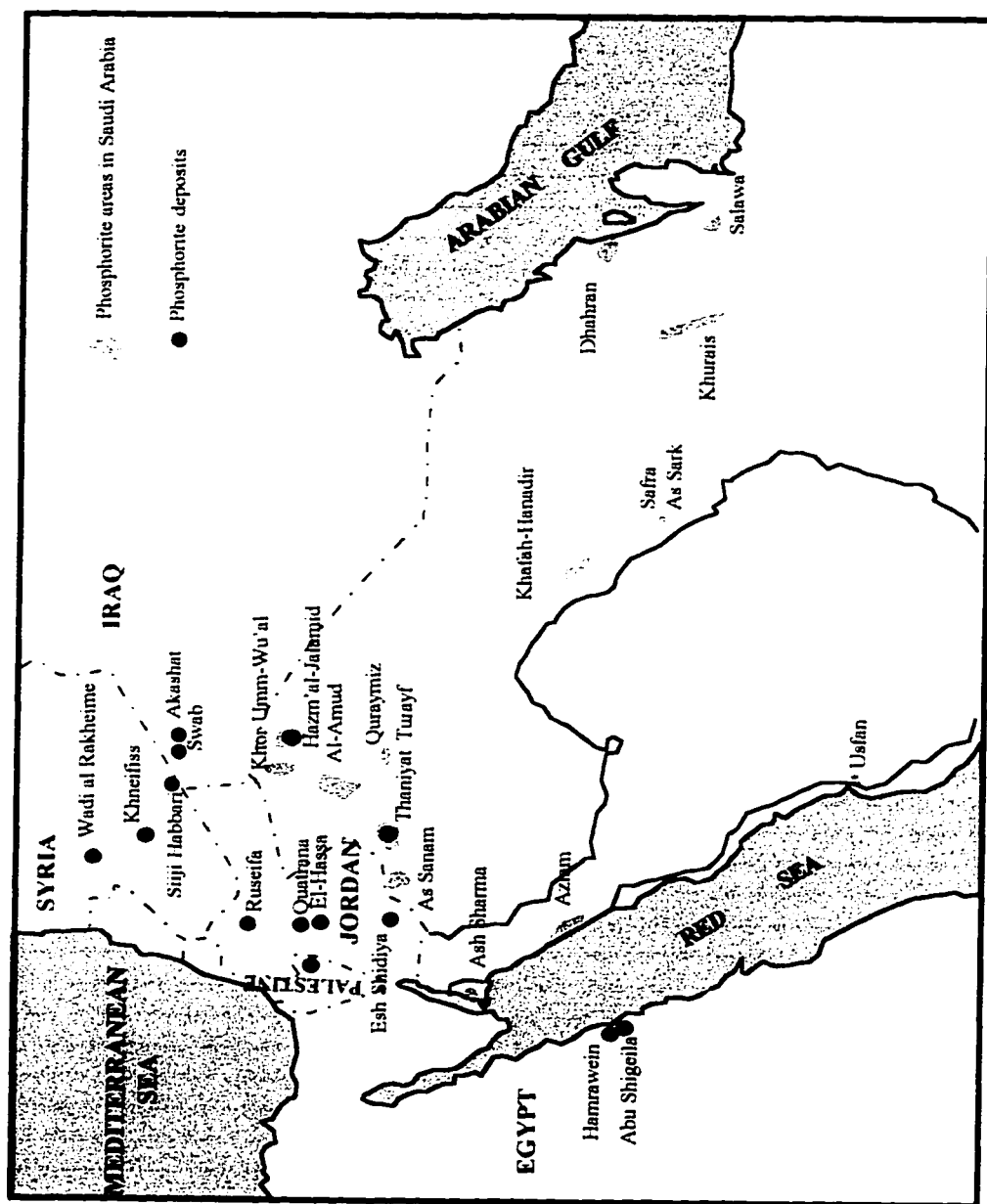


Figure 1.2 Main phosphorite areas and deposits in Saudia Arabia and neighboring countries ( after DGM, 1994)



Figure 1.3 Satellite image showing the location of the study area in the Hazm Al-Jalamid region



The studied deposit is represented by the Thaniyat Turayf Phosphorite which is the basal member of the Early Paleogene Hazm Al-Jalamid Formation. The dominant lithologies of the formation are phosphorite, phosphatic limestone, limestone, dolomite, chalk, and shale. Younger lava flows and surficial deposits cover a large part of the area.

The Hazm Al-Jalamid Formation contains -at least- five distinctive phosphorite horizons with different thicknesses and grades. The two main horizons within the Thaniyat Turayf Phosphorite Member (referred to here as Horizon 1 and Horizon 3 or the Upper and Lower Horizons respectively ) are considered to be the most important deposits in the whole region (Figure 1.4).

## **1.2 Economic Importance of Phosphorite**

Phosphorus is an element vital for the growth of plants, animals, and human beings. Therefore, it is used widely in the production of plant fertilizers, additives to animal foodstuff and in many pharmaceutical compounds, besides other uses, which include the production of chemical compounds (such as phosphoric acid, di-ammonium phosphate, di- and tri- sodium phosphates, mono- and tricalcium phosphates, etc. ), phosphorus paints, detergents, anti-rodents poisons, phosphorus matches, phosphorus bombs, etc. About 80% of the annual world phosphorite production is consumed in the production of fertilizers. However, phosphorus is not found in nature in a free state and hence, can only be sought for in a number of its natural, chemical

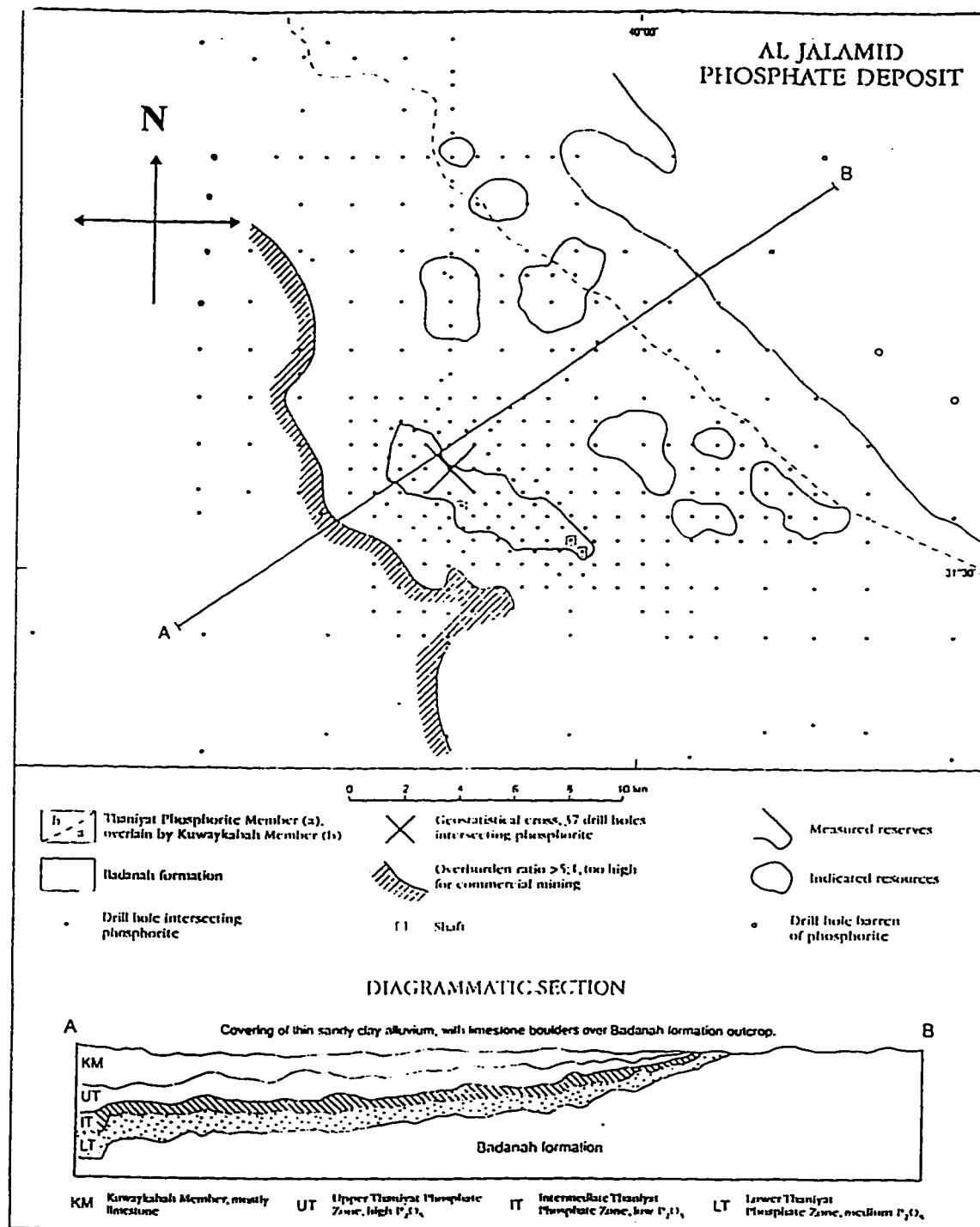


Figure 1.4 NE-SW cross-section in the Hazm Al-Jalamid area (after D'GMR, 1994)

compounds such as the calcium phosphate. The main source of calcium phosphate and hence, of phosphorus in nature is found in sedimentary phosphorite deposits.

The world annual production of phosphorite concentrate was only 3.5 Mt in 1900. It went up to 50 Mt in 1963 and nearly 124 Mt in 1978, (Slansky, 1986). The production in 1992 was over 155 Mt (DGMR, 1994). It is steadily increasing due to increase in demand. Morocco is the largest producer of phosphorite, followed by the U. S. A. and the former U. S. S. R. The world-wide distribution of identified phosphorite resources are shown in Figure 1.5.

### **1.3 Previous Studies**

Most of the previous work carried out -so far- on the phosphorite deposits of northwestern Saudi Arabia was mainly aimed at the establishment of its age, stratigraphic position and the mineralogical composition of the ore. Limited studies, however, were aimed to obtain the primary estimation of the reserves using the classical statistical methods. The following paragraphs summarize the main contributions to the study of the ore.

Phosphorite minerals were first detected in Saudi Arabia by Sheldon (1965) during the examination of cuttings derived from water wells drilled by Aramco close to the TAPLINE near Turayf. Mytton (1966) classified the Paleocene - Eocene succession in the Sirhan - Turayf basin (previously included under the name Hibr

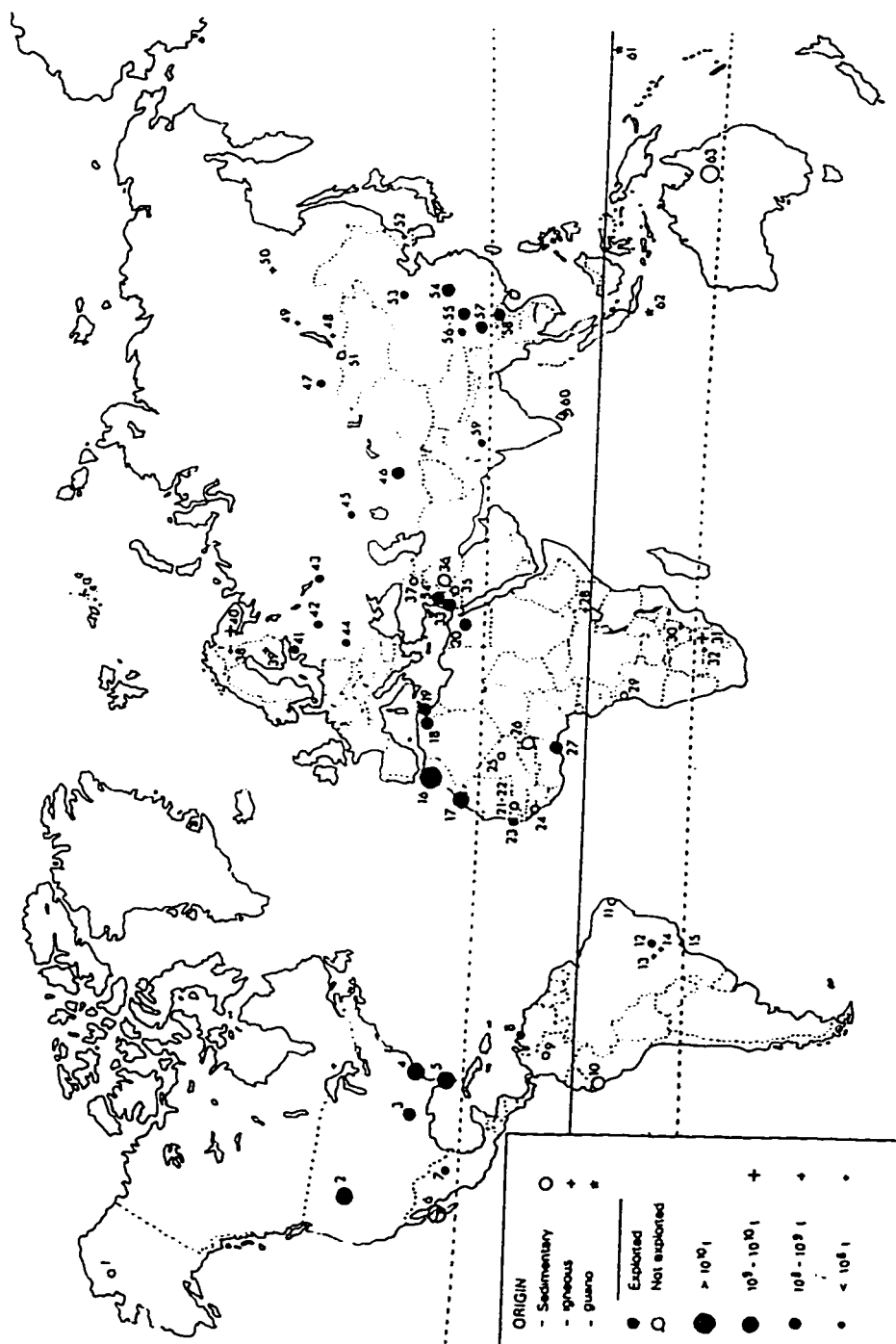


Figure 1.5 World distribution of identified phosphorite resources (after Slansky, 1986)

Formation) into three distinctive members: Lower Hibr Member, Phosphate Member, and Upper Hibr Member. Further studies, conducted by Meissner (1967), and Meissner and Ankary (1972), lead to the identification of four phosphatic intervals. Kluyver and others (1981) assumed a very large hiatus between strata of the Paleocene and those of the Early Eocene age. El-Naggar and others (1982) and El-Naggar and Kamel (1988) raised the Hibr Formation to a group status and identified four formations and at least five phosphorite horizons. Riddler and others (1983) replaced the name Hibr Group by the name Turayf Group, completely overlooking the precedence of the former name. Kamel (1985), and Wasimuddin (1985) reclassified the Hibr Group into three distinctive formations: Hazm Al-Jalamid, Bardawil, and Turayf Formations. The classification was introduced by El-Naggar and others (1982) and adopted by El-Naggar and Kamel (1988).

The Directorate General of Mineral Resources (DGMR) carried out a study for the Hazm Al-Jalamid phosphorite deposit in an area about 18 km<sup>2</sup>, using kriging and other statistical methods. The study revealed the presence of huge reserves of economic phosphorite deposits, with an average grade of 20.35% (DGMR, 1994).

Considering the nature of the previous works, a detailed geostatistical study, involving the spatial distribution of the phosphorite deposit in an area covering about 80 km<sup>2</sup> is deemed necessary to provide more reliable estimates for the reserves in the Hazm Al-Jalamid area.

## **1.4 Objectives of the Present Study**

The present study is based on data derived from 170 drill-holes, and concentrates mainly on the geostatistical evaluation of the deposit with the following specific objectives:

1. Review the geology of the Early Paleogene succession in the Sirhan-Turayf basin in general and in the Hazm Al-Jalamid area in particular.
2. Collection, preparation and description of the data sets.
3. Carrying out the statistical analysis of data including the determination of basic statistical parameters and the construction of histograms and cumulative frequency curves.
4. Carrying out the spatial analysis of the data, including the construction of semivariograms and the determination of geostatistical parameters.
5. Applying appropriate kriging technique for the estimation of the  $P_2O_5$  % values within the deposit.
6. Applying appropriate conditional simulation techniques to simulate the  $P_2O_5$  % values within the deposit, and
7. Derivation of the grade-tonnage relationship for the deposit.

## **1.5 Tools of the Study**

To conduct this study, computer software packages including GEOSTAT (1994), GEOLITH (1994), GSLIB(1994) and other supporting packages such as EXCEL, SIGMA PLOT, SIGMA STAT, AUTOSKETCH, LOTUS123, WINSURFER, CANVAS, MACDRAW and ARC INFO were used. These packages and programs are available in the Geostatistics Computing Laboratory of the Research Institute, The Information Technology Center and the Department of Earth Sciences of King Fahd University of Petroleum and Minerals.

## **CHAPTER 2**

### **GEOLOGY OF THE PHOSPHORITE DEPOSITS IN NORTHWESTERN SAUDI ARABIA**

#### **2.1 Geology of the Sirhan -Turayf Sedimentary Sub-basin:**

The Sirhan-Turayf sedimentary Sub-basin is bounded in the east by numerous fold structures that run almost parallel to the Ha'il arch. In the south, it is bounded by both Paleozoic rocks and the eolian sands of the Great Nafud which cover parts of the Arabian Shield and its Paleozoic sedimentary cover. In the west, it is bounded by both the Basement Rocks of the Arabian Shield and its Paleozoic sedimentary cover, as well as by the Red Sea rift zone. To the north, the basin is apparently connected to the Mediterranean basin of Jordan, Palestine, Sinai and the Levant. The axis of the Sirhan-Turayf basin trends NNW, along the Wadi As Sirhan graben structure, which has the lowest elevation and the thickest sedimentary section in the region.

The northern part of the Sirhan-Turayf Sub-basin is almost flat, featureless area with rare outcrops of the Paleocene-Holocene sedimentary rocks and lava flows.



Several plateaus and escarpments are present in the southern part of the basin, where rocks ranging in age from Silurian/Devonian to Holocene (with a large number of stratigraphic breaks in the succession) outcrop. These include the Devonian, Domat'al-Jandal Group (outcropping near Al-Jauf town), the Early-Middle Cretaceous, Wasia Group (outcropping in the Sakaka area, between the escarpment of Jal Al Jubah Al Gharbi and Jal Al Jubah Ash Sharqi and north of the Great Nafud), the Late Cretaceous, Aruma Group (which outcrops in the Ar'ar region, extending southward to the northern reaches of Sakaka), a few exposures of the Early Paleogene, phosphorite bearing rocks of the Hibr Group, younger lava flows, alluvial deposits, minor eolian sand accumulations, khabras, sabkhas, wadi deposits and alluvial terraces (Figure 2.1). These sequences have an overall thickness of at least 7500 feet (Powers and others, 1966).

The Sirhan-Turayf area is believed to have been a distinct sub-basin, separated by a series of folds that run more or less parallel to the Ha'il Arch (which trends NNW-SSE) from the much larger, Eastern Arabian Sub-basin (Figure 2.2). The phosphorite-bearing, Early Paleogene, Hibr Group was deposited in the restricted to semi-restricted, shallow marine Sirhan Sub-basin, whereas the co-eval, non-phosphoritic, relatively deeper and more open marine Hasa Group was deposited in the Eastern Arabia Sub-basin.

Apparently, the Ha'il Arch and its parallel folds have played an important role in controlling the pattern of deposition at the bottom of the Early Paleogene sea that

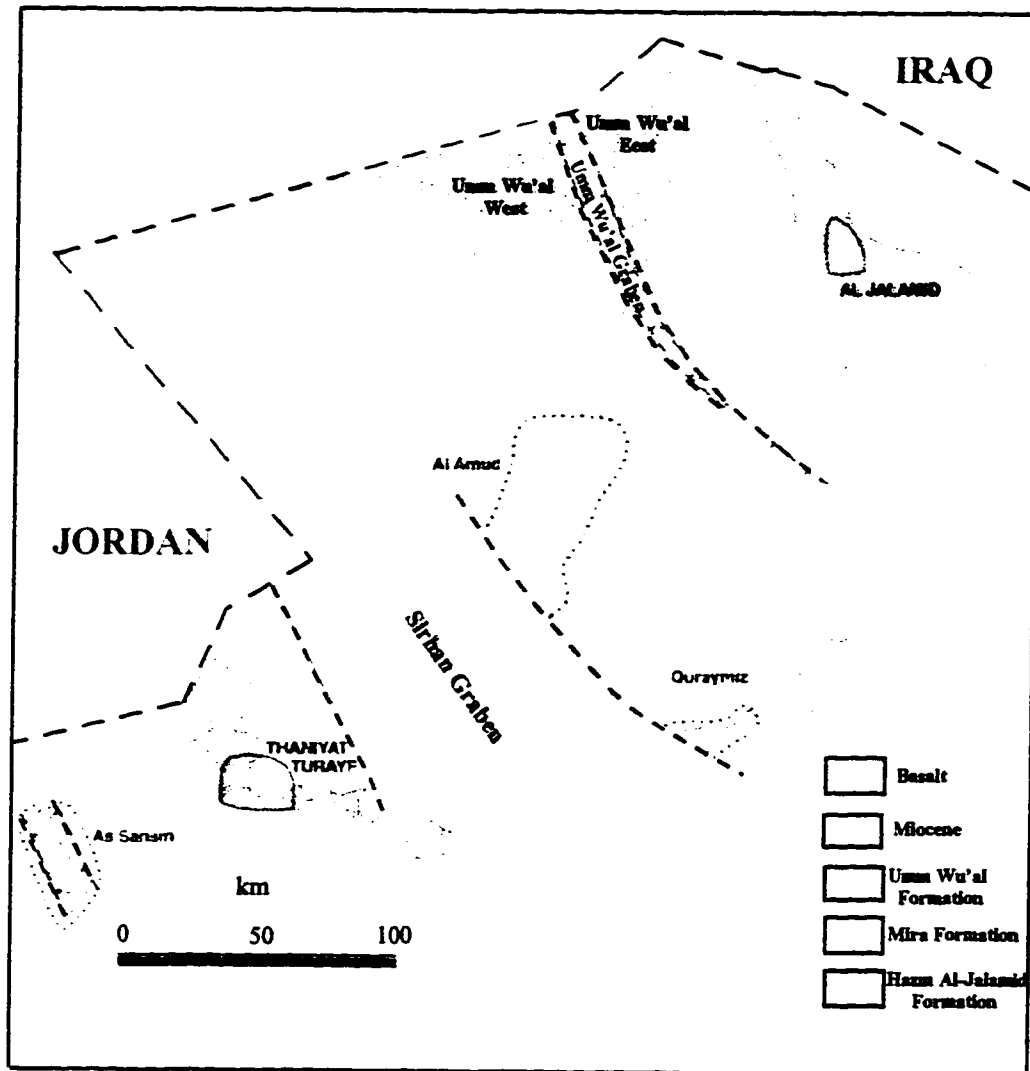


Figure 2.1 Geological map showing different lithologies and graben systems in the Sirhan-Turayf Basin (after DGMR, 1994)

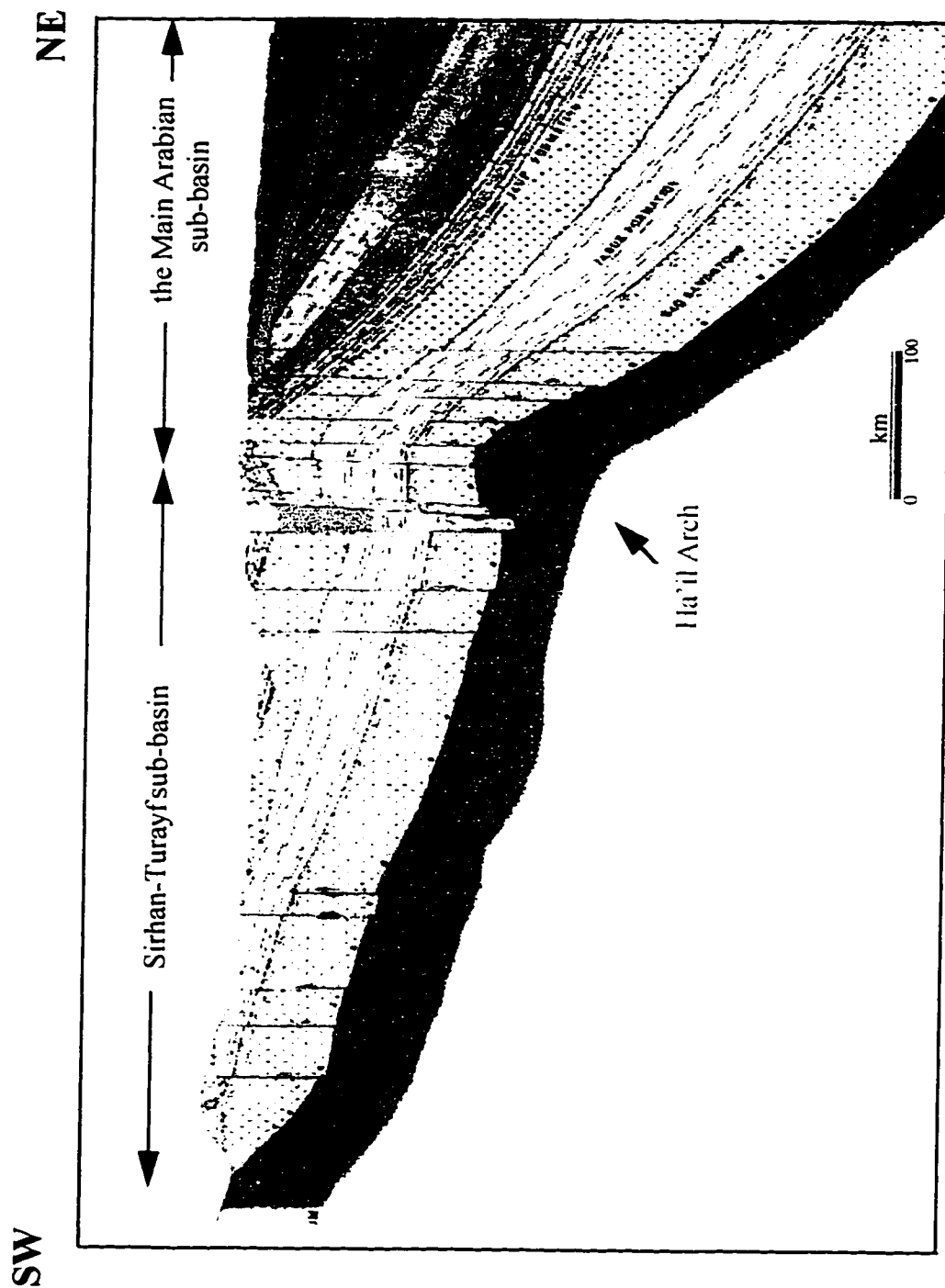


Figure 2.2 NE-SW cross-section through the Northwestern part of Saudi Arabia, showing the Ha'il Arch, separating the Sirhan-Turayf sub-basin from the main Arabian sub-basin (after Aramco, 1995)

covered the northwestern parts of Arabia, and hence the phosphorite deposition in the Sirhan-Turayf Basin. The continuous growth of such swells and the subsidence of adjacent basins were controlled by several fault systems, that run mainly parallel to the arch and include the Umm Wu'al Graben, the Wadi As-Sirhan Graben, the Ar Riyyatan fault complex, Al-Busayta and Al-Qasimah fault systems, etc. In addition, ENE-WSW fault systems (parallel to the Gulf of Aqaba-the Dead Sea Rift) are also present, but seem to be a much younger event than the NNW-SSE faulting. The grabens of both Umm Wu'al and Wadi As-Sirhan structures are oriented N 22° W with up to 1 km width, several kilometers length, and a maximum vertical displacement of 50 m from the graben floor to the flanking hill tops (Meissner and Ankary, 1970).

Lava flows, believed to have spread out from fractures parallel to the Red Sea Fault System cover sediments of the Hibr Group in the northwestern segment of the region. These flows extend northward from the Khabra As Sib for about 225 km to the Jordanian border. They vary in width from 55 km to 100 km and in thickness from 0.5 m to 150 m (Riddler and others, 1986).

In both the Thaniyat Turayf and the Hazm Al-Jalamid areas, the strata are gently dipping with an amount of 0.5° to 3° toward southwest, unless locally disturbed. This gentle dip was observed in outcrops and, at the same time, interpreted from the subsurface data (Riddler and others, 1986).

## **2.2 Geology of the Hazm Al-Jalamid Phosphorite Deposits:**

### **2.2.1 Stratigraphy**

The Hazm Al-Jalamid Phosphorite deposits occur within the Thaniyat Turayf Phosphorite Member which forms the base of the Hazm Al-Jalamid Formation. This formation, in turn, forms the base of the Hibr Group, which is briefly described as follows:

#### ***The Hibr Group***

As mentioned by Powers and others (1966) and Powers (1968), the name Hibr Formation was first introduced by Perg and Owens (1946) after Tel Al-Hibr which is located in Jordan. In the present study, the data used were calibrated according to the stratigraphic column suggested by Riddler and others (1983) as illustrated in Figure 2.3. This classification will be used with some modifications suggested by El-Naggar and others (1982), Kamel (1985), Wasimuddin (1985) and El-Naggar and Kamel (1988). The formation was later raised to group status and named as the Hibr Group. It was dated as Late Cretaceous (Maastrichtian) to Middle Eocene (Lutetian) by Riddler and others, (1983). However, El-Naggar and others (1982), Kamel (1985), Wasimuddin (1985) and El-Naggar and Kamel (1988) suggested a Paleocene (Heersian-Landenian)-Middle Eocene (Lutetian) age based on detailed microfacies

| TIME     | GROUP  | FORMATION | MEMBER               | BED                |
|----------|--------|-----------|----------------------|--------------------|
| TERTIARY | TURAYF | Umm Wu'al | Jirani Limestone     |                    |
|          |        |           | Shihiyah             | Muqannah Coquina   |
|          |        |           | Tarabah              |                    |
|          |        |           | Hamad                | Wu'ayla            |
|          |        |           | Al-Amud              | Rushaydah Coquina  |
|          |        |           |                      | Maida Coquina      |
|          |        |           |                      | Rushayda Claystone |
|          |        |           | Araqah Phosphorite   |                    |
|          |        | Mira      | Sib                  |                    |
|          |        |           | Mindassah            |                    |
|          |        |           | Hawsa                |                    |
|          |        |           | Ghinah Phosphorite   |                    |
|          |        | Jalamid   | Kuwaykabah           | Arus               |
|          |        |           |                      | Ghuzay             |
|          |        |           |                      | Qutayfah           |
|          |        |           | Thaniyat Phosphorite |                    |
|          |        |           |                      |                    |

Figure 2.3 Generalized lithostratigraphic section for the Sirhan-Turayf Basin (after Riddler and others, 1983).

analyses. The group unconformably overlies one or more of the following lithological units in an overstepping manner: the Ar'ar Chalk (the Badanah Formation of Riddler and others, 1986), the Zallum Sandstone (Aruma Group), the Sakaka Sandstone (Wasia Group), the Jauf Formation and the Tawil Sandstone (Domat'Al-Jandal Group) (Kamel, 1985; Wasimuddin 1985 and El-Naggar and Kamel, 1988).

As illustrated in Figure 2.4, the Hibr Group is divided into the following three formations: the Hazm Al-Jalamid, Bardawil, and Turayf Formations. The same formations were later named differently by Riddler and others (1983) as follows: Jalamid, Mira and Umm Wu'al Formations, respectively. The latter classification is more or less the same as the former, with only some minor variations in dating. These formations represent three periods of cyclic carbonate sedimentation comprising repetitive, short, sweeping, on-lapping, transgressive-regressive events over a shallow marine shelf. Significant phosphorite members occur at the base of each sedimentary cycle, with some minor intermediate beds (Riddler and others, 1986). The Hibr Group was described as limestone, chalk, marl and crystalline chert (Riddler and others, 1986). The lithology of the group was summarized by Kamel (1985) as follows:

1. Lower sequence of silicified limestone (the Hazm Al-Jalamid Formation).
2. Middle sequence of limestone and phosphorite horizons (the Bardawil Formation).

| CHRONO-STRATIGRAPHIC UNITS |            |                 |           | LITHO-STRATIGRAPHIC UNITS |                                   |                 |                 |
|----------------------------|------------|-----------------|-----------|---------------------------|-----------------------------------|-----------------|-----------------|
| Era                        | Period     | Epoch           | Age       | Lithology                 | Member                            | Formation       | Group           |
| CENOZOIC                   | Paleogene  | Eocene          | Lutetian  |                           | Al-Harrah Basalt                  |                 | Hibr            |
|                            |            |                 |           |                           |                                   | Turayf          |                 |
|                            |            |                 | Ypresian  |                           |                                   | Bardawil        |                 |
|                            |            |                 |           |                           |                                   |                 |                 |
|                            |            | Paleocene       | Landenian |                           | Al-Hawsah Cherty Chalk            | Hazm Al-Jalamid |                 |
|                            |            |                 |           |                           | Umm Al-Raquabah Silic. Numm. L.S. |                 |                 |
|                            |            |                 |           |                           | W. Wailah Phosphatic Limestone    |                 |                 |
|                            |            |                 |           |                           | Wadi Abu Tulaybah Chalk           |                 |                 |
|                            |            |                 | Heersian  |                           | Thaniyat Turayf Phosphorite       |                 |                 |
|                            |            |                 |           |                           |                                   |                 |                 |
| MESOZOIC                   | CRETACEOUS | Late Cretaceous |           |                           | Ar'ar Chalk                       | Aruma           |                 |
|                            |            |                 |           |                           | Zallum S.S.                       |                 |                 |
| PALEOZOIC                  | DEVONIAN   |                 |           |                           |                                   | Sakaka S.S.     | Domat'al Jandal |
|                            |            |                 |           |                           |                                   | Jauf L.S.       |                 |
|                            |            |                 |           |                           |                                   | Tawil S. S.     |                 |

Figure 2.4 Stratigraphic column for the Sirhan-Turayf Basin (after El-Naggar and others, 1982)



3. Upper sequence of limestone and chert capped by the nummulitic limestone of the Hibr Hill (The Turayf Formation).

### ***The Hazm Al-Jalamid Formation***

This rock unit was named by El-Naggar and others (1982) after the Hazm Al-Jalamid village (along the TAPLINE between the towns of Ar'ar and Turayf). It was divided by Riddler and others. (1983) into two members (i.e. Thaniyat Turayf Phosphorite Member and the Kuwaykabah Limestone Member). Wasimuddin (1985) further divided the formation into five members in the Thaniyat Turayf area (Figure 2.4). In the southern area the Kuwaykabah Limestone Member was divided into mainly non-bioclastic, silty, micritic limestone, and chert of the Qutayfah, Guzay, and Arus beds respectively (Riddler and others, 1986). Based on paleontological grounds and thickness, the beds in Riddler's classification were raised to member ranks and the laminae to beds (Wasimuddin, 1985). Classifications adopted for the Hazm Al-Jalamid Formation by El-Naggar and others (1982) and Riddler and others (1983) can be matched if the three beds in the Thaniyat Phosphorite Member of Riddler's classification are equated with the first three members in the Thaniyat Turayf Phosphorite Member of El-Naggar's classification. In fact, these three members are identical in lithological composition to the three beds forming the Thaniyat Phosphorite Member (Figure 2.5).

The Hazm Al-Jalamid Formation is best exposed in the southwestern part of the basin along the Thaniyat escarpment. It ranges in thickness from 45 m to 120 m. The

| According to Riddler and others (1983) |           |                      | According to El-Naggar and others(1982) |                                       |       |                 |
|----------------------------------------|-----------|----------------------|-----------------------------------------|---------------------------------------|-------|-----------------|
| Group                                  | Formation | Member               | Member                                  | Formation                             | Group |                 |
| Turayf                                 |           |                      |                                         |                                       | Hibr  |                 |
|                                        | Umm-Wu'al |                      |                                         | Turayf                                |       |                 |
|                                        | Mira      |                      |                                         | Bardawil                              |       |                 |
|                                        | Jalamid   | Kuwakabah Limestone  |                                         | Al-Hawsah Cherty Chalk                |       | Hazm Al-Jalamid |
|                                        |           |                      |                                         | U. Al-Raquabah Silic. Numm. Limestone |       |                 |
|                                        |           | Thaniyat Phosphorite |                                         | W Wailah Phosp. L.S.                  |       |                 |
|                                        |           |                      | Wadi Abu Tulaybah Chalk                 |                                       |       |                 |
|                                        |           |                      | Thaniyat Turayf Phosphorite             |                                       |       |                 |

Figure 2.5 Stratigraphic column for the Hibr Group in the Sirhan-Turayf basin

thickness increases to the northwest from the Thaniyat escarpment towards Wadi Al-Ghinah. Conversely, towards the southwest, in the direction of Tabuk, the formation thins out, passing laterally into a probable near-shore facies (Riddler and others, 1986). The Hazm Al-Jalamid Formation is apparently continuous (although not necessarily complete) northward and eastward, in the central escarpment area, being covered by the basalts of Al-Harrah. Progressing east from the Thaniyat escarpment, the Hazm Al-Jalamid Formation dips below younger rock units and reappears between Al-Quraymiz ( $29^{\circ} 57' N$ ,  $39^{\circ} 30' E$ ) and Ar Riyyatan ( $30^{\circ} 00' N$ ,  $39^{\circ} 40' E$ ). It is assumed that the intervening area between the Thaniyat Turayf and Al-Quraymiz was a paleo-topographic high during the time of deposition of the Hazm Al-Jalamid rock unit, and hence the formation was not deposited there. The formation caps the escarpment west and north of Al-Shuwayhiyah, and crops out over the eastern part of the region in Al-Hamad plain, extending northward to the Iraqi border, pinching out around the nose of a plunging anticline in the northeastern part of the region.

***The Thaniyat Turayf Phosphorite Member:***

The Thaniyat Turayf Phosphorite Member crops out in the southwestern part of the basin, along the Thaniyat escarpment, and in both Wadi Al-Ghinah and Wadi Al-Kuwaykabah. In the eastern part of the escarpment, the member comprises a relatively compact interval of phosphorite, chert, shale and dolomicrite. The total thickness of the phosphorite beds within the member ranges between 3m and 5m with up to 7 discrete beds. These can be gathered into two horizons of phosphorite separated by a

low grade phosphatic limestone (Riddler and others, 1986). The phosphorite beds range from a friable, sandy, phosphorite variety to a hard, calcareous phosphorite, containing bioclastic debris and sharks' teeth, and are locally separated by bands of chert or shale (Wasimuddin, 1985).

In Al-Quraymiz area, the Thaniyat Turayf Phosphorite Member ranges in thickness between 0.5m and 2m with a strike length of 10 km. A typical section of this member here comprises from the base: a silicified, coarse, bivalve coquina bed, overlying a lateritic sandstone facies of the Zallum Formation (Aruma Group). Above the coquina bed, a semi-friable to friable, sandy phosphorite interval (10cm to 30cm thick) is present. This interval is overlain by argilleous and phosphoritic limestone, which gradually and laterally changes to phosphoritic, cherty, coarse bivalve coquina in the eastern direction. The member thins out to the north, towards the Iraqi border and becomes lithologically more distinct, whereas the phosphorite beds are interbedded with gray-brown chert and buff, possibly argillaceous limestone (Riddler and others, 1986).

In the Hazm Al-Jalamid area, the Thaniyat Turayf Phosphorite Member changes laterally to the west and east into a cherty, biocalstic limestone facies that is only weakly or non-phosphoritic. Facies distribution was mainly controlled by the paleobathymetry of the sea-bottom (paleo-highs and paleo-lows produced by old, and possibly syn-sedimentary faulting). The member dips gently to the west, becomes more shaly down-dip and comprises two, extensive, friable, semi-friable to hard carbonate-

cemented phosphorite beds. These beds are enclosed in micritic, bioclastic limestones, which become dolomitic towards the base. A slightly lateritized, basal contact with the Ar'ar Chalk is apparent in the drill-holes (Riddler and others, 1986).

Towards the east, erosional remnants over plunging anticlines consist of silicified algal domes lying above a unit, up to 5 m thick and, containing strong accumulations of well-packed, sorted, friable and semi-friable phosphorite. The western outliers have thicker sequences and lithofacies, reflecting a basin-ward trend away from the intertidal conditions (Riddler and others, 1986).

In the extreme northeastern part of the region (northwest of Ar'ar town), the Hazm Al-Jalamid Phosphorite Member is either poorly developed or absent. In this area, blackened, variably silicified and commonly pelletal carbonate beds, capping the Ar'ar Formation is probably equivalent to the Thaniyat Turayf Phosphorite Member (Riddler and others, 1986).

### **2.2.2 Structural Setting**

As mentioned above, the whole structural setting in the Sirhan-Turayf Basin is controlled by the growth of the Ha'il Arch and its parallel structures (block faulting and its associated swell and basin structures). Fault systems, believed to be of reverse type, were developed due to subsidence and local compressions associated with the growth of the drape structures. These faults, which generally follow the arch trend

(NNW-SSE) have been mapped in outcrop and detected in the subsurface of Hazm Al-Jalamid area.

Joint systems, probably related to tension forces caused by uplift associated with the Ha'il Arch complex, were also identified in the eastern margin of the basin. Gentle dipping of beds towards the southwest at  $0.5^{\circ}$  to  $3^{\circ}$  were also observed in the cross-sections of the subsurface of the Hazm Al-Jalamid area. Adjacent to the axes of faults, the fault drags increase the amount of dip as much as  $29^{\circ}$  (Riddler and others, 1986). The lower and upper horizons of phosphorite within the Hazm Al-Jalamid Member were controlled by local paleohighs. Phosphorites were deposited in the southern or southwestern sides of the paleotopographic highs and post-depositional folding has brought the thickest part of the phosphorite accumulation (formerly in the sea-bed hollow) nearer to the surface (Riddler and others, 1986). However, it appears that post-depositional faulting had little effect on the phosphorite beds. NE-SW trending lineaments are in alignment with a possible syn-sedimentary fault systems which has apparently acted as a depositional control in the southern part of the area. In the southeastern part of the area, phosphorite was not recorded and the Thaniyat Turayf Phosphorite Member may be completely absent (Van Eck and others, 1984).

### **2.2.3 Mineralogy of Deposit**

There is no general agreement on the petrographic designation of sedimentary rocks with a predominant phosphorous content. Terminologies such as phosphate, phosphatite, phosphorite, aluminophosphatite, ferriphosphatite or uranophosphatite

were used to describe these rocks. The term phosphorite, however, appears to be the most suitable to describe the sedimentary rock consisting mainly of phosphorous-rich minerals, (Slansky, 1986).

The economic potential of phosphorite is expressed usually in terms of P,  $P_2O_5$  or tricalcium phosphate  $[Ca_3(PO_4CO_3)_3]$ , the relationship between them can roughly be expressed as follows:

$$80\% [Ca_3(PO_4CO_3)_3] = 36.6\% P_2O_5 = 16.5\% P$$

Mineralogical and chemical analyses were carried out on selected phosphorite samples from the Sirhan-Turayf Sub-basin by Peers (1984) and Basham (1984) to determine the nature and association of minerals present. These studies also revealed the liberation characteristics of the contained apatite and gangue minerals. The results of these studies are summarized as follows:

1. Phosphorite deposits of the Sirhan-Turayf Sub-basin are all broadly similar in nature.
2. The  $P_2O_5$  content of these phosphorite deposits ranges between 8% and 33%.
3. The main constituent of the phosphorite deposit is carbonate-apatite (francolite or dahillite)  $[Ca_3(PO_4CO_3)_3(OH,F)]$ .

4. The gangue minerals are calcite and dolomite, varying amounts of quartz, gypsum, basanite and minor amounts of hydrated calcium uranate /vanadate or a yellow secondary mineral metayuyamunite [  $\text{Ca}(\text{UO}_2)_2 (\text{VO}_4)_2 \cdot 3-5 \text{H}_2\text{O}$  ].

Based on the drill-hole data records, the Thaniyat Turayf Phosphorite Member can be divided into three horizons (i.e. two phosphorite horizons separated by a low grade zone) as follows:

1. Lower phosphorite horizon of calcareous and dolomitic, compact to friable phosphorite, beds (3-4 m thick) with an average grade of 17.81%  $\text{P}_2\text{O}_5$ .
2. Intermediate horizon of phosphatic limestone with quartz geodes, (0.5-5 m thick) with an average grade of 9.73 %  $\text{P}_2\text{O}_5$ .
3. Upper horizon of calcareous, compact to friable, phosphorite beds (4-7m thick ) with an average grade of 20.03%  $\text{P}_2\text{O}_5$ .

The phosphorite grains in the Hazm Al-Jalamid deposit range in diameter from 50 to 300 microns (DGMR, 1994). SEM observations indicate that the phosphorite grains have different concentrations. This can be explained by a possible polygenetic origin and/or a poly-diagenetic history. The SEM observations and the physical tests also indicate that the phosphorite grains break cleanly from the carbonate matrix. Such behavior can be a considerable advantage in ore enrichment (DGMR, 1994).



#### 2.2.4 Economic Potential of Deposit

The Thaniyat Turayf Phosphorite Member in the Hazm Al-Jalamid area is probably the most important phosphorite occurrence-so far discovered- in the Sirhan-Turayf Sub-basin. It contains the majority of both the demonstrated (1070 Mt at 20.16%  $P_2O_5$ ) and the identified resources (4120 Mt at 19.31%  $P_2O_5$ ) in the region.

Within the demonstrated resource, the base estimated reserve is 310 Mt at 23.07%  $P_2O_5$  and the average cut-off grade is 20%  $P_2O_5$ . Maximum stripping ratio of aggregate overburden thickness to aggregate phosphorite bed thickness is 5:1 (Riddler and others, 1986). The inferred reserve is 425 Mt at 25.20%  $P_2O_5$  that gives a base of total identified reserve 735 Mt at 24.30%  $P_2O_5$  (Riddler and others, 1986). Later geostatistical study conducted by the USGS on behalf of the DGMR in 1992, within an area of 18 km<sup>2</sup> indicated the presence of 400 Mt (213 Mt as measured reserves and 187 Mt as indicated resources) of phosphorite with an average  $P_2O_5$  grade of 20.35% (DGMR, 1994). The current study geostatistically assessed and estimated the reserve within an area of 80 km<sup>2</sup> in the same region using local estimation and conditional simulation methods. This has proved that the Upper Horizon contains 1008 x 10<sup>6</sup> tonnes at an average  $P_2O_5$  grade of 20%, while, the Lower Horizon contains 553 x 10<sup>6</sup> tonnes at an average  $P_2O_5$  grade of 18%.

### 2.2.5 Origin of Deposit

Since the discovery of sedimentary phosphorites, many hypotheses have been proposed about their origin. These include the chemogenic, volcanogenic, biolitic, biochemical, and metasomatic hypotheses and some combinations of such hypotheses. Al-Bassam and Hagopin (1983) suggested that the immediate source of Paleocene phosphorus in the area appears to have been biogenic and that phosphorite was most probably precipitated in the shallow, phosphorus-rich, semi-restricted environment of near-shore lagoons, near the sediment-water interface under high pH and reducing conditions. Later, diagenetic processes did play an important role in developing many petrographic and geochemical characteristics of the phosphorite grains. The majority of these processes appear to have been subjected to several stages of reworking by currents and waves before they were finally deposited mechanically in the favorable traps (Wasimuddin, 1985).

The abundance of organic matter seems to be due to the dissociation of organic phosphorite which was most probably the local source of phosphorus and carbonate concentrations in solutions that were required for the precipitation of carbonate-hydroxyl apatite. The phosphorite was originally precipitated directly and/or by replacement of calcareous mud in an environment characterized by very high biologic activity, rich in phosphorus and silica, probably reducing, and was occasionally affected by waves, and oceanic as well as wind-driven currents (Wasimuddin, 1985). The upwelling currents which resulted from the interaction of oceanic currents, winds,

and the Coriolis force, was the main source of phosphorus and hence nutrients upon which the biologic occurrence depended as summarized in Figure 2.6.

Wasimuddin (1985) listed the evidences of the upwelling mechanism in the area as follows:

1. Presence of cool water faunas at low paleoaltitudes probably brought from sea beds by upwelling currents.
2. Abundance of phosphatic fish relics in most phosphorite and phosphoritic beds.
3. Abundance of siliceous microfossils which mainly exist in deep sea water.
4. Indication of local oxygen deficiency.
5. Low Cerium content of the phosphorite in nearby countries such as Syria.

On the regional scale, evidence of active upwelling currents during the Late Cretaceous-Eocene times in the Tethyan sea have been recorded, and appear to have served as transporting agents of phosphorus and silica from the deeper parts of the ocean to the shallower warmer parts (Sheldon, 1981).

The field and laboratory observations on the Hazm Al-Jalamid phosphorite deposits have suggested the following:

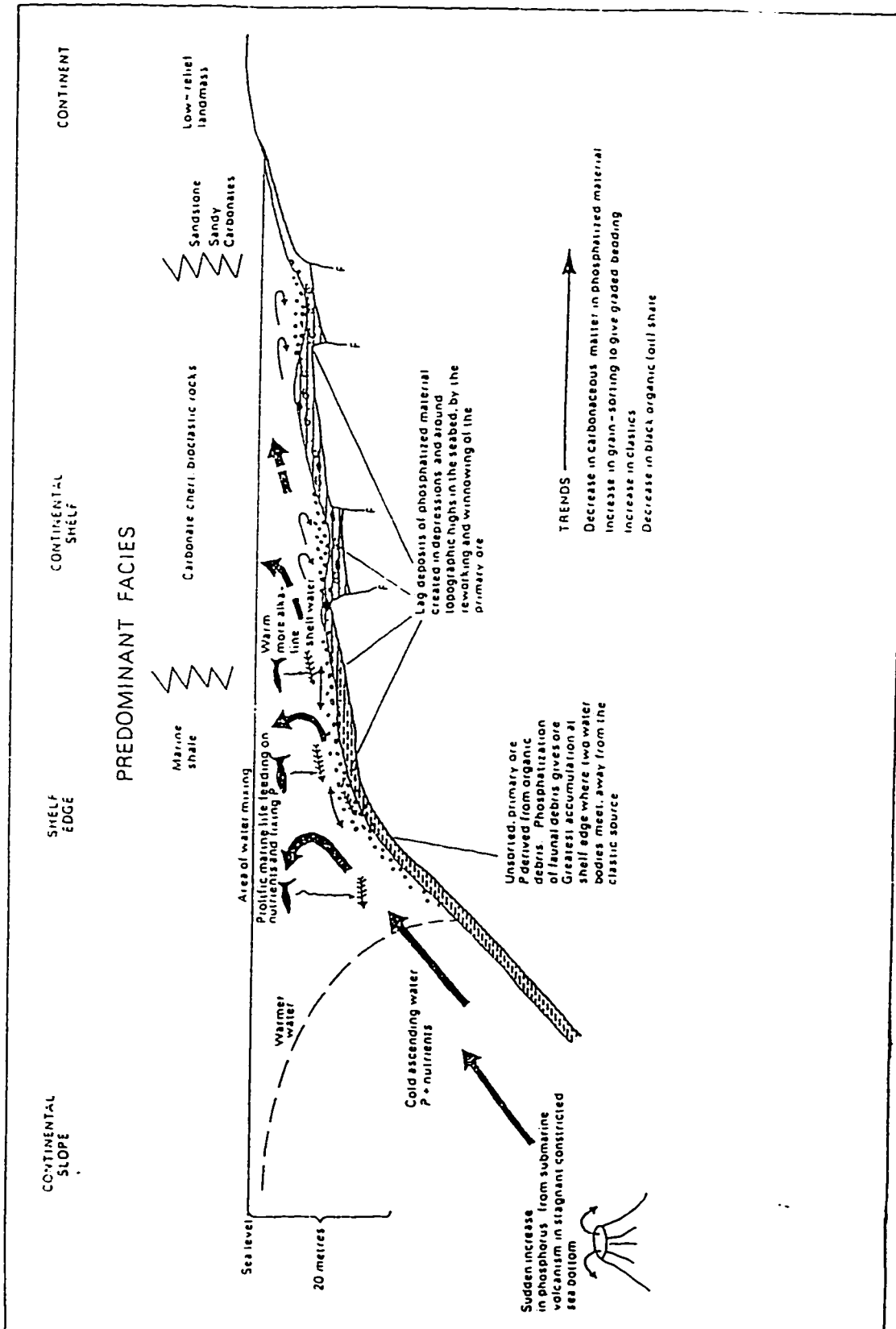


Figure 2.6 Model for sedimentary phosphorite deposition and accumulation (after Riddler and others, 1986)

1. Within the Early-Paleogene Tethyan transgression over northwestern Arabia, an inner shelf was formed with a number of paleo-highs and restricted areas, created by local tectonic and/or topographic swells and basins within huge syncline of the Sirhan-Turayf Sub-basin.
2. Upwelling currents provided this restricted and semi-restricted inner shelf with phosphorus, nutrients and other elements.
3. Fishes and other living organisms in the sub-basin consumed the phosphorus and the nutrients required by their bodies and provided an intermediate stage in the cycle of phosphorite formation.
4. When fishes and other organisms died, their bodies started to decompose and hence phosphorus was concentrated in the restricted parts of the sub-basin.
5. When the restricted waters became enriched with phosphorus, the chemical processes in the sub-basin started to precipitate phosphates in the form of Tricalcium Phosphate  $[\text{Ca}_3(\text{PO}_4\text{CO}_3)_3]$  or other similar forms either by direct precipitation or by chemical replacement.
6. The precipitate was subjected to post depositional processes. The pellets were formed due to the local currents and hence different phases of diagenesis such as reworking leaching, and recrystallization took place.

## **CHAPTER 3**

### **DATA SET DESCRIPTION**

#### **3.1 Drilling Programs**

Several exploration programs were conducted to evaluate the phosphorite deposits of the Sirhan-Turayf Sub-basin after its first discovery in 1965. Exploration was started in 1977 by the private sector in the Thaniyat Turayf area, but was stopped shortly due to infrastructural problems. At the same time, a much larger regional assessment was undertaken by the Riofinex Co. on behalf of the DGMR as part of the Second Five Years Plan (1975-1980). The assessment included the preparation of a number of geologic reconnaissance maps for an area of about 100,000 km<sup>2</sup>, undertaking of a radiometric survey, and implementation of a large drilling and trenching programs (DGMR, 1994).

About 256 trenches at 1km intervals with an average depth of 2 meters were dug and a total of 681 drill-holes were drilled in the Sirhan - Turayf region. These operations led to the establishment of the data bank required for further geological, geochemical, mineralogical, and geostatistical studies. The drilling program included

regional stratigraphic, infill stratigraphic, follow-up for specific work areas, infill for specific areas and geostatistical drilling programs for the promising areas. The drilling program was undertaken by the Arabian Drilling Company (ADC), Rockfall, and Riofinex. Drill-holes were dug using Percussion, coring, mixed (percussion and coring), and reserve circulation methods (Riddler and others, 1986).

Regional stratigraphic holes were drilled first at 20 km centers. This was followed by drilling the infill and follow-up holes in specific areas at 10 km, 5 km, and 1 km centers. Later, a cross pattern drill-holes for the geostatistical studies were drilled in the Hazm Al-Jalamid phosphorite deposit at 141 meters spacing.

Out of 305 holes drilled in the Hazm Al-Jalamid area, data from only 170 holes were used in the present study. Based on the presence of high concentrations of  $P_2O_5$ , low stripping ratios, low impurities and the acceptable inter-holes spacing, a sub-set area covering 80 km<sup>2</sup> in the central part of the prospect was selected (Figure 3.1). The original drill-hole data record included easting and northing coordinates, top and bottom of each sample, grades in percent of the different chemical and mineralogical compositions, lithology log, method of drilling, and the pit size.

### **3.2 Chemical Composition of Phosphorite Samples**

Rock samples were collected every half meter along the drill-holes and analyzed in the USGS, BRGM, and Riofenix laboratories in Jeddah. Some samples, were also analyzed in the Robertson Research Laboratories in Britain and in Australia. The

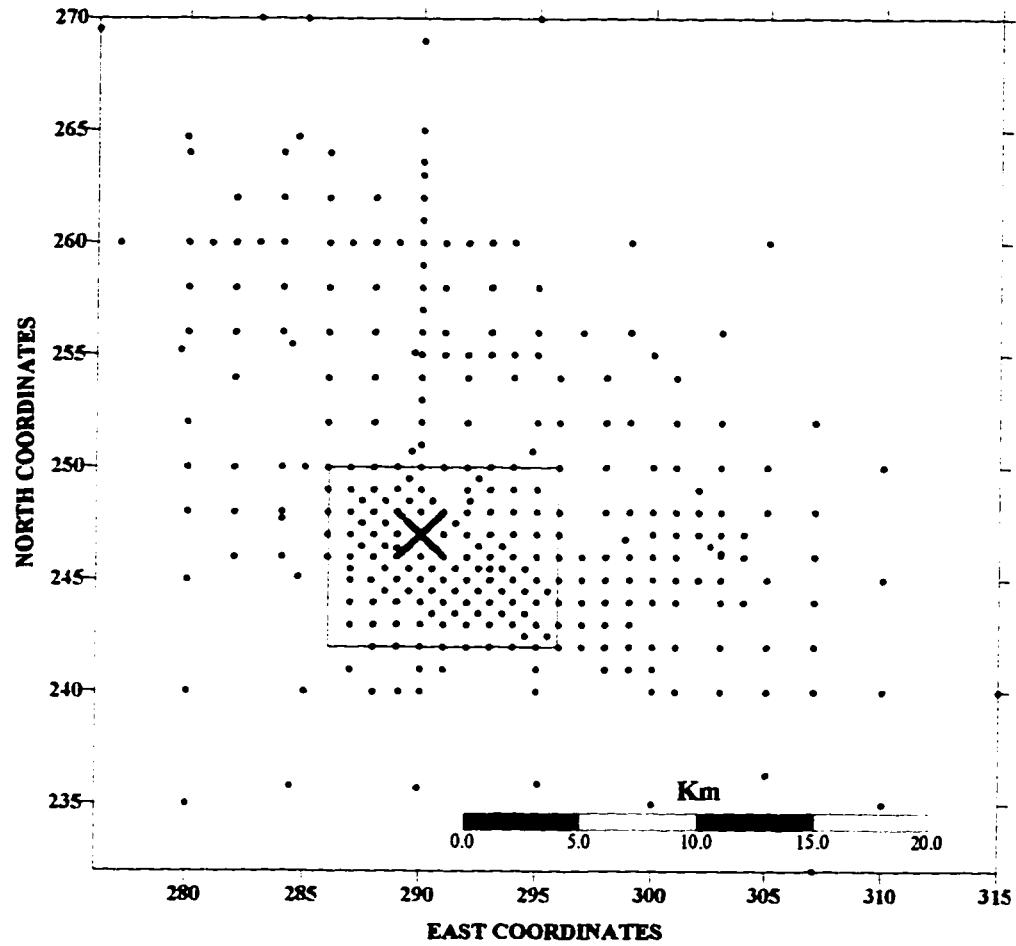


Figure 3.1 The selected study area for the present study in the Hazm Al-Jalamid region



samples were analyzed using the atomic absorption, volumetric, gravimetric, and induced cobalt plasma (ICP) methods. Rich phosphorite samples were analyzed twice, using different methods for precision and accuracy. This duplicated test, however, showed more or less the same results.

The chemical analyses included grade determination in percent of chemical compounds such as :  $P_2O_5$ ,  $SiO_2$ ,  $Al_2O_3$ ,  $Fe_2O_3$ ,  $CaO$ , and  $MgO$  , and minerals such as apatite, dolomite and calcite (Appendix A). Complete results of for the samples retrieved from 77 drill-holes, and only partial results for samples retrieved from the remaining 93 drill-holes, were made available for the present study.

### 3.3 Preparation of Data Sets

Some preparation on the raw data was necessary before using the GEOSTAT or the GEOLITH packages. Some data were eliminated in separate files for reference, while the required data were converted to ASCII format acceptable by both the packages. The data preparation is summarized as follows:

1. Based on both the lithology and the phosphorite content, the data were separated into three distinctive horizons. These horizons were given the code numbers of 111, 222 and 333 to differentiate between them during processing.
2. For each horizon, a master file containing X, Y, and Z-coordinates (the depth of the sample from the collar), values of  $P_2O_5$  in percentages and code

numbers was prepared. An example from this master file with some descriptions is given in Appendix B.

3. The master file for each horizon was processed to derive the complete data for both the statistical and the geostatistical analyses. This processed master file contains X, Y and Z coordinates drill-hole names, average  $P_2O_5$  values, thickness of each horizon, accumulation and the code numbers. Appendix C shows an example of this processed master file providing input for the GEOSTAT package.

## **CHAPTER 4**

### **SUB-SET AREA SELECTION AND DESCRIPTION OF DEPOSIT**

#### **4.1 Sub-set Area Selection**

This study focuses on 80 km<sup>2</sup> area out of a total of 1000 km<sup>2</sup> in the Hazm Al-Jalamid region. This selected area contains the most economic part of the phosphorite deposit as far as grade, thickness and stripping ratio are concerned. The selection of this area, which contains 170 drill-holes, was based on the following factors:

1. Phosphorite grade ( $P_2O_5$  %)
2. Stripping ratio (ratio of overburden to ore thickness)
3.  $Al_2O_3 + Fe_2O_3$ ,  $SiO_2$  and  $MgO$  contents and  $CaO / P_2O_5$  ratio, and
4. Drill-hole spacing

Lithologic logs for about 305 holes drilled in the Hazm Al-Jalamid area were reviewed in the light of the above mentioned factors. As a result of this review, the study area was selected. Each of these factors will be discussed in detail in the following sections:

#### 4.1.1 Phosphorite Grade ( $P_2O_5$ %) :

The economic limit of the percentage grade of  $P_2O_5$  (i. e. the cut-off grade) differs from one deposit to another, based on the amount of reserves, the associated impurities and the stripping ratio. Slansky (1986) and Notholt (1994) suggested 18%  $P_2O_5$ , while others accepted 10% or even 5 % to be the limit in case of large reserves with an acceptable stripping ratio. The 15%  $P_2O_5$  is generally the separating grade between one phosphorite horizon and the other in the Hazm Al-Jalamid area. Therefore, the cut-off grade of 15%  $P_2O_5$  is chosen to be the limit in the present study.

Ore enriching and beneficiating methods such as the dust-removal technique, sorting by grain size (either wet or dry), calcination at 700-900°C followed by washing (to reduce the proportion of  $CaCO_3$ ), flotation (to eliminate silica) and magnetic separation (to eliminate ferruginous particles) can upgrade the running ore to 30-38%  $P_2O_5$ . Moreover, the chlorine content can generally be reduced by washing in fresh water (Slansky, 1986).

Studies carried out on the phosphorite deposits of the Hazm Al-Jalamid area indicate that the  $P_2O_5$  content can be enriched to 32% by using simple upgrading techniques such as calcination followed by flotation (DGMR, 1994).

#### **4.1.2 Stripping Ratio:**

This is defined as the ratio of the thickness of overburden to the thickness of ore body. The acceptable stripping ratio in case of phosphorite deposits differs from one ore to another, depending on the average grade, the amount of reserves and the mine design. A ratio of 5 : 1 (i.e. 5 meters of overburden to 1 meter of phosphorite) is generally accepted worldwide (Notholt, 1994).

Unless locally disturbed the Hazm Al-Jalamid deposit is generally dipping towards the southwest (Figure 1.4). By computing the stripping ratios from the drill-holes in that direction, the limiting boundary can be defined. The average stripping ratio in the selected area is about 2.9 : 1. However, due to local structures, some higher ratios (within acceptable limits) were detected (Table 4.1).

#### **4.1.3 $\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ , $\text{SiO}_2$ and $\text{MgO}$ Contents and $\text{CaO} / \text{P}_2\text{O}_5$ Ratio:**

It is a commonly acceptable that the  $\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$  content of the phosphorite ore should be less than 5%,  $\text{MgO}$  content should be less than 1.5% and  $\text{SiO}_2$  content less than 10%. The ratio of  $\text{CaO}$  to  $\text{P}_2\text{O}_5$  should not exceed 1.55 : 1. These numbers, however, are not fixed as slight changes can be accommodated depending on several factors that include the amount of the reserves, the  $\text{P}_2\text{O}_5$  grade and the upgrading costs (Notholt, 1994). However, the increase in the ratio of such impurities in the ore can lead to great difficulties in its beneficiation and upgrading, and hence increase its cost.

Table 4.1 Stripping ratio based on some drill-holes in the study area

| DRILL-HOLE                                              | STRIPPING RATIO | DRILL-HOLE | STRIPPING RATIO |
|---------------------------------------------------------|-----------------|------------|-----------------|
| JAL269                                                  | 2.76 : 1        | JAL491     | 1.43 : 1        |
| JAL360                                                  | 2.14 : 1        | JAL493     | 2.73 : 1        |
| JAL361                                                  | 1.32 : 1        | JAL494     | 2.26 : 1        |
| JAL370                                                  | 2.02 : 1        | JAL504     | 3.50 : 1        |
| JAL446                                                  | 2.22 : 1        | JAL505     | 1.87 : 1        |
| JAL449                                                  | 3.53 : 1        | JAL550     | 2.02 : 1        |
| JAL452                                                  | 3.74 : 1        | JAL568     | 1.64 : 1        |
| JAL453                                                  | 4.25 : 1        | JAL570     | 1.77 : 1        |
| JAL454                                                  | 2.32 : 1        | JAL610     | 3.75 : 1        |
| JAL455                                                  | 2.53 : 1        | JAL612     | 2.50 : 1        |
| JAL465                                                  | 4.56 : 1        | JAL613     | 1.63 : 1        |
| JAL466                                                  | 4.06 : 1        | JAL614     | 2.28 : 1        |
| JAL467                                                  | 2.61 : 1        | JAL615     | 3.86 : 1        |
| JAL601                                                  | 2.59 : 1        | JAL616     | 2.83 : 1        |
| JAL603                                                  | 2.23 : 1        | JAL617     | 1.01 : 1        |
| JAL604                                                  | 1.56 : 1        | JAL619     | 2.48 : 1        |
| JAL605                                                  | 3.03 : 1        | JAL575     | 1.29 : 1        |
| JAL606                                                  | 2.22 : 1        | JAL578     | 1.37 : 1        |
| JAL607                                                  | 1.59 : 1        | JAL579     | 2.18 : 1        |
| JAL608                                                  | 2.75 : 1        | JAL581     | 2.06 : 1        |
| JAL609                                                  | 2.02 : 1        | JAL582     | 2.24 : 1        |
| JAL470                                                  | 2.76 : 1        | JAL584     | 2.97 : 1        |
| JAL475                                                  | 2.89 : 1        | JAL624     | 1.78 : 1        |
| JAL479                                                  | 2.68 : 1        | JAL656     | 4.68 : 1        |
| JAL620                                                  | 2.13 : 1        | JAL668     | 3.02 : 1        |
| JAL621                                                  | 3.24 : 1        | JAL671     | 4.53 : 1        |
| JAL622                                                  | 5.40 : 1        | JAL674     | 4.54 : 1        |
| JAL625                                                  | 3.65 : 1        | JAL754     | 4.96 : 1        |
| JAL659                                                  | 3.07 : 1        |            |                 |
| JAL669                                                  | 3.55 : 1        |            |                 |
| JAL672                                                  | 3.57 : 1        |            |                 |
| JAL712                                                  | 3.71 : 1        |            |                 |
| JAL480                                                  | 2.75 : 1        |            |                 |
| JAL481                                                  | 3.50 : 1        |            |                 |
| JAL490                                                  | 4.58 : 1        |            |                 |
| JAL623                                                  | 5.68 : 1        |            |                 |
| JAL655                                                  | 3.76 : 1        |            |                 |
| JAL667                                                  | 3.25 : 1        |            |                 |
| JAL670                                                  | 3.55 : 1        |            |                 |
| JAL673                                                  | 4.39 : 1        |            |                 |
| The average stripping ratio of the study area = 2.9 : 1 |                 |            |                 |

In the Hazm Al-Jalamid deposit, relatively high percentage of impurities has been recorded, but they are generally acceptable due to the huge reserves and the high  $P_2O_5$  content. The chemical composition of the phosphorite beds in Horizons 1 and 3 are computed and listed in Tables 4.2 and 4.3 respectively. The average values for some chemical components in the two horizons are also listed in Table 4.4.

#### **4.1.4 Drill-hole Spacing**

For geostatistical studies, the spacing between drill- holes should be planned in such a way that the resulting data are adequately closely spaced to reveal the spatial behavior of the variables in the horizontal directions.

The Hazm Al-Jalamid area was subjected to several phases of drilling programs as pointed out earlier. Drilling with 5 km, 2 km, and 1 km intervals was carried out for the general appraisal of the deposit and 704 and 140 meters intervals for the geostatistical studies (Riddler and others, 1986).

The drill-hole pattern in the selected area was designed such that the spacing between the holes is 1 km along N-S and E-W directions and 704 m along NW-SE and NE-SW directions. In addition, infill drilling with 140 m spacing was conducted in the central part of the area along NE-SW and NW-SE directions. In the surrounding area, spacing between the holes is much wider as shown in Figure 3.1.

Table 4.2 Various chemical components of the phosphorite in Horizon I

| Drill-hole | Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub> % | MgO % | SiO <sub>2</sub> % | CaO : P <sub>2</sub> O <sub>5</sub> |
|------------|-------------------------------------------------------------------|-------|--------------------|-------------------------------------|
| JAL356     | 0.34                                                              | 7.85  | 1.28               | 2.26 : 1                            |
| JAL370     | 0.85                                                              | 7.87  | 1.95               | 2.36 : 1                            |
| JAL371     | 0.41                                                              | 7.80  | 1.20               | 2.24 : 1                            |
| JAL446     | 0.48                                                              | 9.22  | 3.68               | 3.13 : 1                            |
| JAL452     | 0.53                                                              | 0.81  | 2.99               | 2.42 : 1                            |
| JAL453     | 0.32                                                              | 2.40  | 2.74               | 2.17 : 1                            |
| JAL454     | 0.29                                                              | 2.81  | 0.82               | 2.67 : 1                            |
| JAL465     | 0.24                                                              | 8.12  | 3.10               | 2.48 : 1                            |
| JAL466     | 0.70                                                              | 8.75  | 0.65               | 2.37 : 1                            |
| JAL470     | 0.34                                                              | 4.83  | 3.54               | 2.47 : 1                            |
| JAL479     | 0.65                                                              | 3.52  | 3.90               | 2.26 : 1                            |
| JAL480     | 0.42                                                              | 0.49  | 3.41               | 2.58 : 1                            |
| JAL481     | 0.45                                                              | 8.18  | 1.97               | 2.78 : 1                            |
| JAL490     | 0.45                                                              | 4.66  | 6.30               | 2.55 : 1                            |
| JAL491     | 0.45                                                              | 6.14  | 1.52               | 2.35 : 1                            |
| JAL504     | 0.26                                                              | 8.18  | 2.40               | 2.63 : 1                            |
| JAL505     | 0.39                                                              | 5.83  | 2.58               | 2.12 : 1                            |
| JAL550     | 0.46                                                              | 6.45  | 3.33               | 2.26 : 1                            |
| JAL568     | 0.43                                                              | 0.32  | 1.62               | 2.64 : 1                            |
| JAL570     | 0.25                                                              | 7.03  | 2.59               | 2.36 : 1                            |
| JAL578     | 0.49                                                              | 13.55 | 5.57               | 2.22 : 1                            |
| JAL579     | 0.31                                                              | 0.89  | 2.25               | 2.51 : 1                            |
| JAL481     | 0.33                                                              | 2.44  | 2.51               | 2.18 : 1                            |
| JAL582     | 0.39                                                              | 4.02  | 2.06               | 2.19 : 1                            |
| JAL584     | 0.31                                                              | 0.27  | 1.62               | 2.57 : 1                            |
| JAL602     | 0.37                                                              | 4.56  | 1.17               | 2.37 : 1                            |
| JAL608     | 0.51                                                              | 0.39  | 2.07               | 2.98 : 1                            |
| JAL712     | 0.64                                                              | 0.24  | 3.07               | 2.89 : 1                            |
| JAL612     | NR                                                                | 7.59  | NR                 | 2.68 : 1                            |
| JAL613     | NR                                                                | 4.03  | NR                 | 2.68 : 1                            |
| JAL615     | NR                                                                | 8.90  | NR                 | 2.71 : 1                            |
| JAL617     | NR                                                                | 3.43  | NR                 | 2.65 : 1                            |
| JAL620     | NR                                                                | 6.33  | NR                 | 2.44 : 1                            |
| JAL621     | NR                                                                | 1.76  | NR                 | 3.31 : 1                            |
| JAL623     | NR                                                                | 0.19  | NR                 | 2.34 : 1                            |
| JAL624     | NR                                                                | 6.67  | NR                 | 2.76 : 1                            |
| JAL655     | NR                                                                | 8.96  | NR                 | 2.78 : 1                            |
| JAL656     | NR                                                                | 7.00  | NR                 | 2.58 : 1                            |
| JAL659     | NR                                                                | 0.43  | NR                 | 3.03 : 1                            |
| JAL667     | NR                                                                | 4.45  | NR                 | 2.06 : 1                            |
| JAL668     | 0.29                                                              | 4.09  | 2.66               | 2.35 : 1                            |
| JAL669     | NR                                                                | 2.72  | NR                 | 2.16 : 1                            |
| JAL670     | NR                                                                | 3.49  | NR                 | 2.42 : 1                            |
| JAL671     | NR                                                                | 6.26  | NR                 | 2.12 : 1                            |
| JAL673     | NR                                                                | 5.93  | NR                 | 2.53 : 1                            |



Table 4.3 Various chemical components of the phosphorite ore in Horizon 3

| Drill-hole | Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub> % | MgO % | SiO <sub>2</sub> % | CaO : P <sub>2</sub> O <sub>5</sub> |
|------------|-------------------------------------------------------------------|-------|--------------------|-------------------------------------|
| JAL269     | 0.49                                                              | 7.45  | 0.60               | 2.19 : 1                            |
| JAL359     | 0.27                                                              | 10.53 | 0.65               | 2.45 : 1                            |
| JAL370     | 0.45                                                              | 9.78  | 0.70               | 2.43 : 1                            |
| JAL371     | 0.48                                                              | 8.97  | 0.94               | 2.25 : 1                            |
| JAL446     | 0.37                                                              | 9.76  | 0.80               | 2.38 : 1                            |
| JAL449     | 0.12                                                              | 7.05  | 0.48               | 2.14 : 1                            |
| JAL452     | 0.51                                                              | 9.12  | 2.18               | 2.37 : 1                            |
| JAL453     | 0.18                                                              | 8.25  | 0.72               | 2.27 : 1                            |
| JAL454     | 0.40                                                              | 9.81  | 0.80               | 2.24 : 1                            |
| JAL455     | 0.51                                                              | 6.67  | 6.75               | 3.05 : 1                            |
| JAL465     | 0.40                                                              | 10.77 | 0.65               | 2.03 : 1                            |
| JAL466     | 0.71                                                              | 10.19 | 0.43               | 2.46 : 1                            |
| JAL467     | 0.41                                                              | 6.95  | 2.47               | NR                                  |
| JAL470     | 0.38                                                              | 10.86 | 0.54               | 2.66 : 1                            |
| JAL475     | 0.36                                                              | 6.95  | 1.32               | 2.27 : 1                            |
| JAL480     | 0.40                                                              | 7.80  | 1.07               | 2.49 : 1                            |
| JAL494     | 0.42                                                              | 6.58  | 1.38               | 2.47 : 1                            |
| JAL495     | NR                                                                | 9.37  | NR                 | 2.14 : 1                            |
| JAL503     | 0.47                                                              | 9.68  | 0.68               | 2.29 : 1                            |
| JAL505     | 0.48                                                              | 11.35 | 0.60               | 2.34 : 1                            |
| JAL550     | 0.29                                                              | 8.58  | 0.96               | 2.19 : 1                            |
| JAL568     | 0.37                                                              | 1.87  | 0.25               | 2.94 : 1                            |
| JAL575     | 0.44                                                              | 8.70  | 2.83               | 2.55 : 1                            |
| JAL578     | 0.31                                                              | 7.51  | 2.22               | 2.34 : 1                            |
| JAL579     | 0.38                                                              | 7.73  | 0.75               | 2.62 : 1                            |
| JAL581     | 0.38                                                              | 9.60  | 0.70               | 2.19 : 1                            |
| JAL582     | 0.33                                                              | 10.59 | 1.25               | 2.38 : 1                            |
| JAL584     | 0.32                                                              | 9.00  | 0.58               | 2.22 : 1                            |
| JAL605     | NR                                                                | 10.60 | NR                 | 2.67 : 1                            |
| JAL606     | NR                                                                | 8.63  | NR                 | 2.56 : 1                            |
| JAL607     | NR                                                                | 8.00  | NR                 | 2.29 : 1                            |
| JAL608     | NR                                                                | 8.77  | NR                 | 2.46 : 1                            |
| JAL610     | NR                                                                | 7.04  | NR                 | 2.58 : 1                            |
| JAL611     | NR                                                                | 7.08  | NR                 | 2.57 : 1                            |
| JAL612     | NR                                                                | 7.80  | NR                 | 2.45 : 1                            |
| JAL614     | NR                                                                | 5.98  | NR                 | 2.57 : 1                            |
| JAL616     | NR                                                                | 6.33  | NR                 | 2.36 : 1                            |
| JAL619     | NR                                                                | 6.75  | NR                 | 2.51 : 1                            |
| JAL620     | NR                                                                | 10.18 | NR                 | 2.69 : 1                            |
| JAL621     | NR                                                                | 9.13  | NR                 | 2.61 : 1                            |
| JAL622     | NR                                                                | 8.93  | NR                 | 2.82 : 1                            |
| JAL623     | NR                                                                | 6.85  | NR                 | 2.26 : 1                            |
| JAL624     | NR                                                                | 8.92  | NR                 | 2.19 : 1                            |
| JAL625     | NR                                                                | 10.99 | NR                 | 2.40 : 1                            |
| JAL655     | NR                                                                | 8.19  | NR                 | 2.53 : 1                            |
| JAL656     | NR                                                                | 8.02  | NR                 | 2.40 : 1                            |
| JAL668     | 0.30                                                              | 10.43 | 1.13               | 2.27 : 1                            |
| JAL754     | NR                                                                | 9.86  | NR                 | 2.47 : 1                            |

Table 4. 4      Average percentages of the main chemical components of the phosphorite ore in the study area

| Horizons  | Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub> (%) | MgO (%) | SiO <sub>2</sub> (%) | CaO : P <sub>2</sub> O <sub>5</sub> |
|-----------|---------------------------------------------------------------------|---------|----------------------|-------------------------------------|
| Horizon 1 | 0.43                                                                | 4.89    | 2.57                 | 2.50 : 1                            |
| Horizon 3 | 0.38                                                                | 8.52    | 1.23                 | 2.42 : 1                            |

## 4.2 Description of Deposit

In this section, isotenor and isopach maps, as well as 3-D surface diagrams and cross-sections for the phosphorite deposit will be presented and discussed. These maps, which give a clear idea about the behavior of the deposit, are helpful in the subsequent geostatistical analysis.

### 4.2.1 Isotenor Maps

These are contour maps with the contour lines connecting equal values of the ore. In our case, isotenor maps can give a general idea about the distribution of the  $P_2O_5$  % within the deposit. As mentioned earlier, the deposit consists of three horizons; namely Horizon 1, Horizon 2 and Horizon 3. The Horizon 1 and Horizon 3 include good quality phosphorite, whereas the Horizon 2 represents low grade intermediate zone.

The isotenor map for Horizon 1 (Figure 4.1) indicates that higher values of  $P_2O_5$  are concentrated in the central basin elongated NW-SE direction. The highest peak is observed in the southwestern corner. The  $P_2O_5$  grades for Horizon 2 appear to be more randomly distributed with higher values in the central area (Figure 4.2). The isotenor map for Horizon 3 shows circular to semicircular contours within the NW-SE

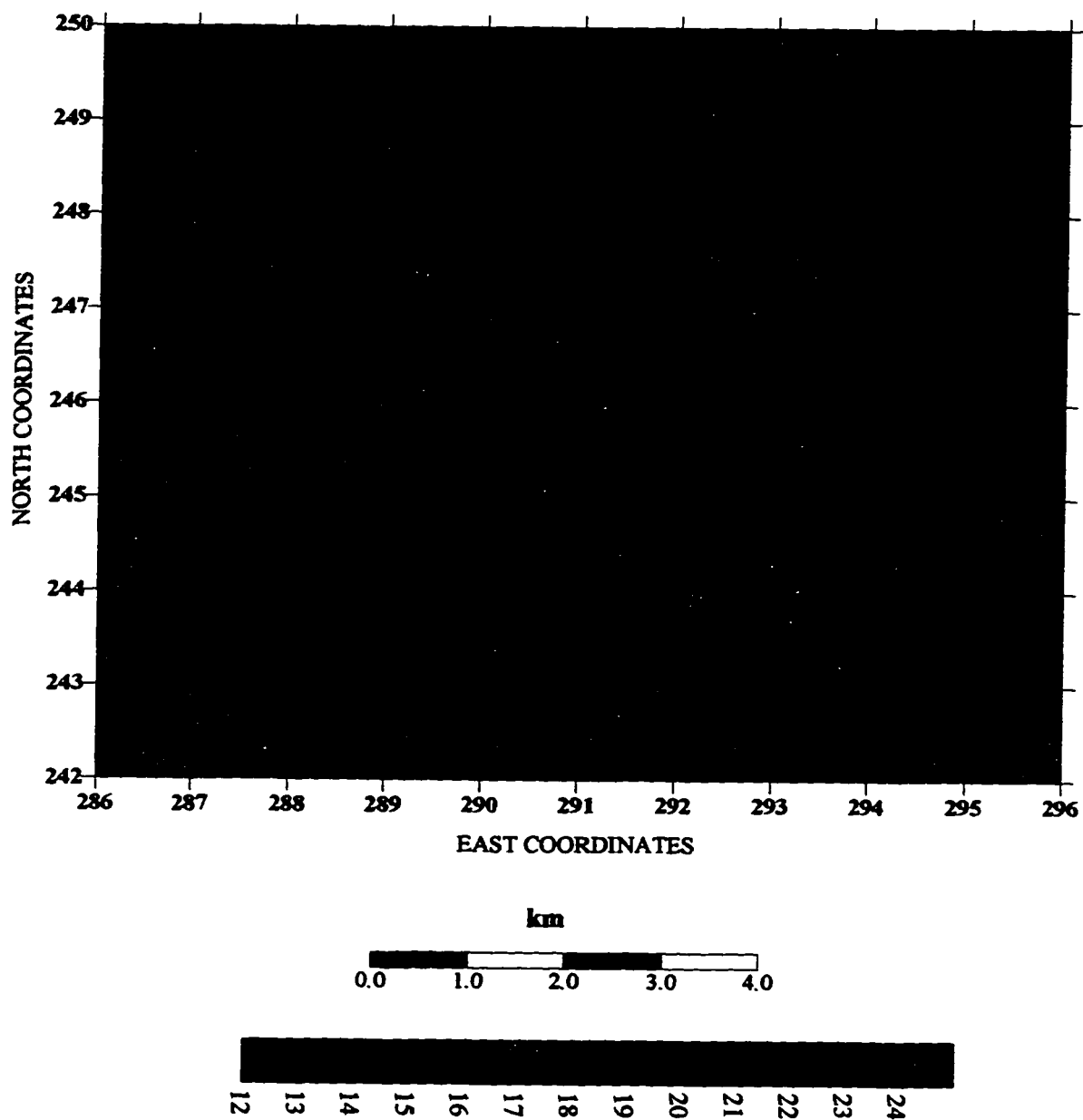


Figure 4.1 Isotenor map for P<sub>2</sub>O<sub>5</sub> % within Horizon 1 in the selected area

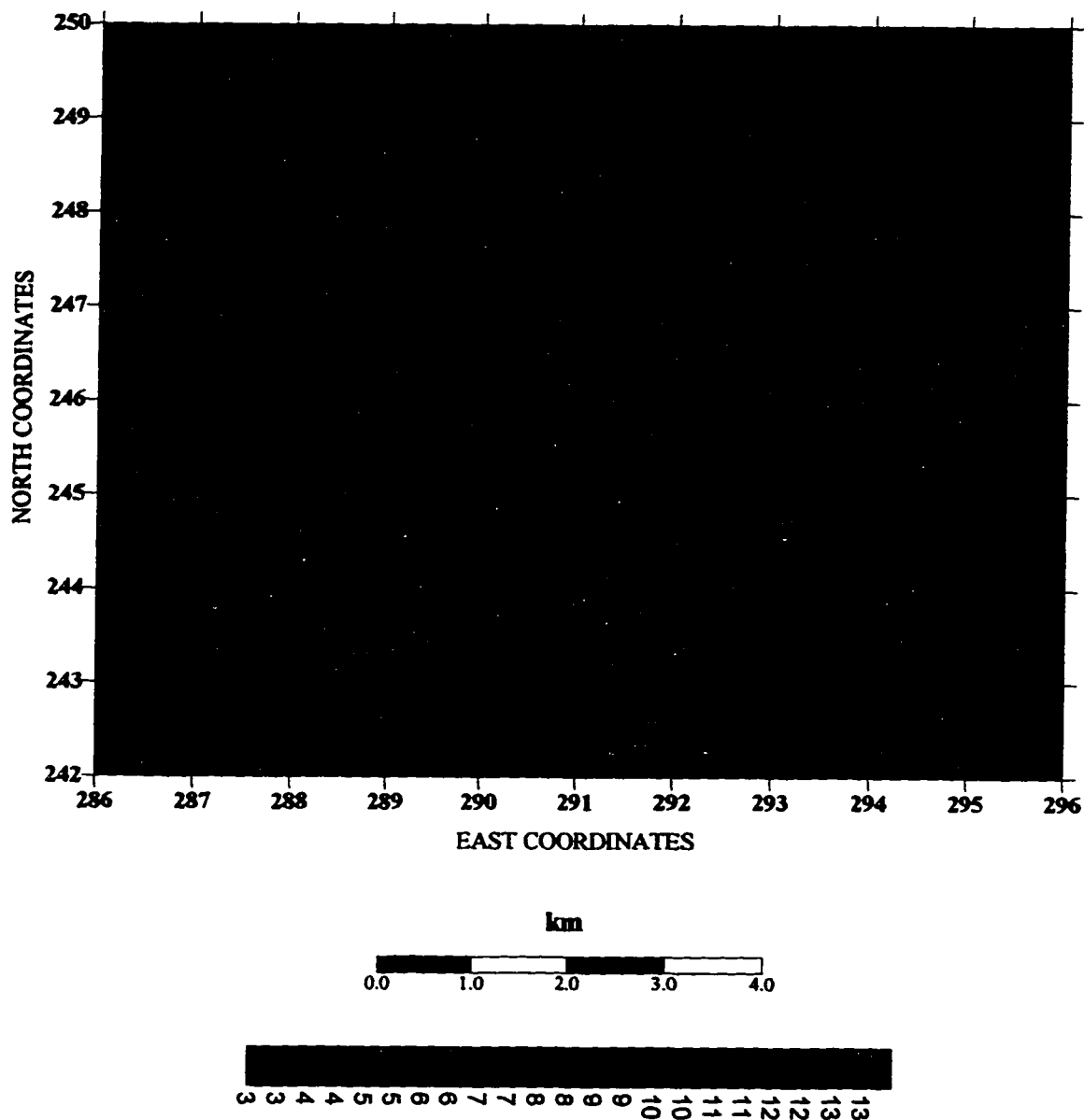


Figure 4.2 Isotenor map for P<sub>2</sub>O<sub>5</sub> % within Horizon 2 in the selected area

trending basin (Figure 4.3). Circular contours which reflect the presence of lenticular structures within the deposit are also common in Horizons 2.

#### **4.2.2 Isopach Maps**

These are contour maps with the contour lines connecting equal thicknesses. It gives a valuable information about variation in the thickness of the orebody. Comparison of the isopach map with the respective isotenor map provides valuable information about the relationship between the thickness and the grade.

Isopach maps for the three phosphorite horizons are illustrated in Figures 4.4 to 4.6. The concentric to semi-concentric shapes are clearly evident in these maps, confirming the lenticular nature of the deposit.

Comparing both the isotenor and the isopach maps for each horizon, the relationship between the thickness and the grade becomes obvious. Generally, thicker areas have higher percentages of  $P_2O_5$  as the process of chemical replacement leading to high concentrations of  $P_2O_5$  requires thick sediments together with their biochemical

#### **4.2.3 The 3-D Surface Diagrams**

These diagrams, which are illustrated in Figures 4.7 to 4.9, show the distribution of  $P_2O_5$  % in each of the three horizons in a three-dimensional view. The relief of the surface indicates the concentration of  $P_2O_5$ . Such diagrams show clearly that the concentration of  $P_2O_5$  increases in the northwestern part of the area. Various

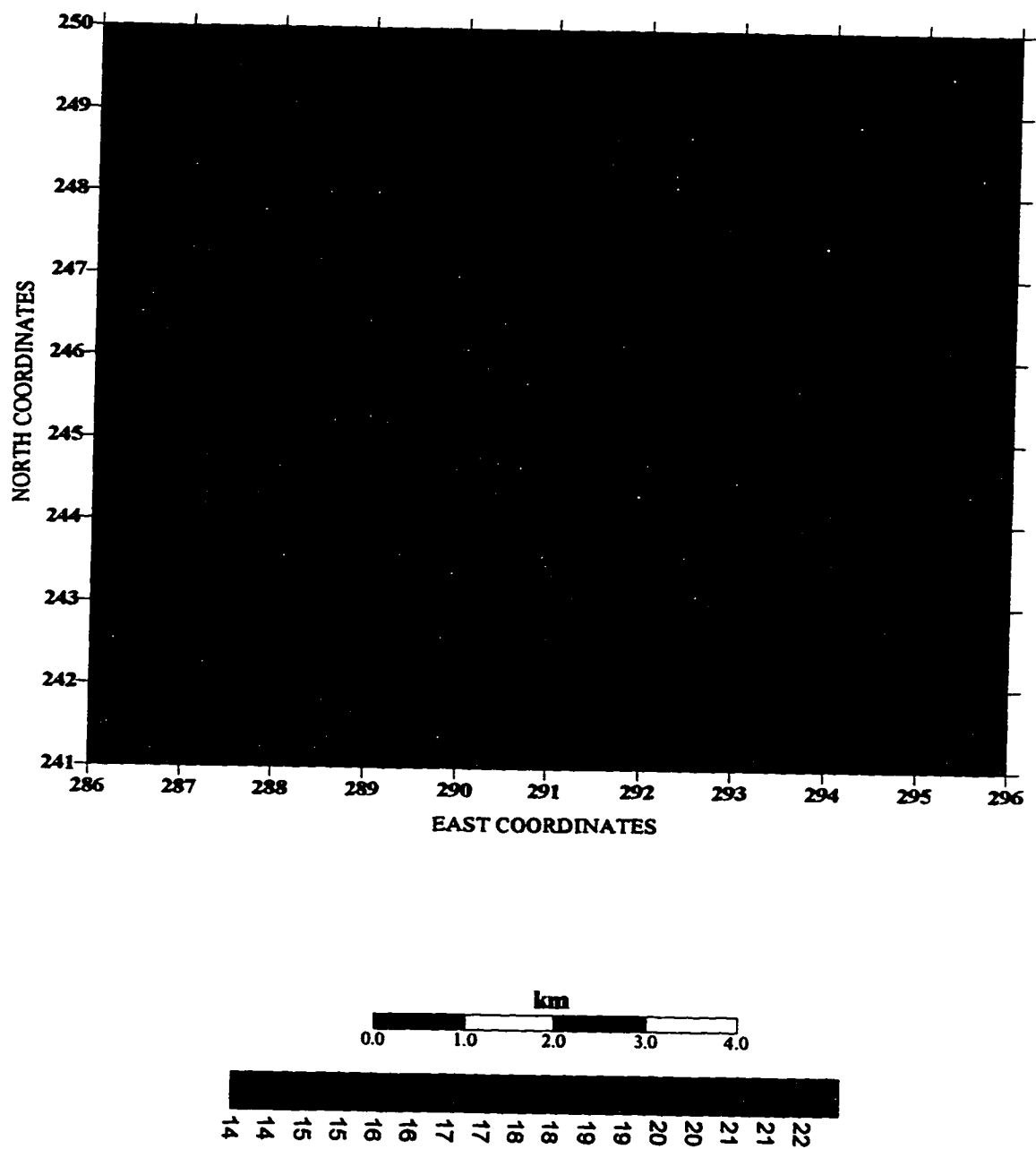


Figure 4.3 Isotenor map of  $P_2O_5$  % within Horizon 3 in the selected area

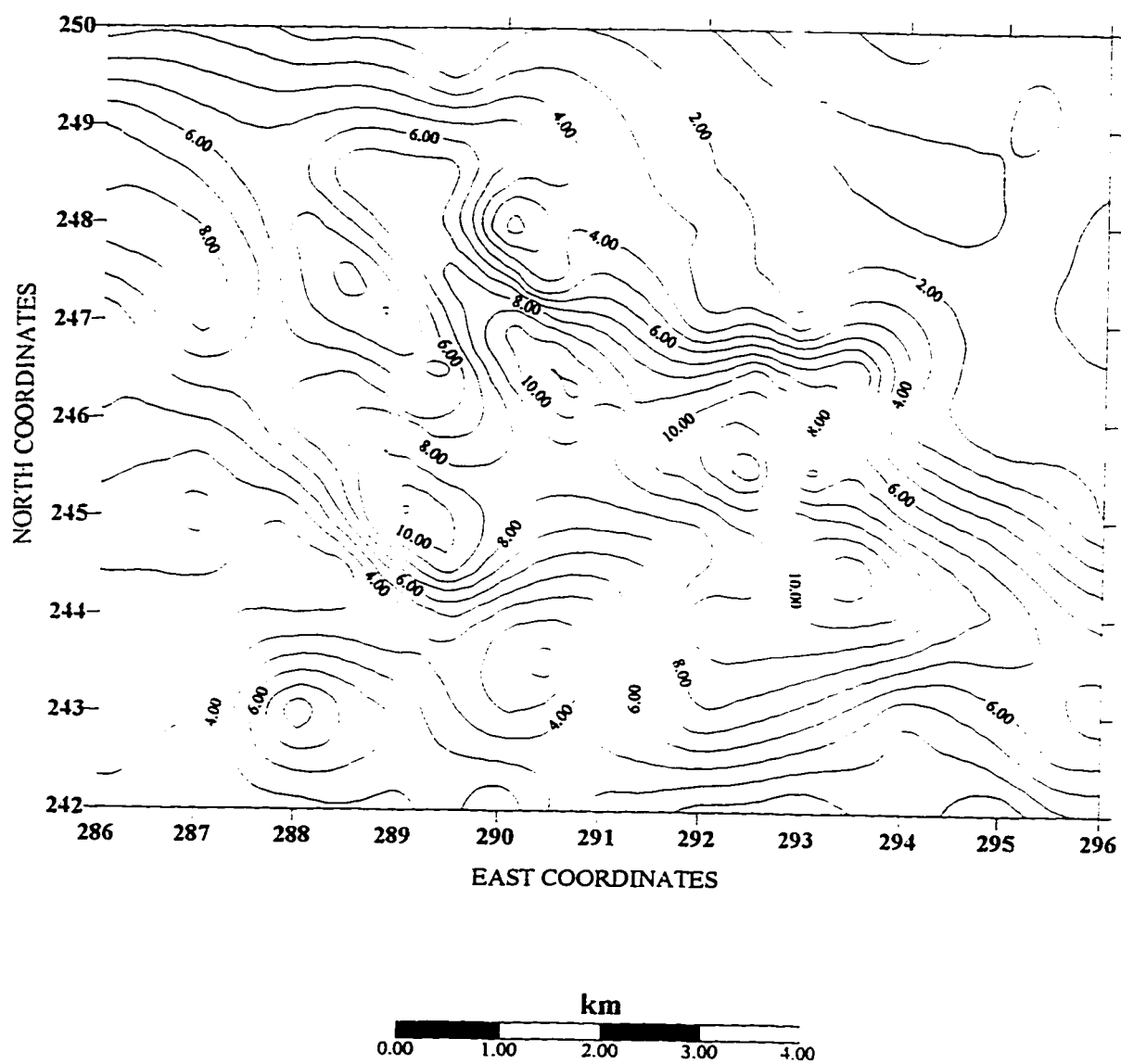


Figure 4.4 Isopach map of the phosphorite for Horizon 1



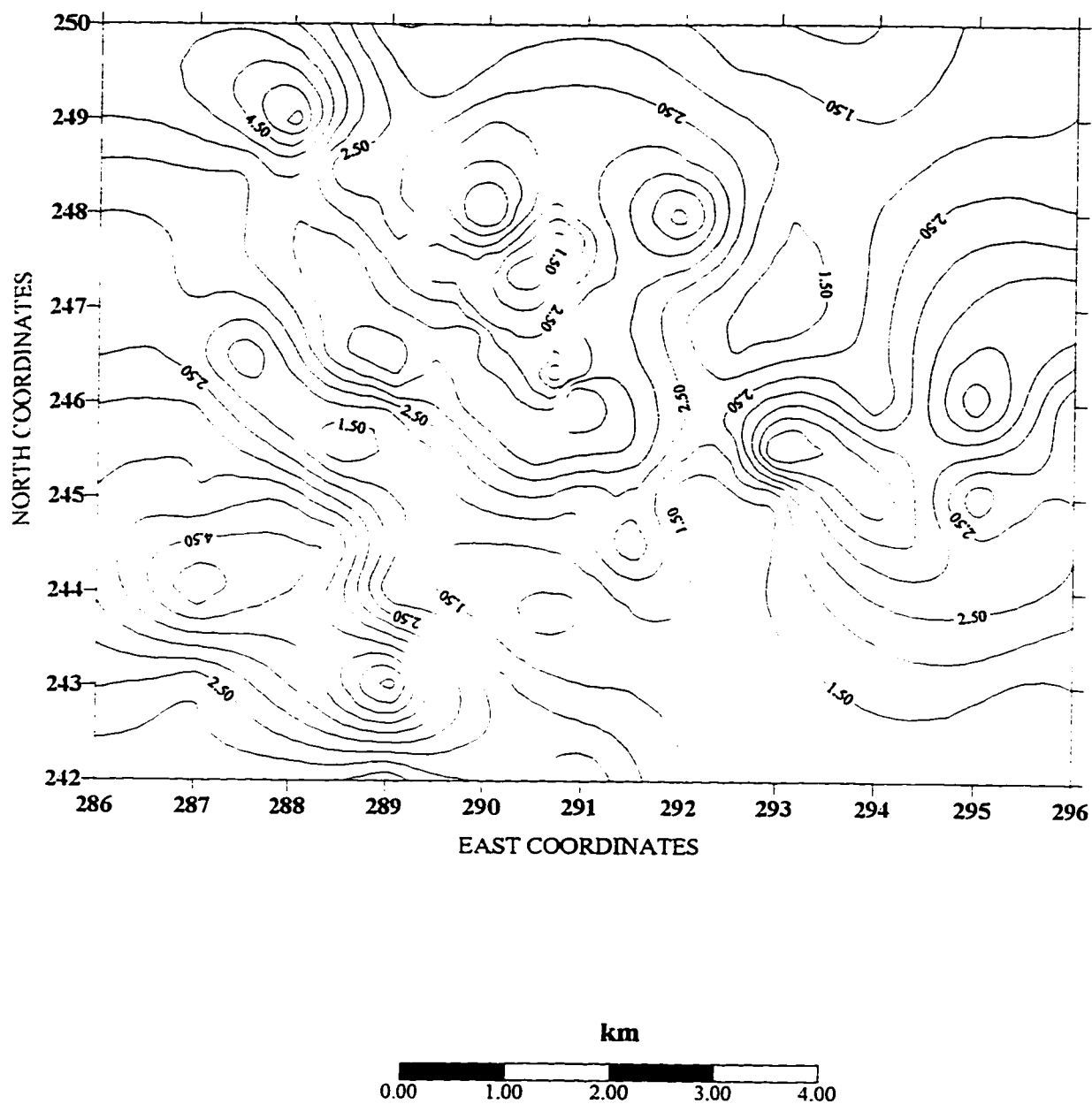


Figure 4.5 Isopach map of phosphorite for Horizon 2

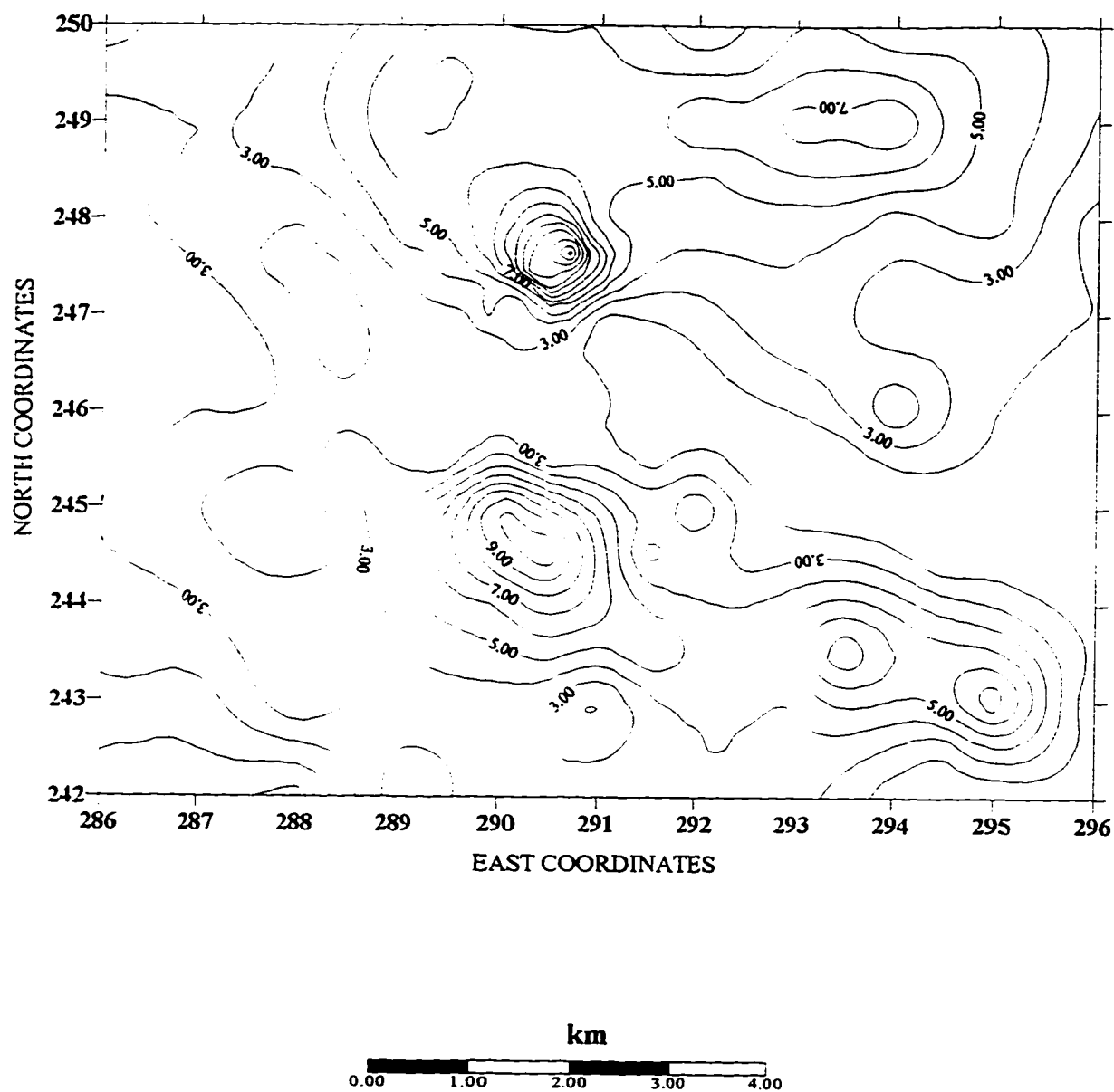


Figure 4.6 Isopach map of the phosphorite for Horizon 3

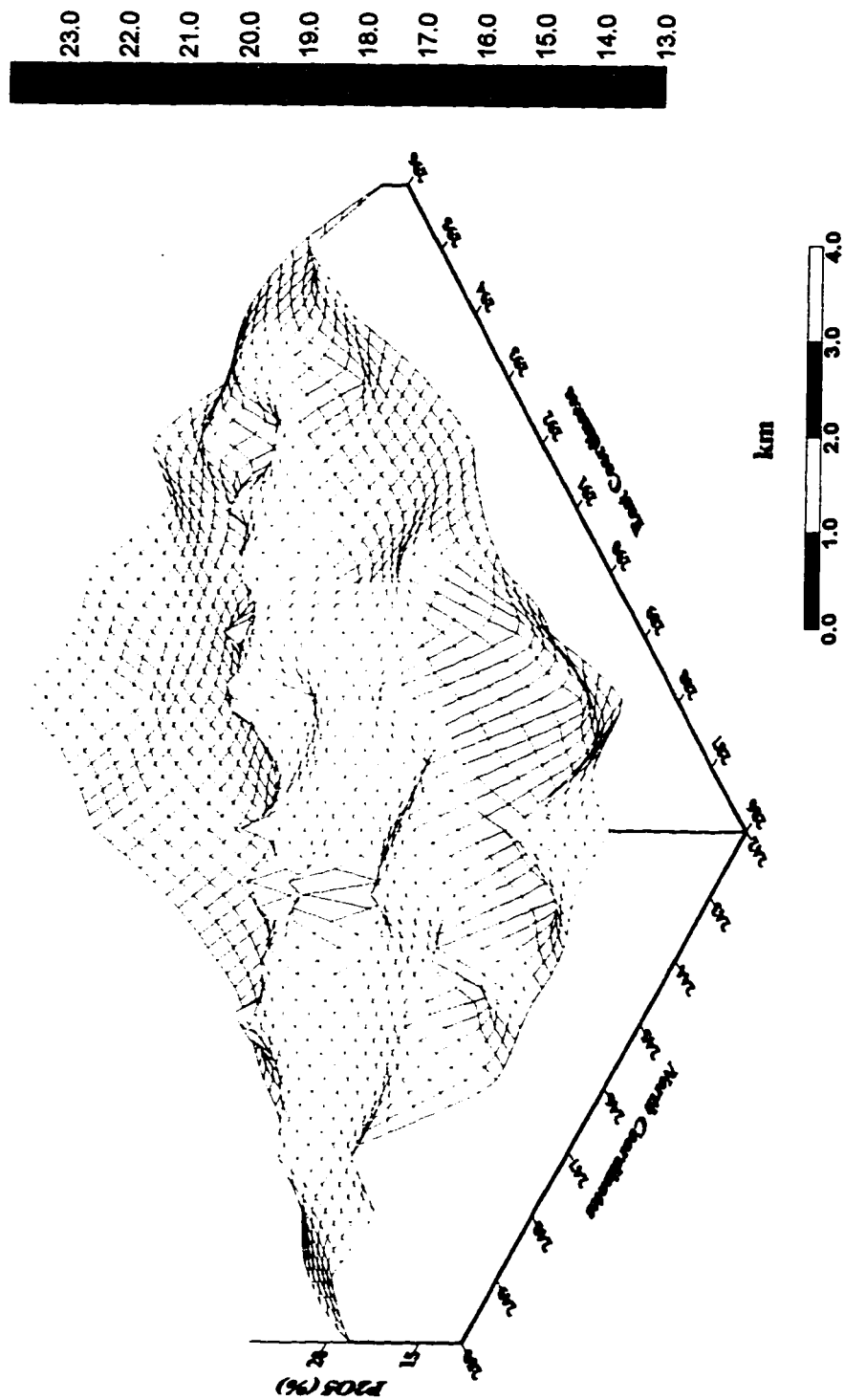


Figure 4.7 3D surface diagram illustrating the distribution of P<sub>2</sub>O<sub>5</sub> % within Horizon 1 in the selected area

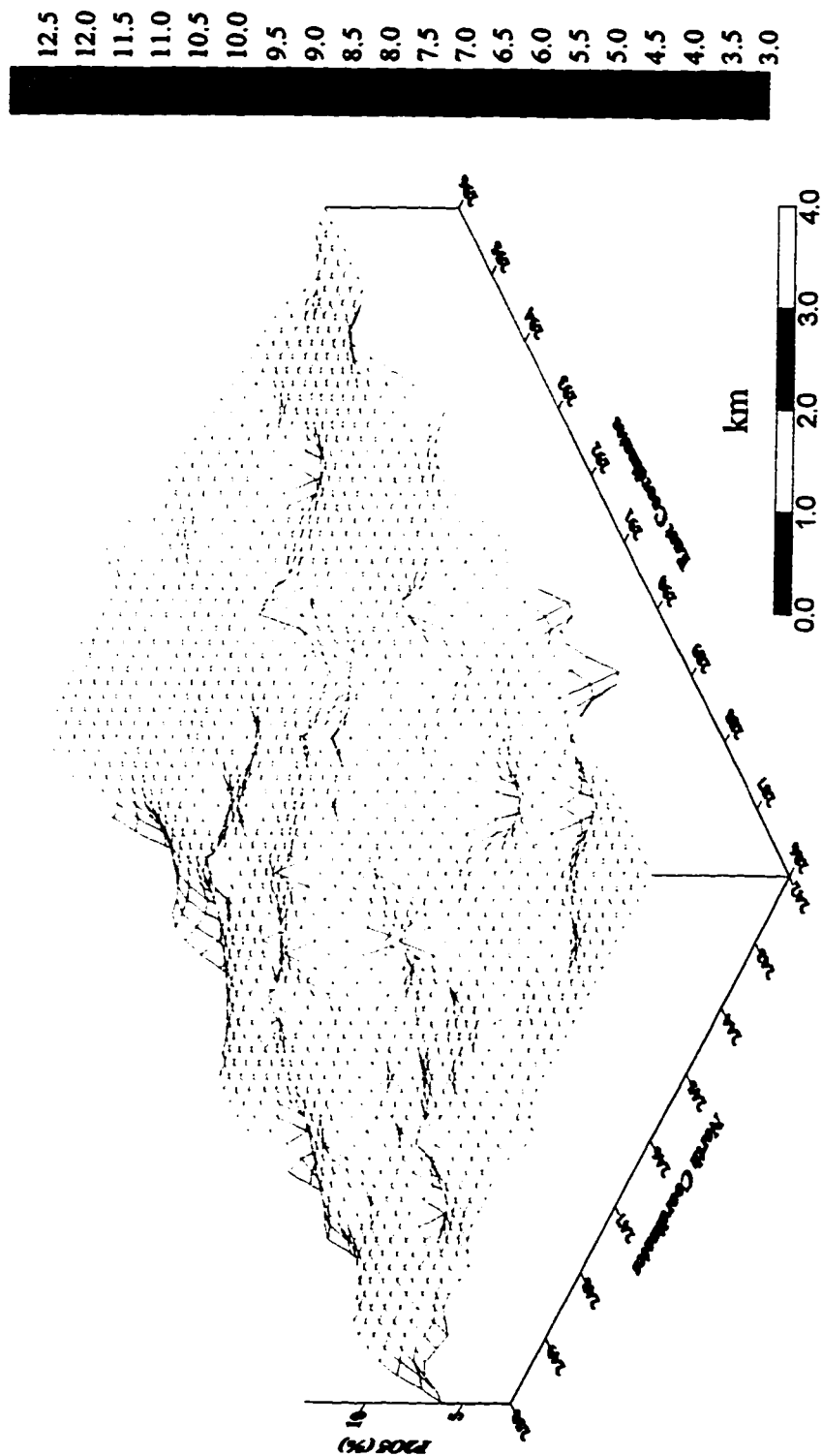


Figure 4.8 3D surface diagram illustrating the distribution of P2O5 % within Horizon 2 in the selected area

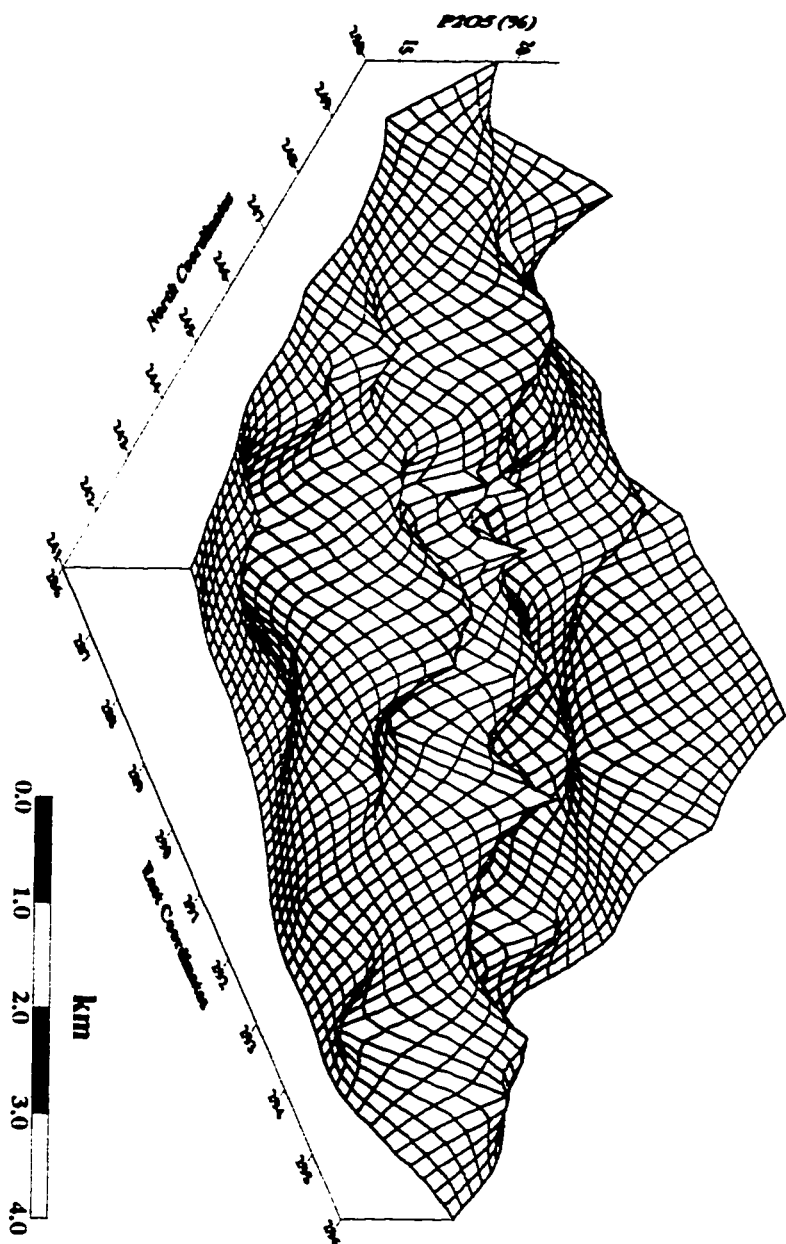


Figure 4.9 3D surface diagram illustrating the distribution of P<sub>2</sub>O<sub>5</sub> % within Horizon 3 in the selected area

21  
21  
20  
19  
18  
17  
16  
15  
14

peaks reflect the shapes of the lenses. Horizon 1 generally occupies the synclinal structure, whereas Horizon 3 consists of a series of lenses with varying diameters and thicknesses (with an average diameter of 2.4 km, and a maximum thickness of 9 meters).

#### **4.2.4 Geological Cross-sections**

To get a clear idea about the nature and shape of the phosphorite deposit, cross-sections were drawn in both the direction of dip (NE-SW) and the direction of strike (NW-SE). These are illustrated in Figure 4.10 and 4.11 respectively. The cross-sections show the configuration of the phosphorite horizons.

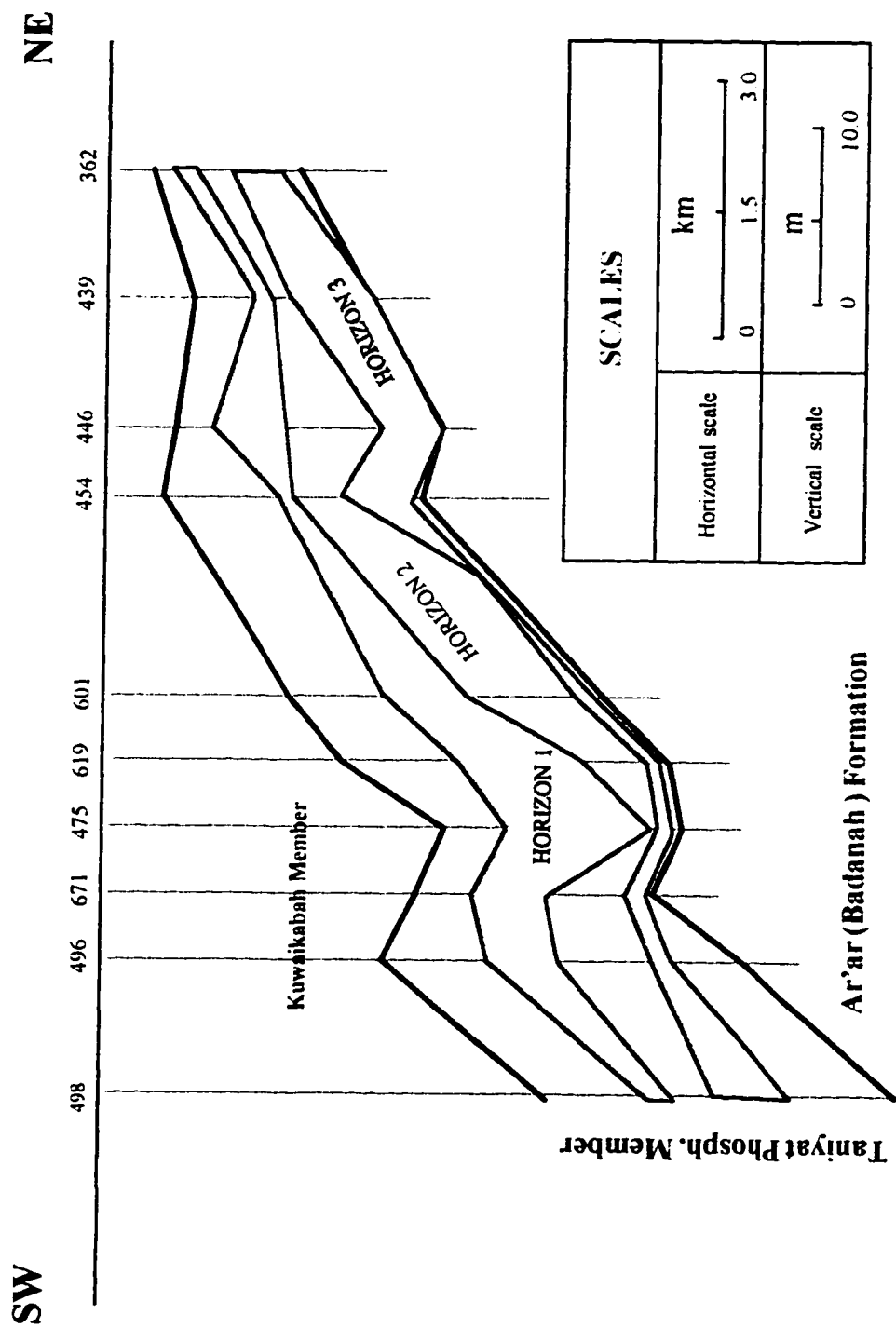


Figure 4.10 NE-SW cross section in the study area parallel to the dip direction showing the two phosphorite horizons

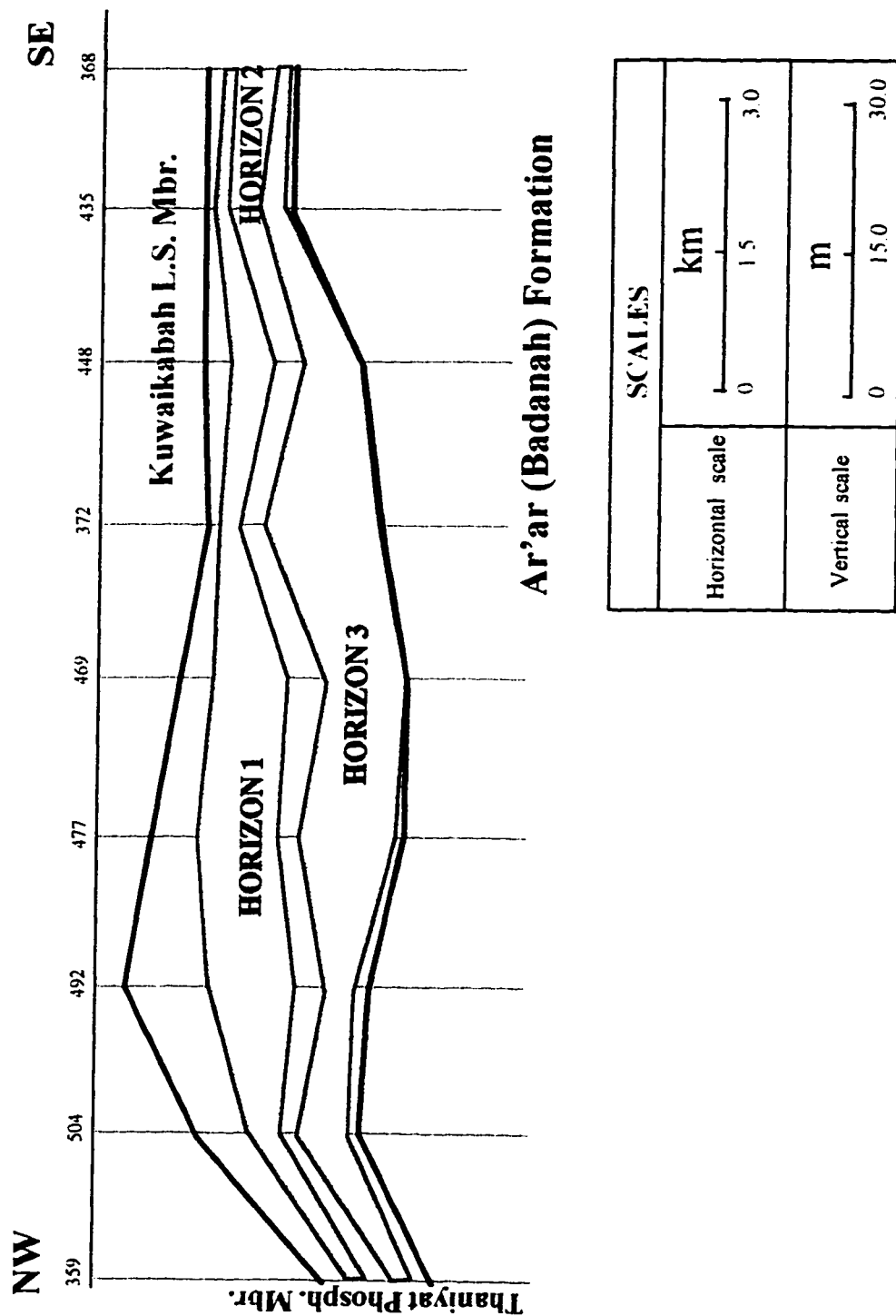


Figure 4.11 NW-SE cross section in the study area along the strike direction showing the two phosphorite horizons



## **CHAPTER 5**

### **STATISTICAL ANALYSIS**

#### **5.1 Introduction**

Statistical parameters such as the mean, median, mode, variance, standard deviation, coefficient of variation, skewness, kurtosis, minimum and maximum can provide valuable information about the data. It is also common to construct histograms and cumulative frequency curves to provide a visual summary of data and to indicate the type of distribution of the variables.

For the Hazm Al-Jalamid phosphorite deposit, an elementary statistical analysis has been conducted, together with construction of histograms and cumulative frequency curves. The results of such analysis are presented and discussed in the following sections:

#### **6.2 Statistical Parameters**

In this study, the three groups of statistical parameters have been calculated. Parameters of the first group are mean, median, mode, minimum and maximum which give indication about the location of distribution. The second group includes variance,

and standard deviation are used to describe the variability. The third group represented by the skewness and kurtosis indicate the shape of distribution.

The statistical analyses have been carried out for 3451 representative samples after a process of filtration. The filtering process were conducted to exclude the samples belonging to the overlying Kuwaykabah Carbonate Member and the underlying Ar'ar Formation. The second step was to separate the samples which belong to the Thaniyat Turayf Phosphorite Member into its three lithologically distinctive horizons. Statistical analysis for each horizon was carried out separately. Table 5.1 shows the statistical parameters of  $P_2O_5$  for the three horizons. Appendix D shows statistical parameters of  $P_2O_5$  for individual drill-holes intersecting each horizon. Statistical parameters were also calculated for both the thickness and the accumulation of each of the horizons individually and listed in Tables 5.2 and 5.3.

The coefficients of variation for the three horizons are less than 0.5, indicating the homogeneity of the  $P_2O_5$  distribution within the deposit. The same coefficient values for both the thickness and the accumulation are relatively high due to a considerable variation in the thickness of the deposit (Sahin, 1993).

### **5.3 Histograms and Frequency Distributions**

Histogram is a valuable tool in determining the type of distribution and in detecting abnormal high or low sample values. Histograms were constructed for  $P_2O_5$  %, thickness and accumulation representing the three horizons and are illustrated in

Table 5.1 Statistical parameters for  $P_2O_5$  % within the three horizons

| HORIZON | NO.HOLES | NO.SAMPLES | MEAN  | MEDIAN | MODE  | VARIANCE | STD.DEV. | C.V. | SKENNESS | KURTOSIS | MINIMUM | MAXIMUM |
|---------|----------|------------|-------|--------|-------|----------|----------|------|----------|----------|---------|---------|
| 1       | 141      | 1670       | 20.03 | 20.32  | 24.22 | 21.85    | 4.67     | 0.23 | -0.27    | 2.51     | 12.63   | 25.42   |
| 2       | 124      | 657        | 9.73  | 10.10  | 12.48 | 8.94     | 2.99     | 0.31 | -0.38    | 3.00     | 2.15    | 13.24   |
| 3       | 148      | 1124       | 17.81 | 17.59  | 16.94 | 16.94    | 3.69     | 0.21 | 0.10     | 3.08     | 13.20   | 22.10   |

Table 5.2 Statistical parameters for thickness representing the three horizons

| HORIZON | NO.HOLES | MEAN | MEDIAN | MODE | VARIANCE | ST. DEV. | C.V. | SKEWNESS | KURTOSIS | MINIMUM | MAXIMUM |
|---------|----------|------|--------|------|----------|----------|------|----------|----------|---------|---------|
| 1       | 141      | 5.88 | 5.73   | 7.80 | 9.52     | 3.09     | 0.53 | 0.10     | 1.90     | 1.00    | 13.00   |
| 2       | 124      | 2.64 | 2.47   | 1.83 | 1.46     | 1.21     | 0.46 | 0.62     | 2.80     | 1.00    | 6.00    |
| 3       | 148      | 3.80 | 2.50   | 1.50 | 6.44     | 2.54     | 0.67 | 2.23     | 9.92     | 1.00    | 16.00   |

Table 5.3 Statistical parameters for accumulation representing the three horizons

| HORIZON | NO.HOLES | MEAN   | MEDIAN | MODE  | VARIANCE | ST. DEV. | C. V. | SKEWNESS | KURTOSIS | MINIMUM | MAXIMUM |
|---------|----------|--------|--------|-------|----------|----------|-------|----------|----------|---------|---------|
| 1       | 141      | 117.93 | 119.19 | 22.79 | 4645.24  | 68.16    | 0.58  | 0.20     | 1.96     | 14.10   | 274.85  |
| 2       | 124      | 25.81  | 24.41  | 24.41 | 161.80   | 12.72    | 0.49  | 0.58     | 2.92     | 3.23    | 60.98   |
| 3       | 148      | 67.64  | 57.94  | 43.23 | 2110.39  | 45.94    | 0.68  | 2.20     | 9.55     | 14.60   | 300.94  |

Figures 5.1 to 5.9. The histograms of  $P_2O_5$  for Horizons 1 and 2 revealed slight negative skewness, whereas the corresponding histogram for Horizon 3 revealed positive skewness. However, they were considered to be approximately symmetrical and no logarithmic transformation of sample values was carried out. Histograms for both thickness and accumulation are asymmetrical with positive skewness. Bimodal behavior is also obvious in thickness and accumulation histograms of Horizon 1.

The distribution is said to be leptokurtic if  $k > 3$ , platykurtic if  $k < 3$  and normal if  $k = 3$  where  $k$  is the moment coefficient of kurtosis (Sahin, 1993). The coefficient of kurtosis for  $P_2O_5$  within Horizon 1 is estimated to be 2.51 indicating platykurtic nature of  $P_2O_5$  distribution in this horizon. The same parameters for Horizon 2 and Horizon 3 were estimated to be 3.00 and 3.08 respectively. The results indicate that the distributions for both thickness and accumulation representing Horizon 1 and 2 are platykurtic and the corresponding distributions representing Horizon 3 are leptokurtic.

#### 5.4 Cumulative Frequency Plots

These plots are cumulative frequency values in percentages plotted in probability scale against the mean values plotted in normal scale. If a straight line is obtained, the samples are said to be normally distributed. So the cumulative frequency plot is a useful tool to confirm the normality of the distribution.

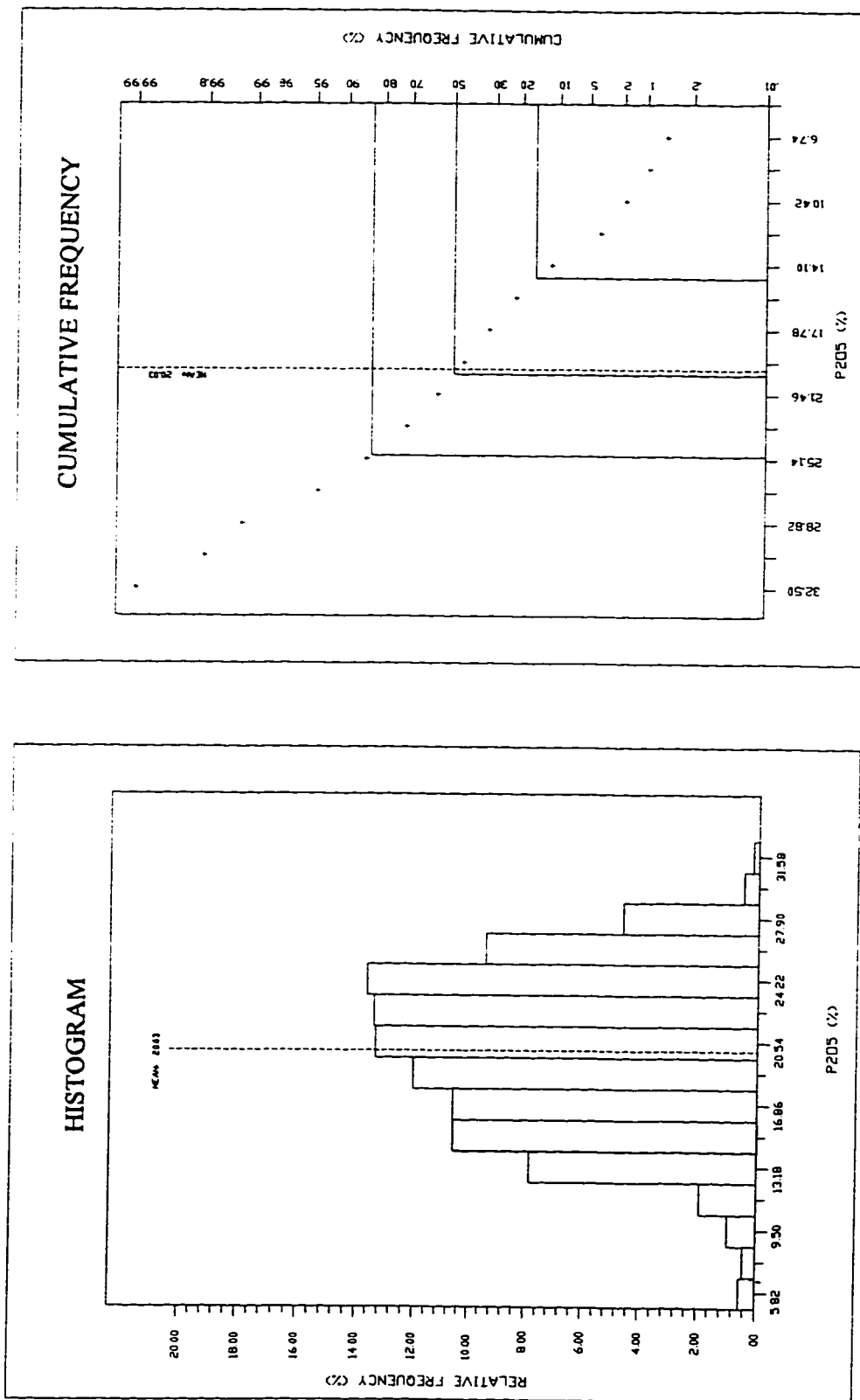


Figure 5.1 Histogram and cumulative frequency plots of P2O5 % within Horizon 1

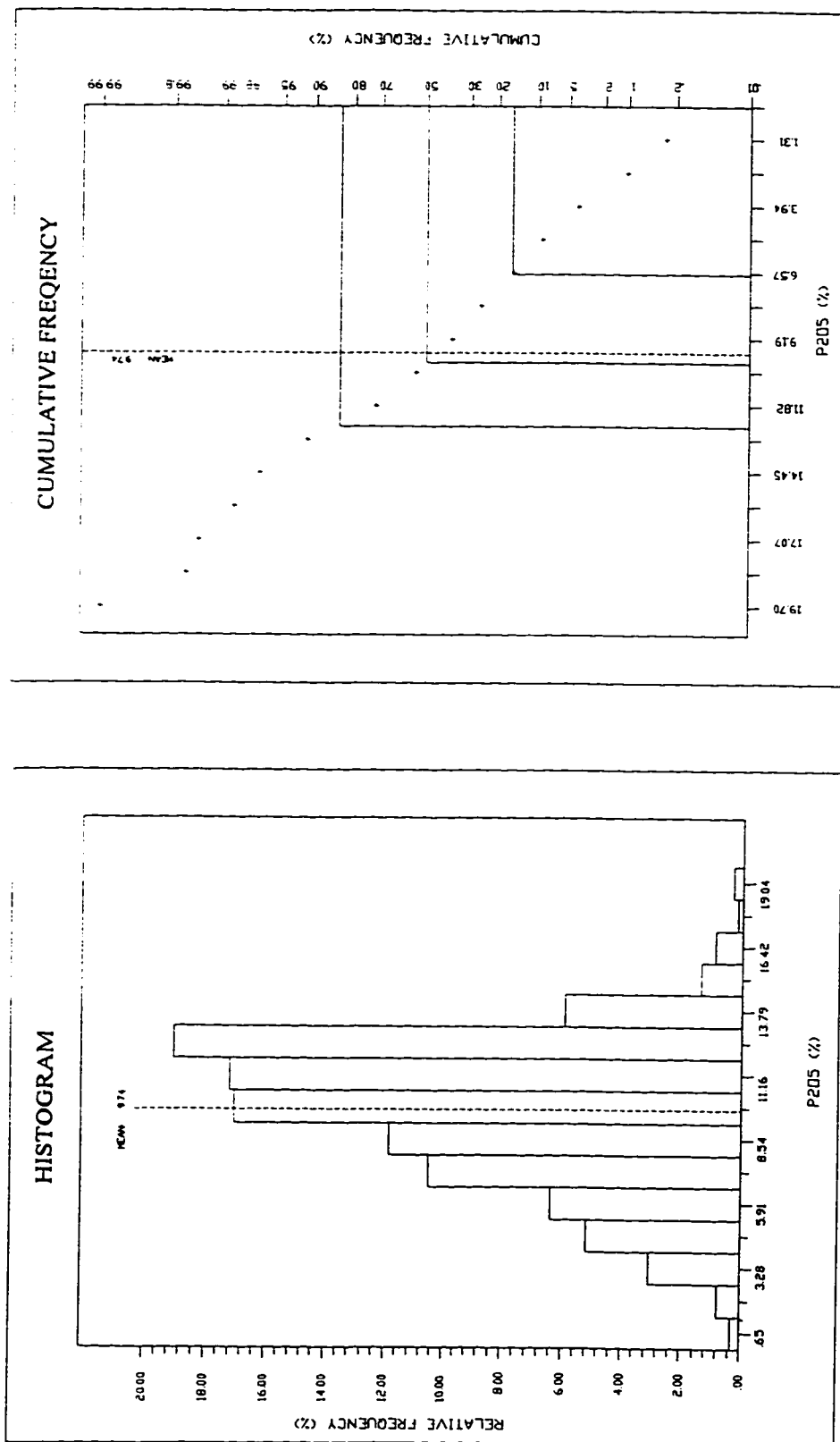


Figure 5.2 Histogram and cumulative frequency plots of P2O5 % within Horizon 2



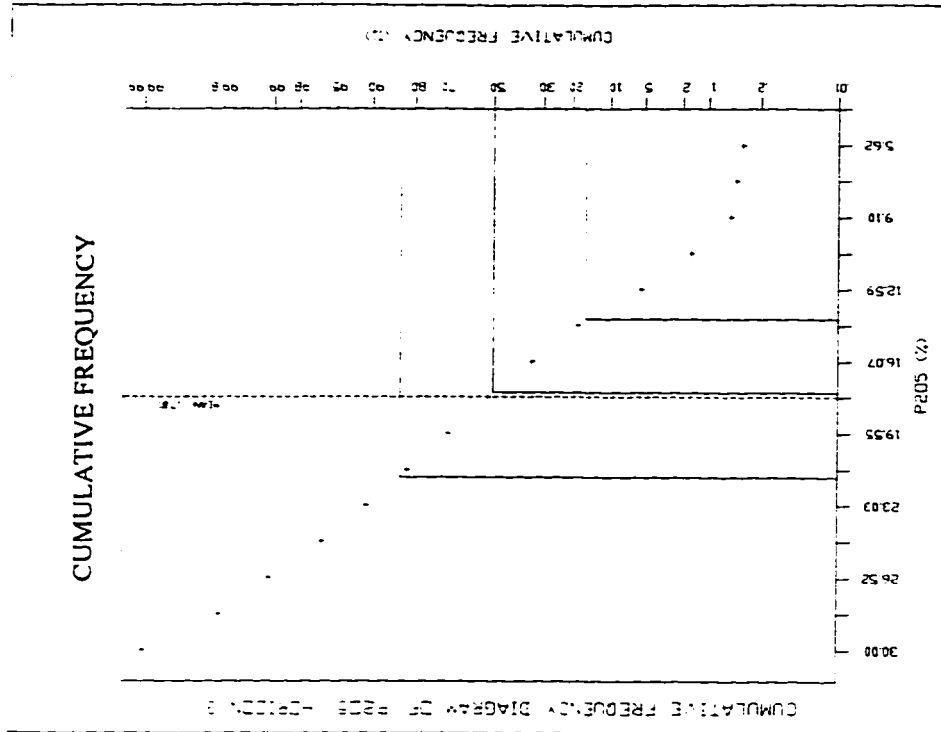
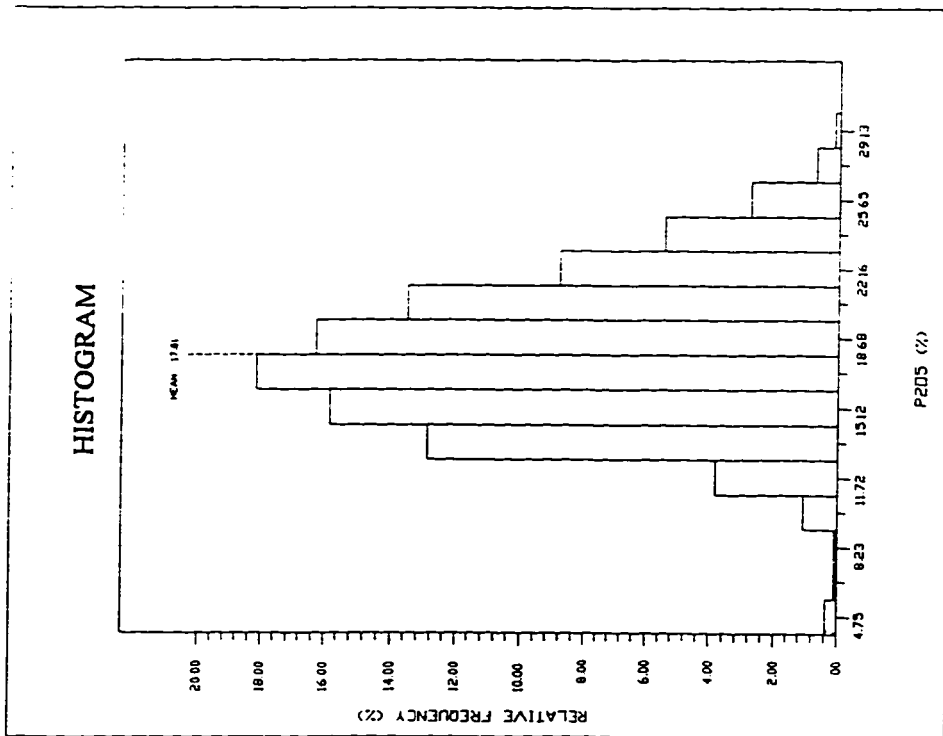


Figure 5.3 Histogram and cumulative frequency plots of P2O5 % within Horizon 3

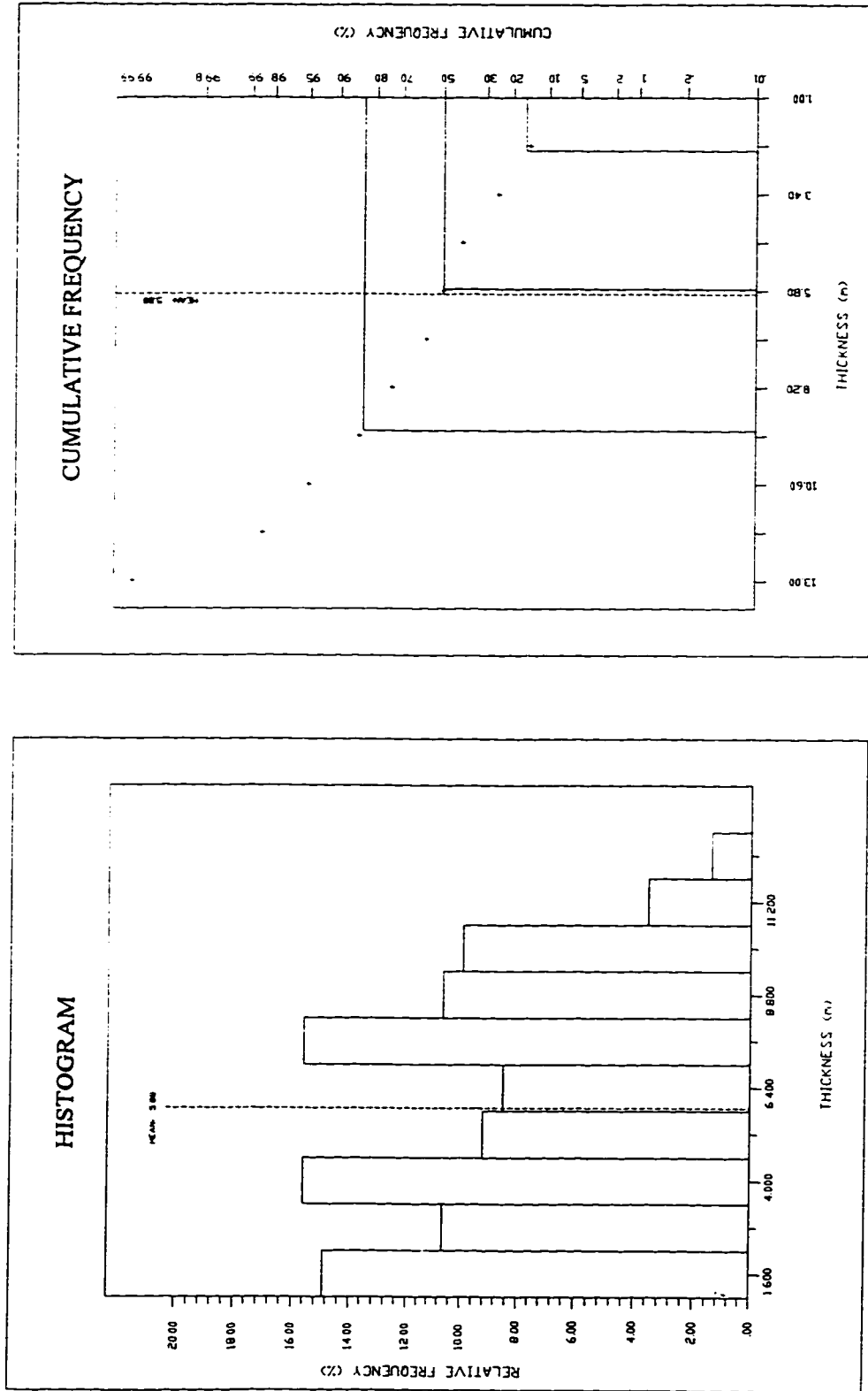


Figure 5.4 Histogram and cumulative frequency plots of the thickness representing Horizon 1

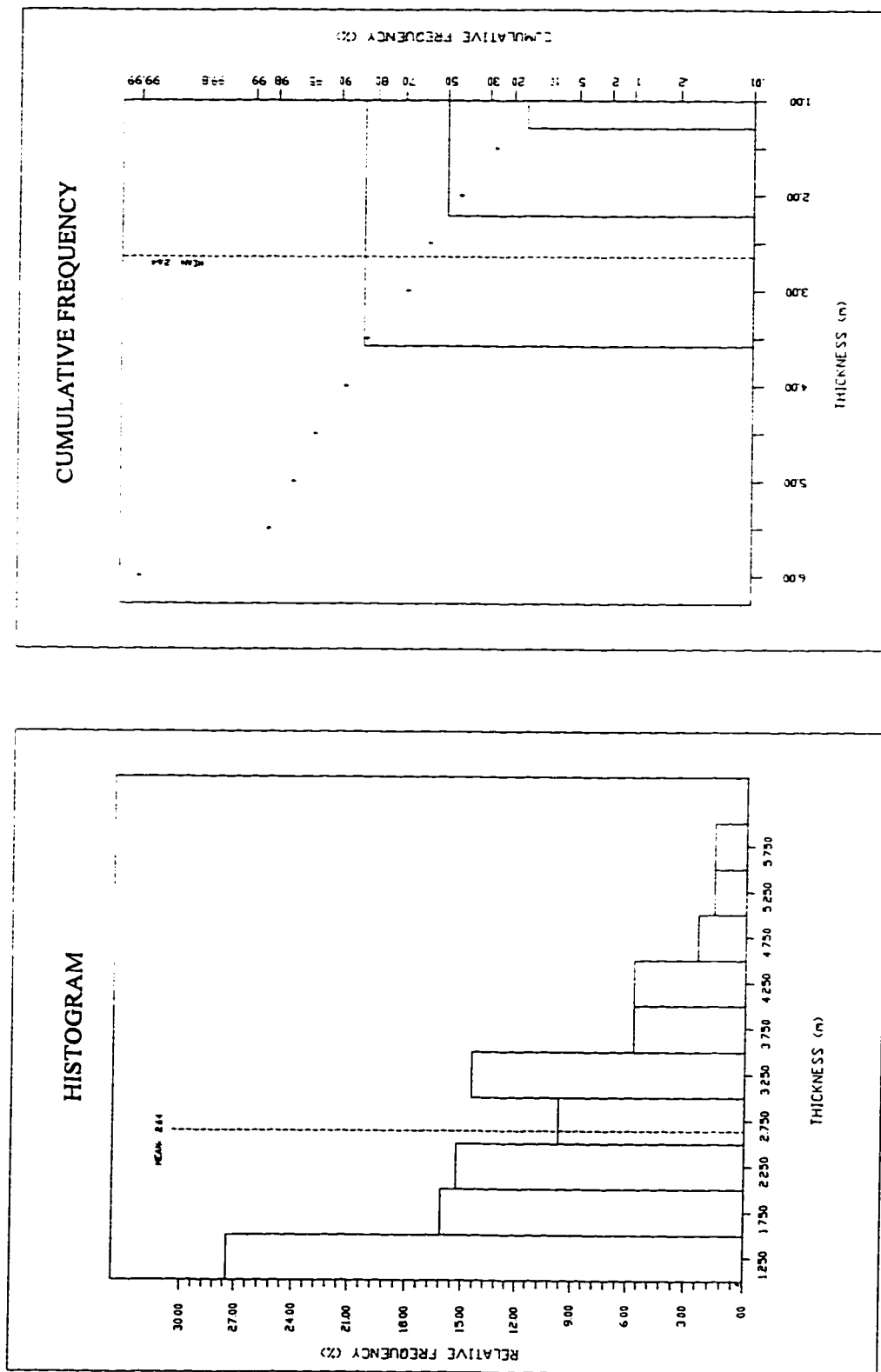


Figure 5.5 Histogram and cumulative frequency plots of thickness representing Horizon 2

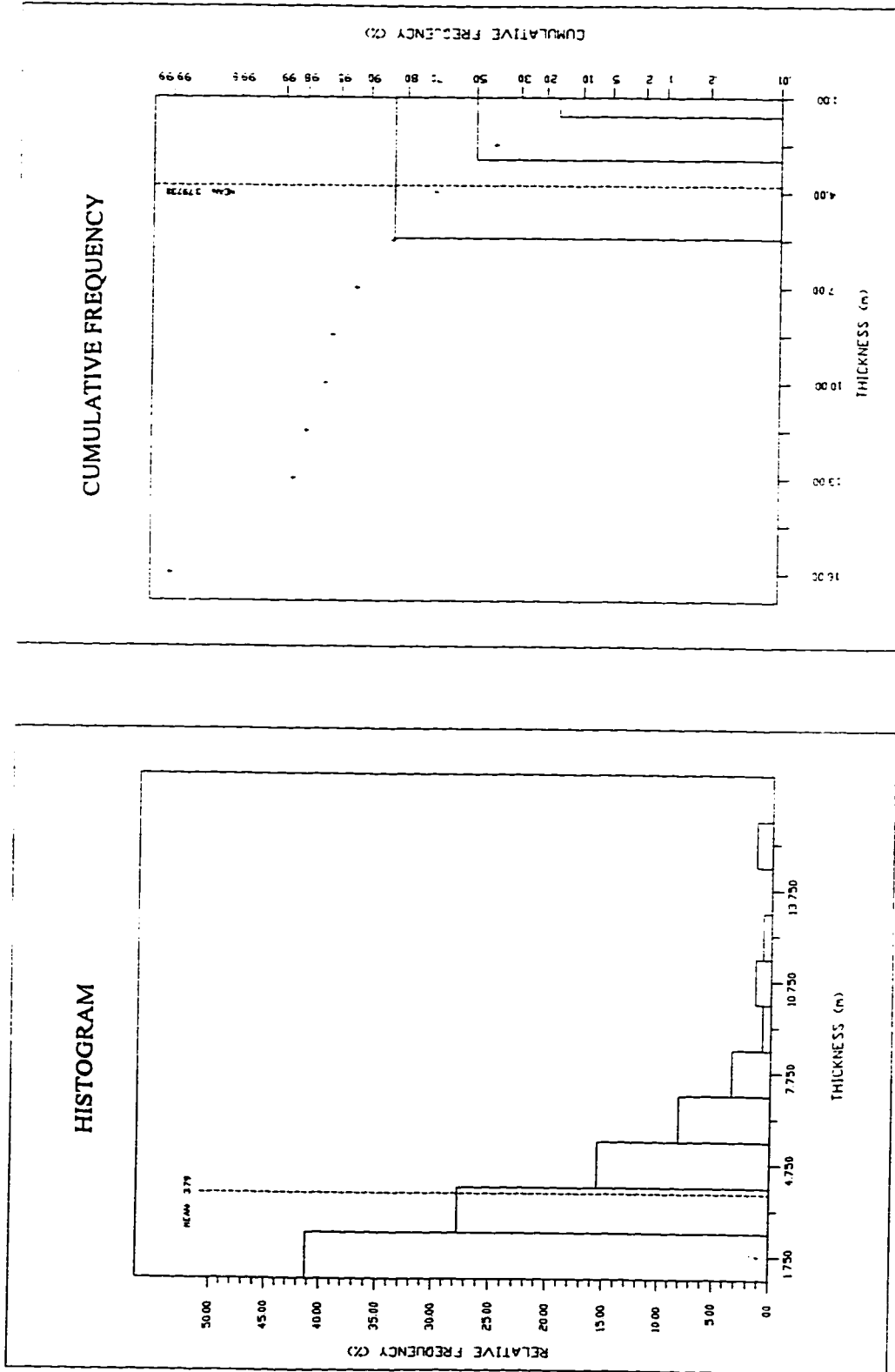


Figure 5.6 Histogram and cumulative frequency plots of the thickness representing Horizon 3

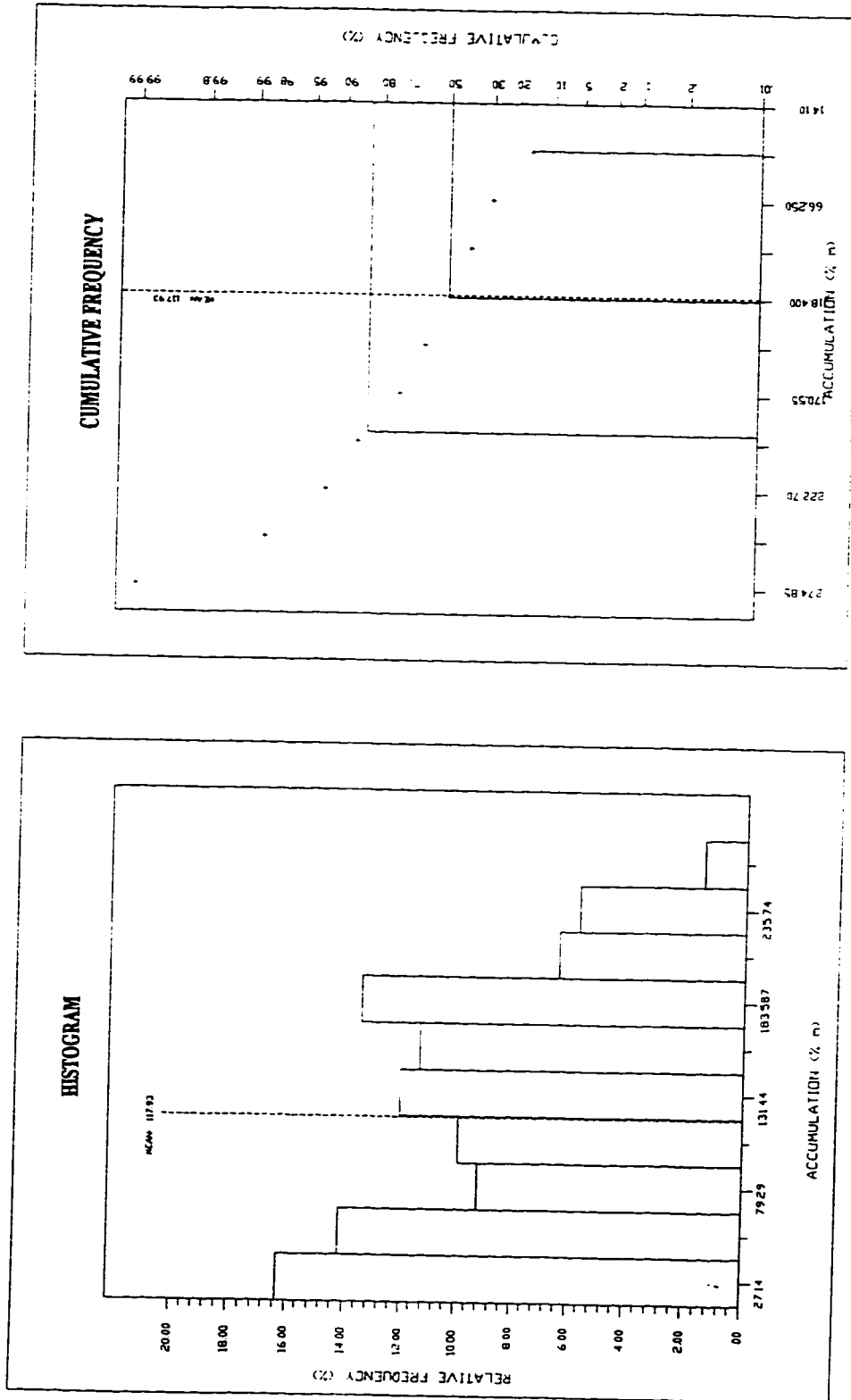


Figure 5.7 Histogram and frequency plots of the accumulation representing Horizon I

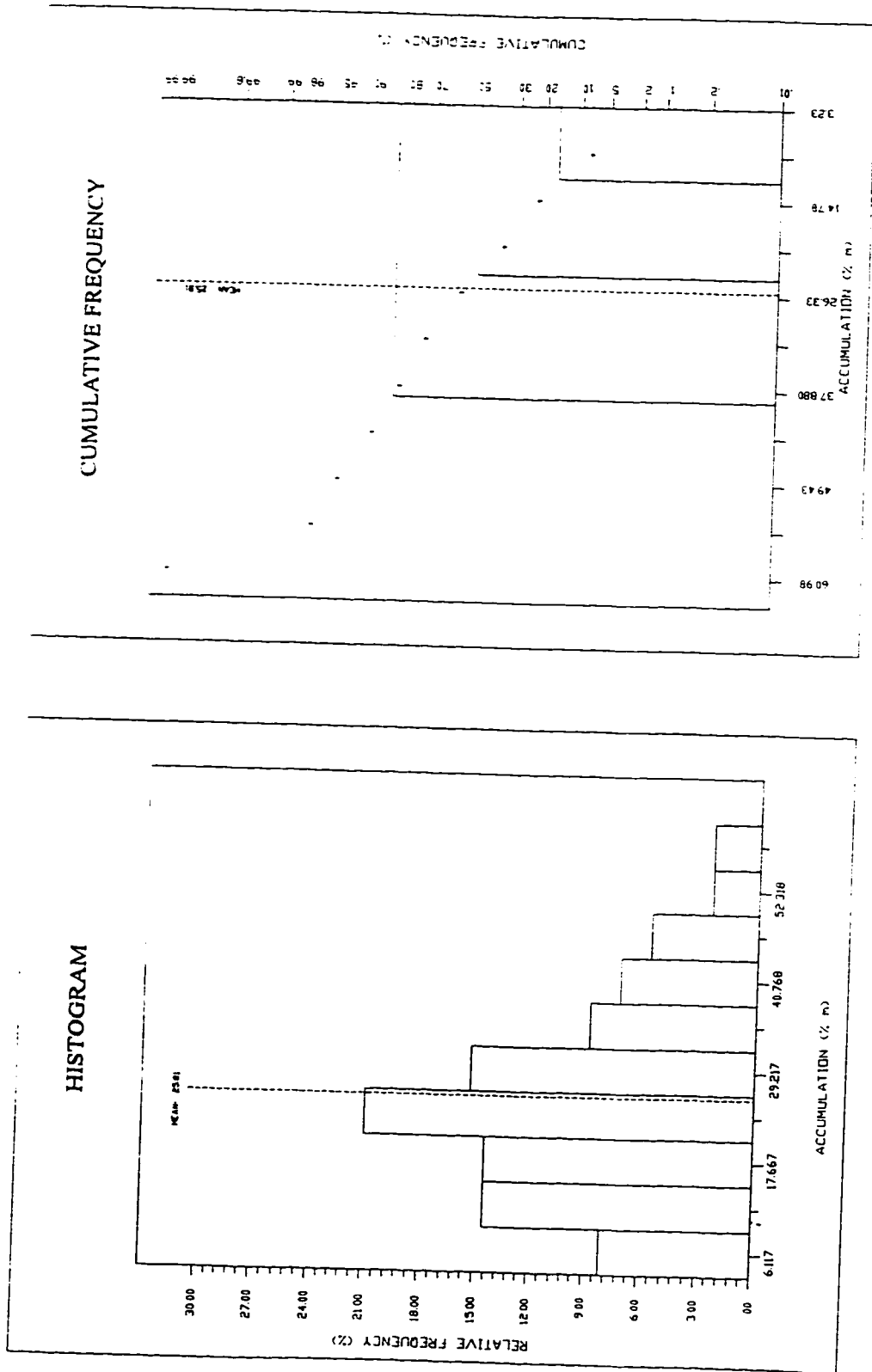


Figure 5.8 Histogram and cumulative frequency plots of accumulation representing Horizon 2

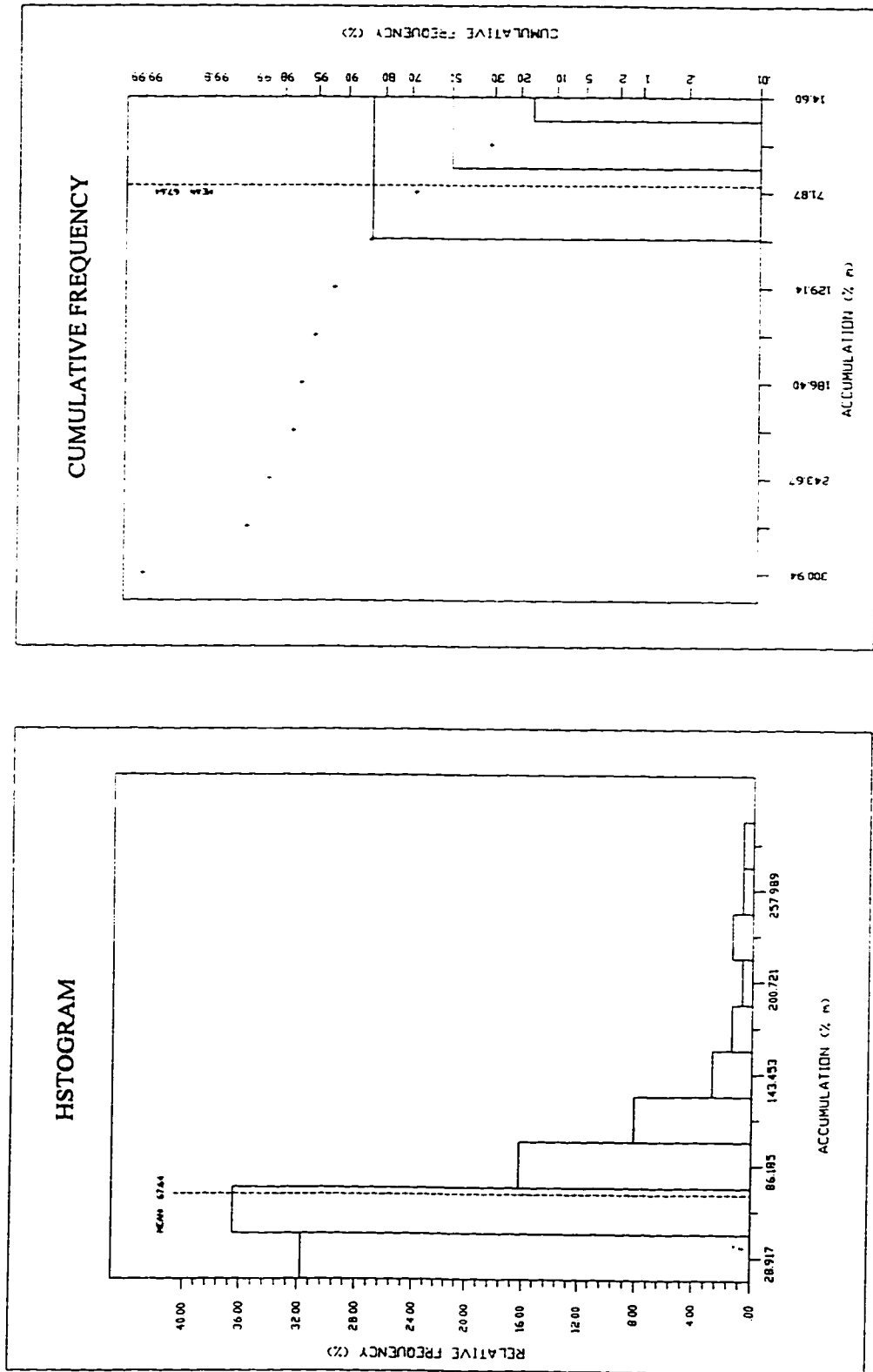


Figure 5.9 Histogram and cumulative frequency plots of accumulation representing Horizon 3

The cumulative frequency plots for the  $P_2O_5$  % within the three horizons are represented by straight lines as illustrated in Figures 5.1 to 5.9. confirming the normal distribution of  $P_2O_5$  % values in these horizons.

The histograms and cumulative frequency plots for the thickness and accumulation for the three horizons revealed asymmetrical behavior reflecting the irregular distribution of the thickness of deposit.



## **CHAPTER 6**

### **SPATIAL ANALYSIS**

#### **6.1 Introduction**

Geostatistical techniques are based on the spatial relationship between variable values. In this manner geostatistical methods differ from conventional statistical techniques. The spatial relationship between the sample values has been formulated by the theory of regionalized variable. This relationship can be represented by a mathematical function that demonstrates the behavior of geological phenomena in space.

In this chapter, the spatial analyses for the phosphorite horizons in the study area were carried out using semivariograms based on the infill and the original drill-holes data. These analyses were performed in the vertical direction and in several horizontal directions. This is followed by fitting of proper models to the experimental semivariograms representing two phosphorite horizons.

## 6.2 Semivariogram

### 6.2.1 Definition

The semivariogram is a mathematical function for quantifying the similarity or dissimilarity between sample values as a function of the distance between sample locations. It can also be defined as the half of the mean squared difference between sample values separated by vector  $h$ . The theoretical expression for semivariogram is given as follows:

$$\gamma(h) = 1/2 E [ Z(x_i) - Z(x_i + h) ]^2 \quad (6.1)$$

The experimental semivariogram is computed from the samples using the following mathematical expression:

$$\gamma(h) = 1/2 \sum_{i=1}^n 1/n(h) [Z(x_i) - Z(x_i + h)]^2 \quad (6.2)$$

where  $Z(x_i)$  and  $Z(x_i + h)$  are sample values at locations  $x_i$  and  $x_i + h$  separated by a vector  $h$  and  $n(h)$  is the total number of sample pairs. Many authors prefer to use the term variogram in place of semivariogram.

### 6.2.2 Theoretical Models

The direct use of experimental semivariogram can lead to singular matrices, multiple solutions, or negative mean-square errors in the kriging system of equations.

To overcome these problems, the experimental semivariogram is replaced by admissible functions that have been proven to assure a unique solution to the normal equations and non-negative mean square error (Olea, 1994). These functions, which are fitted to each experimental semivariogram, are referred to as model semivariogram. Model semivariograms can be classified into two categories depending on the presence or absence of sill (Rendu, 1978).

### ***Models with sill***

#### **a) The spherical model**

The spherical model is the most commonly used model in practice. The simple spherical model is illustrated in Figure 6.1. It is characterized by three parameters denoted by  $a$ ,  $C_0$  and  $C$ .  $a$  is referred to as the *range*,  $C_0$  *nugget variance*,  $C$  *spatial variance* and  $C_0 + C$  the *sill*. The general expression for the simple spherical model is given as follows:

$$\begin{aligned} \gamma(h) &= C_0 + C \left[ \frac{3h}{2a} - \frac{1}{2}(h/a)^3 \right] && \text{for } h < a \\ \gamma(h) &= C_0 + C && \text{for } h \geq a \end{aligned} \quad \left. \vphantom{\begin{aligned} \gamma(h) &= C_0 + C \left[ \frac{3h}{2a} - \frac{1}{2}(h/a)^3 \right] \\ \gamma(h) &= C_0 + C \end{aligned}} \right\} \quad (6.3)$$

The general expression for the compound spherical model with two nested structures is given as follows:

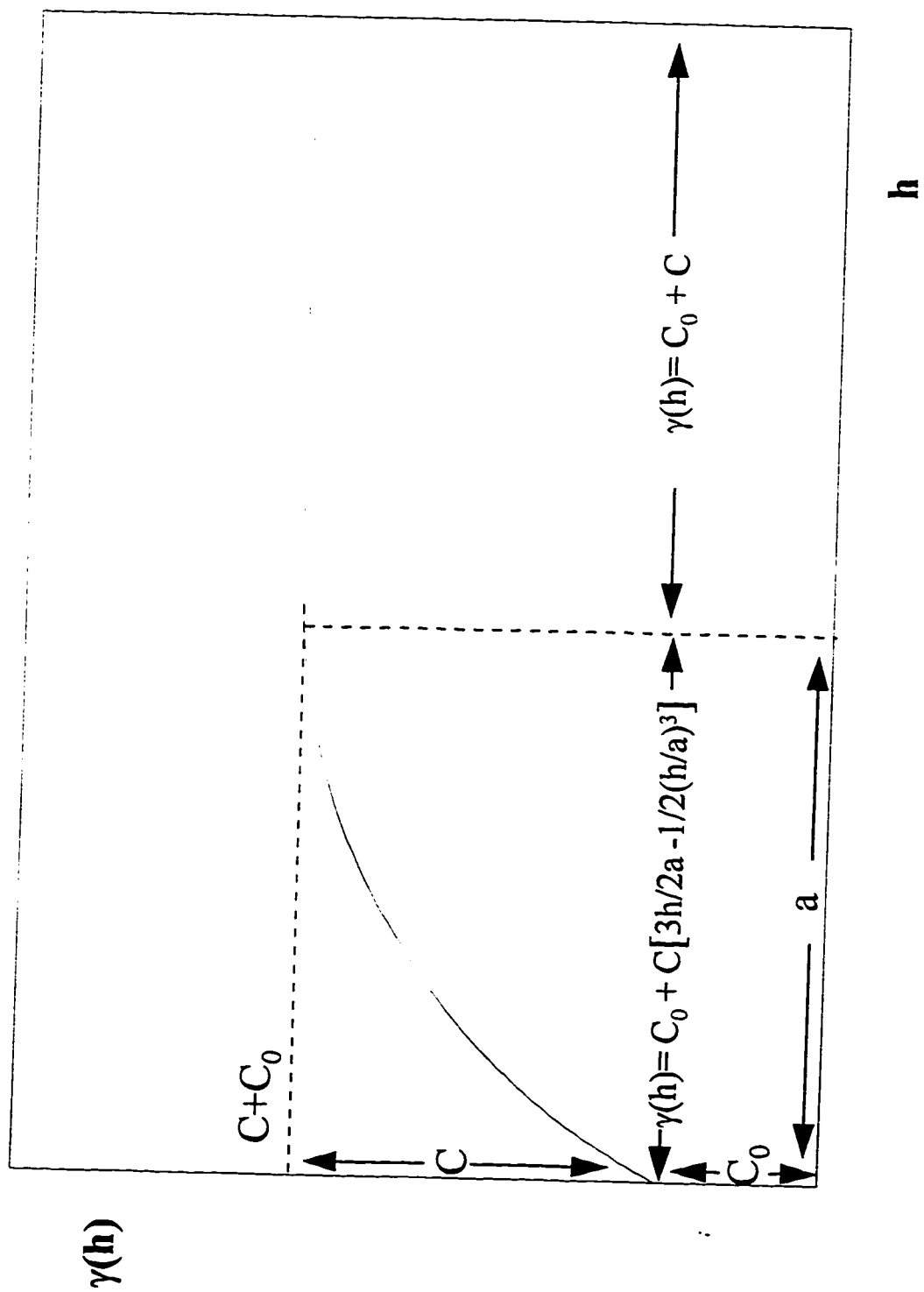


Figure 6.1 Spherical model of semivariogram

$$\begin{aligned}
 \gamma(h) &= C_o + C_1 [3/2(h/a_1) - 1/2(h/a_1)^3] + C_2 [3/2(h/a_2) - 1/2(h/a_2)^3] && \text{for } h < a_1 < a_2 \\
 \gamma(h) &= C_o + C_1 + C_2 [3/2(h/a_2) - 1/2(h/a_2)^3] && \text{for } a_1 < h < a_2 \\
 \gamma(h) &= C_o + C_1 - C_2 && \text{for } h \geq a_2 > a_1
 \end{aligned} \tag{6.4}$$

### b) The exponential model

This model is characterized by three parameters denoted by  $a$ ,  $C_o$  and  $C_o + C$  as shown in Figure 6.2. The general expression for this model is given as follows:

$$\gamma(h) = C_o - C[1 - e^{(-h/a)}] \tag{6.5}$$

This model reaches the sill only asymptotically. The range  $a$  in this model has no precise geometric relationship as the range of the spherical model.

### c) The Gaussian model

The Gaussian model is characterized by a parabolic behavior near the origin as illustrated in Figure 6.3 and Figure 6.4. It is expressed as follows:

$$\gamma(h) = C_o + C [1 - e^{(-h^2/a^2)}] \tag{6.6}$$

The tangent at the origin intersects the  $\gamma(h) = C_o + C$  line at the distance approximately equal to  $a/\sqrt{3}$ .

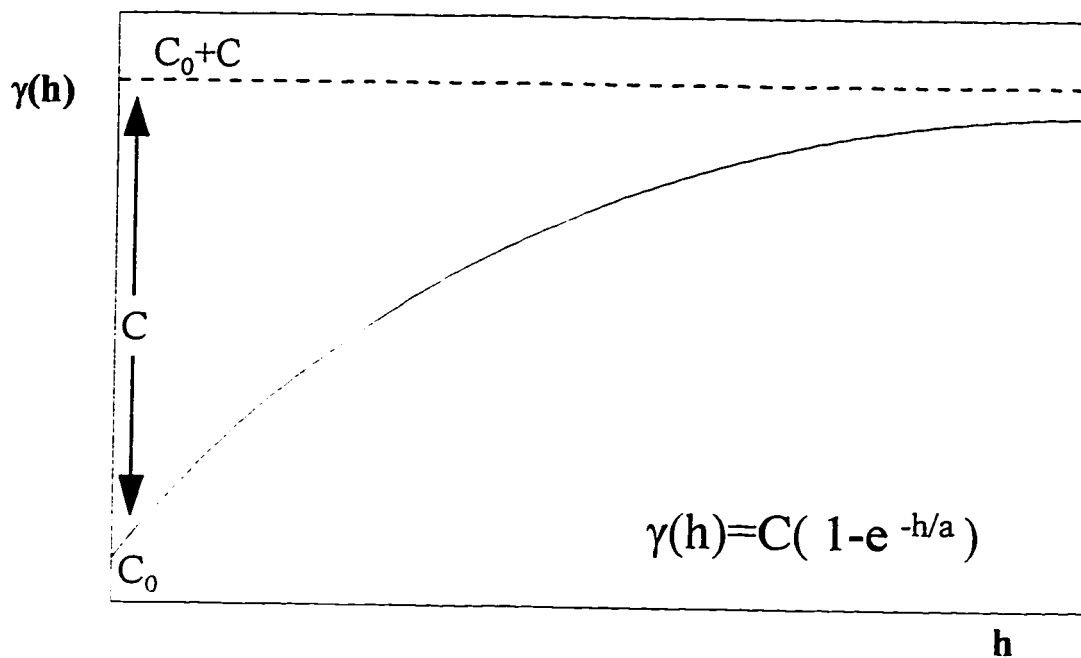


Figure 6.2 Exponential model of semivariogram

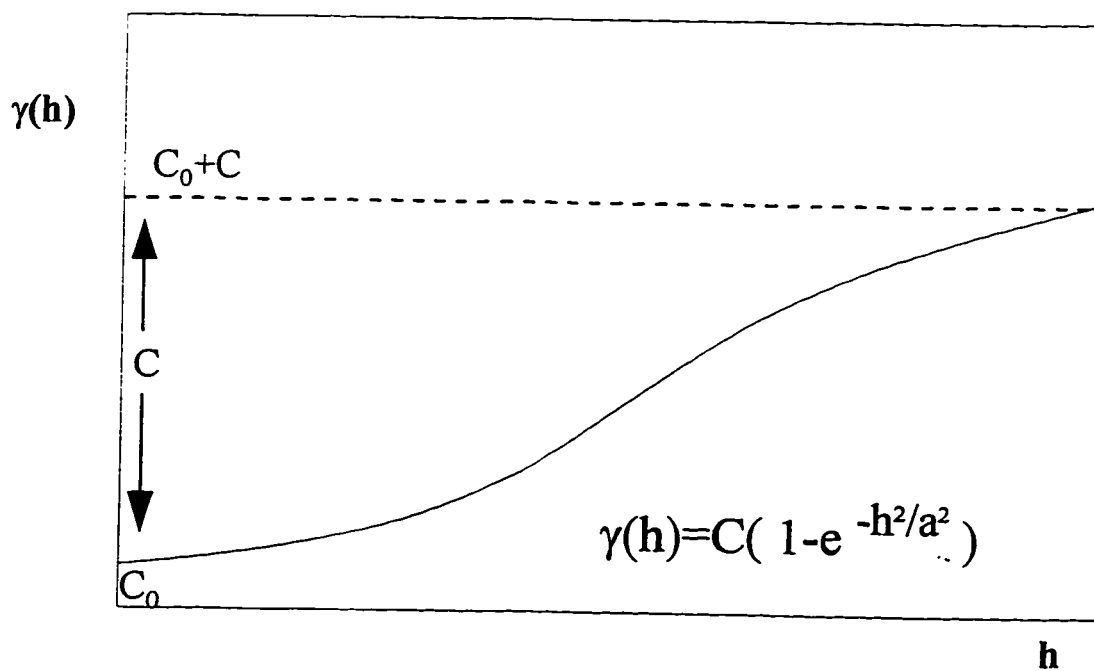


Figure 6.3 Gaussian model of semivariogram

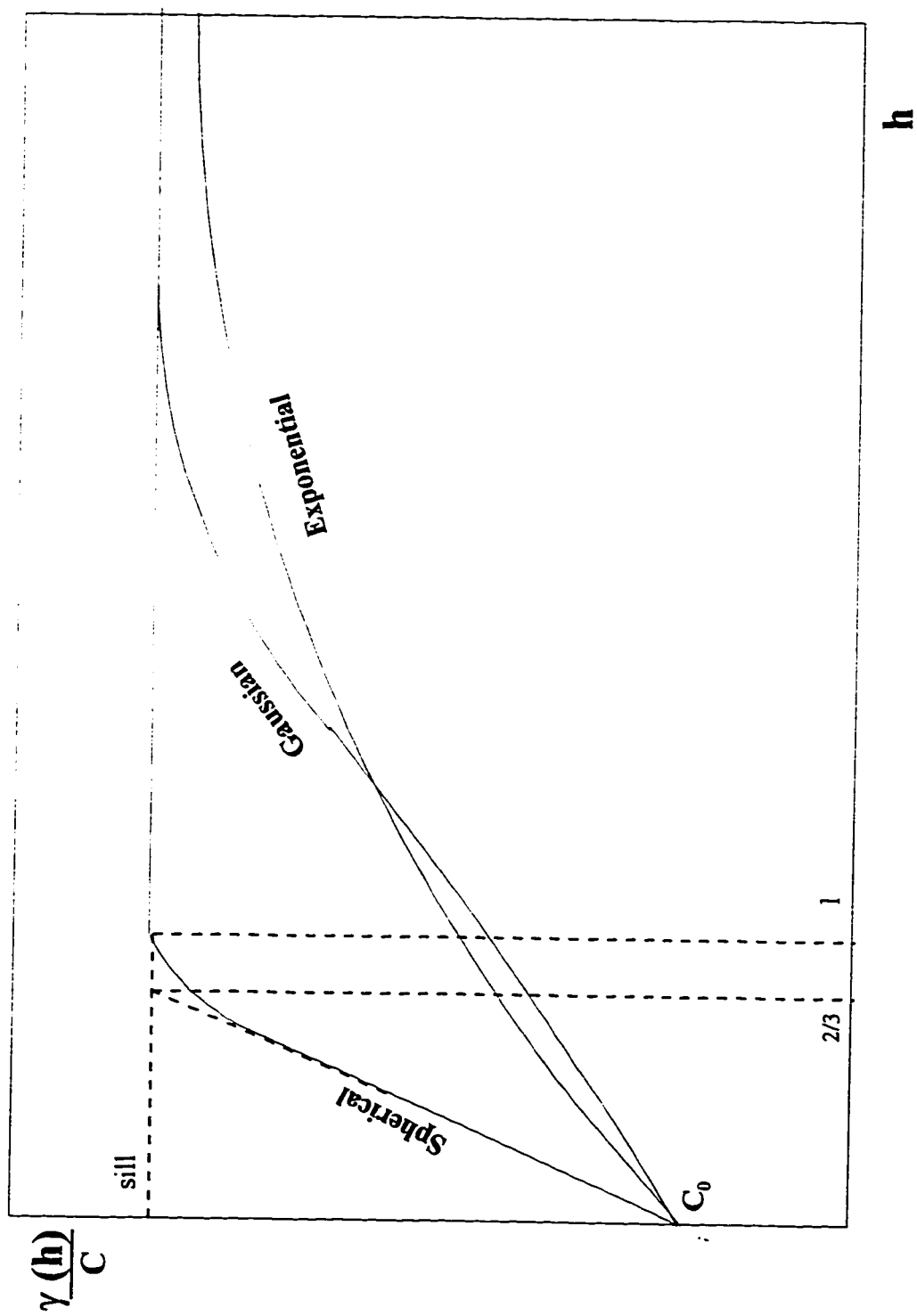


Figure 6.4 Models of semivariograms with sills (after Rendu, 1978)

### ***Models without sill***

#### **a) The linear ( power ) model**

The liner model can be expressed as follows:

$$\gamma(h) = \omega h \quad (6.7)$$

where  $\omega$  is the slope at the origin. A more general model, illustrated in Figure 6.5, can be represented by the following equation:

$$\gamma(h) = \omega h^\theta \quad (6.8)$$

where  $0 < \theta < 2$

#### **b) The De Wjsian model**

This model gives a good fit to the experimental semivariogram that shows straight line on semi-logarithmic paper (Figure 6.6). The general expression is given as follows:

$$\gamma(h) = 3 \alpha \ln h \quad (6.9)$$

where  $\alpha$  is a constant known as the *coefficient of absolute dispersion*.

### **6.2.3 Choice of models**

Due to the similarities between some models, difficulties are often encountered in the selection of models. The general guidelines which should followed in selecting models are listed below (Sahin and Royle, 1994):



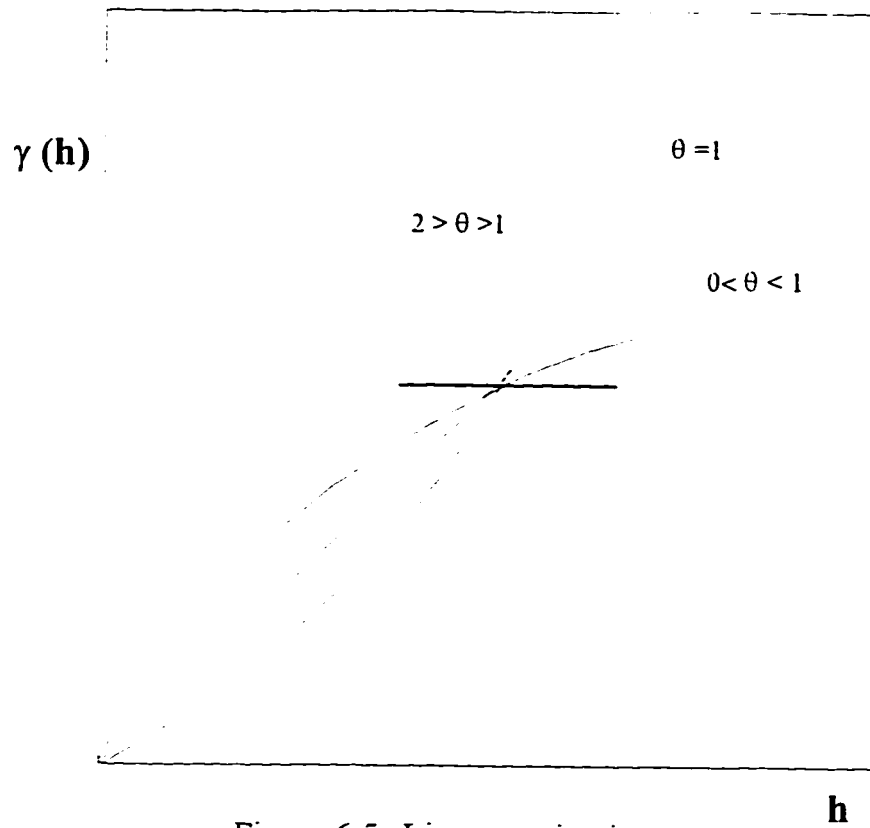


Figure 6.5 Linear semivariogram

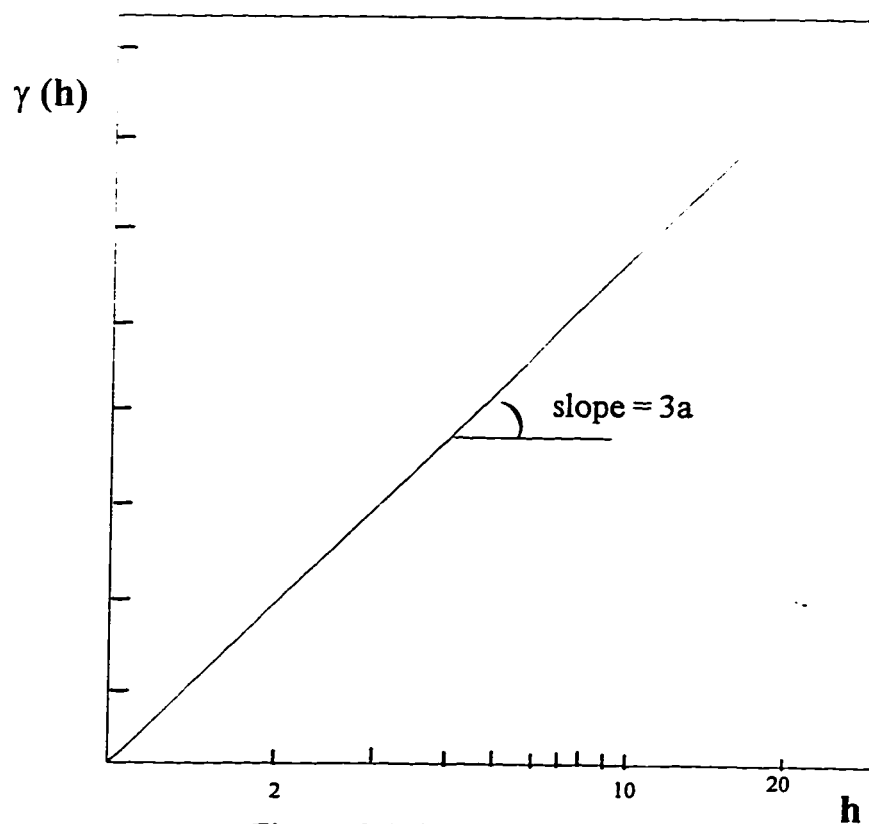


Figure 6.6 De Wijsian semivariogram

1. The model should fit well to the experimental points near the origin.
2. When anisotropy exists, a consistent model should be fitted in each direction.
3. If the semivariogram increases as  $h$  increases without displaying any sill value, then either linear or De Wijsian model should be considered.
4. If the semivariogram reaches the sill slowly an exponential model, otherwise spherical model must be chosen.

The basic steps in fitting a spherical are listed below:

1. Fix  $C_0$  from the vertical semivariogram. Since the vertical and horizontal semivariograms are based on the same data with the same support,  $C_0$  for both will be the same.
2. Fix the value of sill. This can be done with reasonable accuracy by knowing statistical variance and the behavior of the semivariogram.
3. Draw a tangent at  $h = 0$ . This tangent will intersect the sill at point with  $h = 2a/3$ . Read this value from the graph and calculate  $a$ .
4. Substitute the values of parameters for several values of  $h$  in the general expression and obtain corresponding values of  $\gamma(h)$ . Plot  $\gamma(h)$  values against  $h$ .
5. If the fit is not considered satisfactory, change the value of parameters (one at the time) to get better fit.

#### 6.2.4 Semivariogram and Geologic Characteristics

The regionalized variables generally display spatial patterns that are the result of sedimentary, metamorphic, magmatic or structural processes. Semivariogram is a measure of the spatial variations of these variables. Therefore, analyzing the behavior of semivariograms in light of geological information, it is possible to identify the geological controls. The most important characteristics that can be revealed by the semivariogram are:

##### *Continuity*

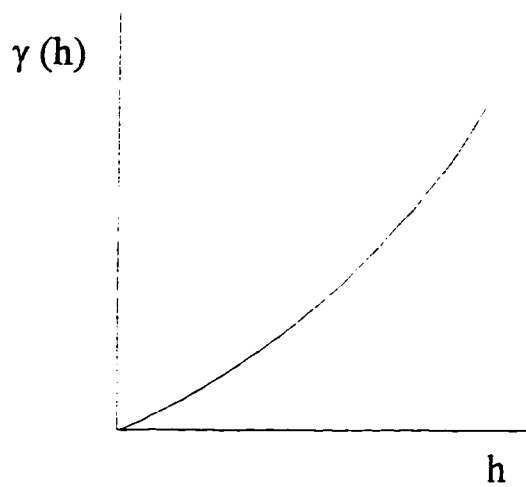
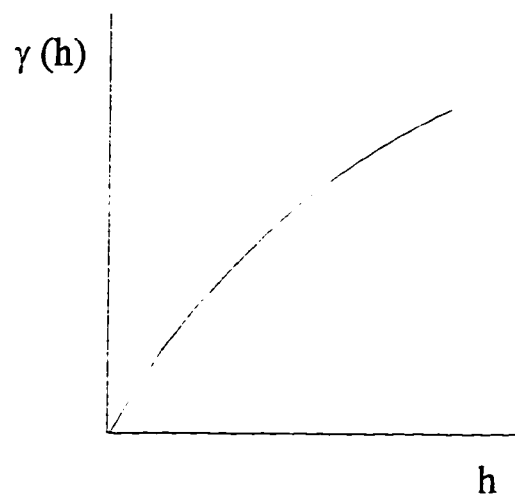
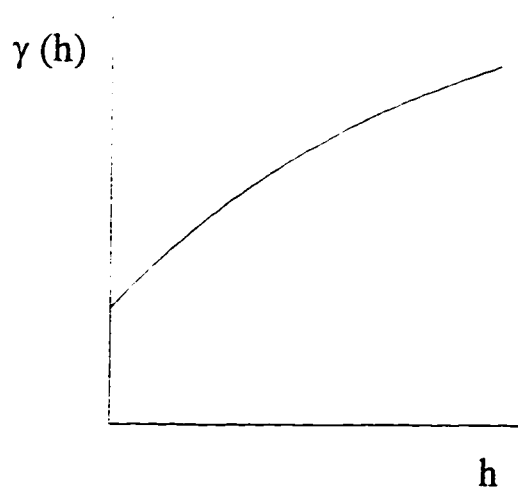
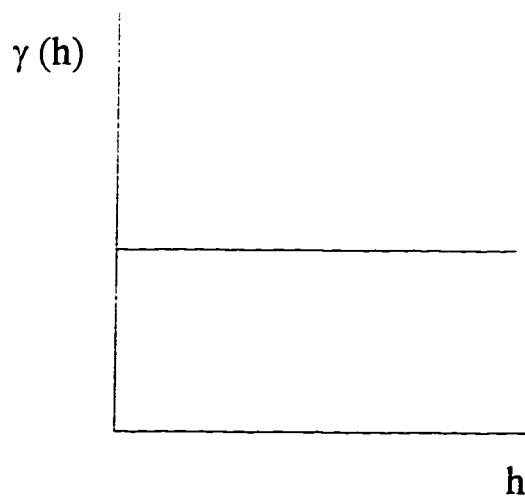
The behavior of the semivariogram near the origin characterizes the degree of spatial continuity of the regionalized variable. Four types of behavior can be recognized as illustrated in Figure 6.7 and outlined below.

##### a) *Continuous Type*

This type exhibits a parabolic behavior near the origin as illustrated in Figure 6.7a and characterizes a variable with a high degree of continuity.

##### b) *Linear Type*

This type has oblique tangent at the origin and indicates an average continuity (Figure 6.7b). Many base-metal deposits exhibit this type of behavior.

**a) Continuous type****b) Linear type****c) Nugget type****d) Random type****Figure 6.7** Types of continuity

#### c) *Nugget Type*

This type shows discontinuity at the origin as illustrated in Figure 6.7c and reflects considerable variability between two neighboring points.

#### d) *Random Type*

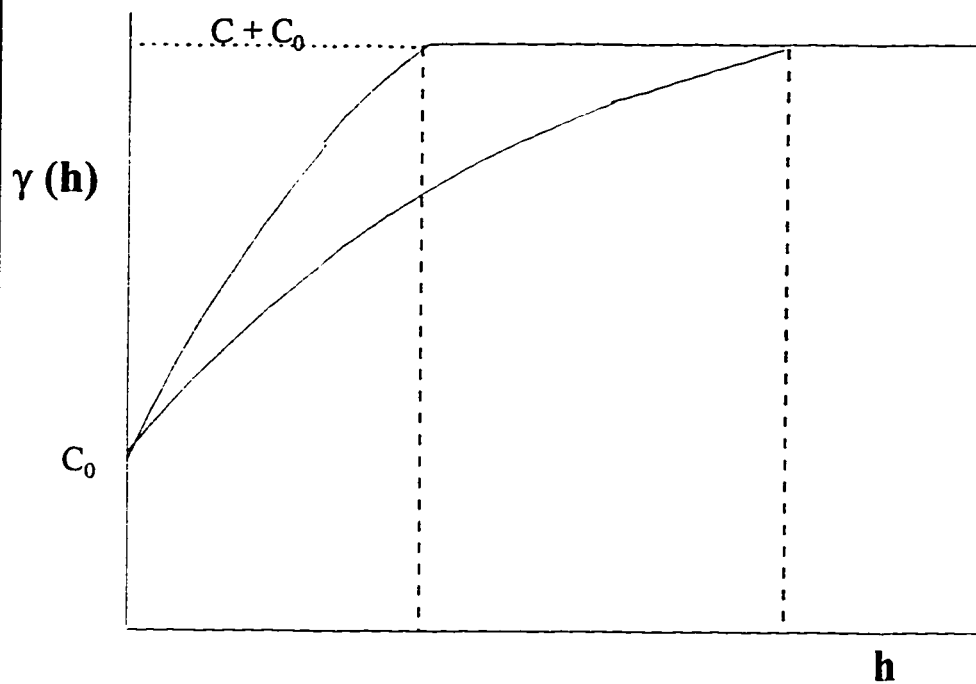
This type reflects purely random behavior and represents the lack of correlation between samples at any distance (Figure 6.7d). It is rarely observed in nature.

### ***Zone of Influence***

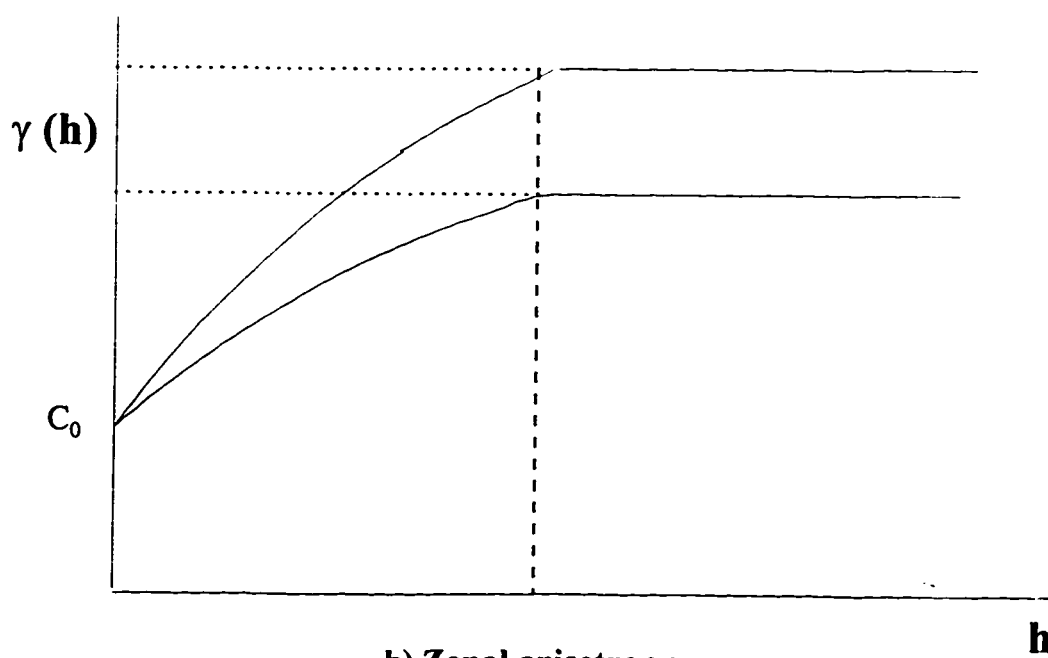
The zone of influence corresponds to the distance at which  $\gamma(h)$  reaches the sill. This distance, which is referred to as the *range* ( $a$ ), represents the average dimensions of the geological structures such as bedding, lenses and basins. The samples separated by a distance greater than the dimensions of these structures are most likely uncorrelated, whereas the samples located within the boundaries of the structures are correlated.

### ***Anisotropies***

When the semivariograms along different directions are identical, the regionalized variable is said to be *isotropic*. Two types of anisotropy can be distinguished : *geometrical* and *zonal* anisotropies. The geometrical anisotropy is characterized by different ranges in different directions (Figure 6.8a). This is due to the presence of structures that have unequal dimensions such as micro-basin and lenses. The zonal anisotropy is characterized by different sills in different directions (Figure



**a) Geometrical anisotropy**



**b) Zonal anisotropy**

Figure 6.8 Types of anisotropies

6.8b). This due to presence of layering or zonation commonly observed in some deposits such as stratiform deposits.

### **6.3 Spatial Analysis for the Hazm Al-Jalamid Deposit**

Spatial analysis for Hazm Al-Jalamid deposit was performed using semivariograms of  $P_2O_5$  % based on the data from infill drill holes and the original drill holes. Semivariograms were computed in horizontal and vertical directions within Horizon 1 and Horizon 3. These semivariograms are presented and discussed in the following paragraphs:

#### **6.3.1 Semivariograms for Horizon 1**

##### ***Vertical semivariograms***

The vertical semivariograms, based on the data from both the infill and the original drill-holes intersecting Horizon 1, revealed spherical behavior with a range of about 4 m (Figure 6.9).  $C_0$  value obtained from these semivariograms was used to fix the values of  $C_0$  in the corresponding horizontal semivariograms. The minimum lag distance was chosen to be 0.5 m (i. e. equal to sample support) in all vertical semivariogram computation.

##### ***Horizontal semivariograms for the infill drill-holes***

As mentioned earlier, 40 vertical drill-holes were drilled in the area along two perpendicular lines intersecting at the center. These drill-holes are located at 140 m

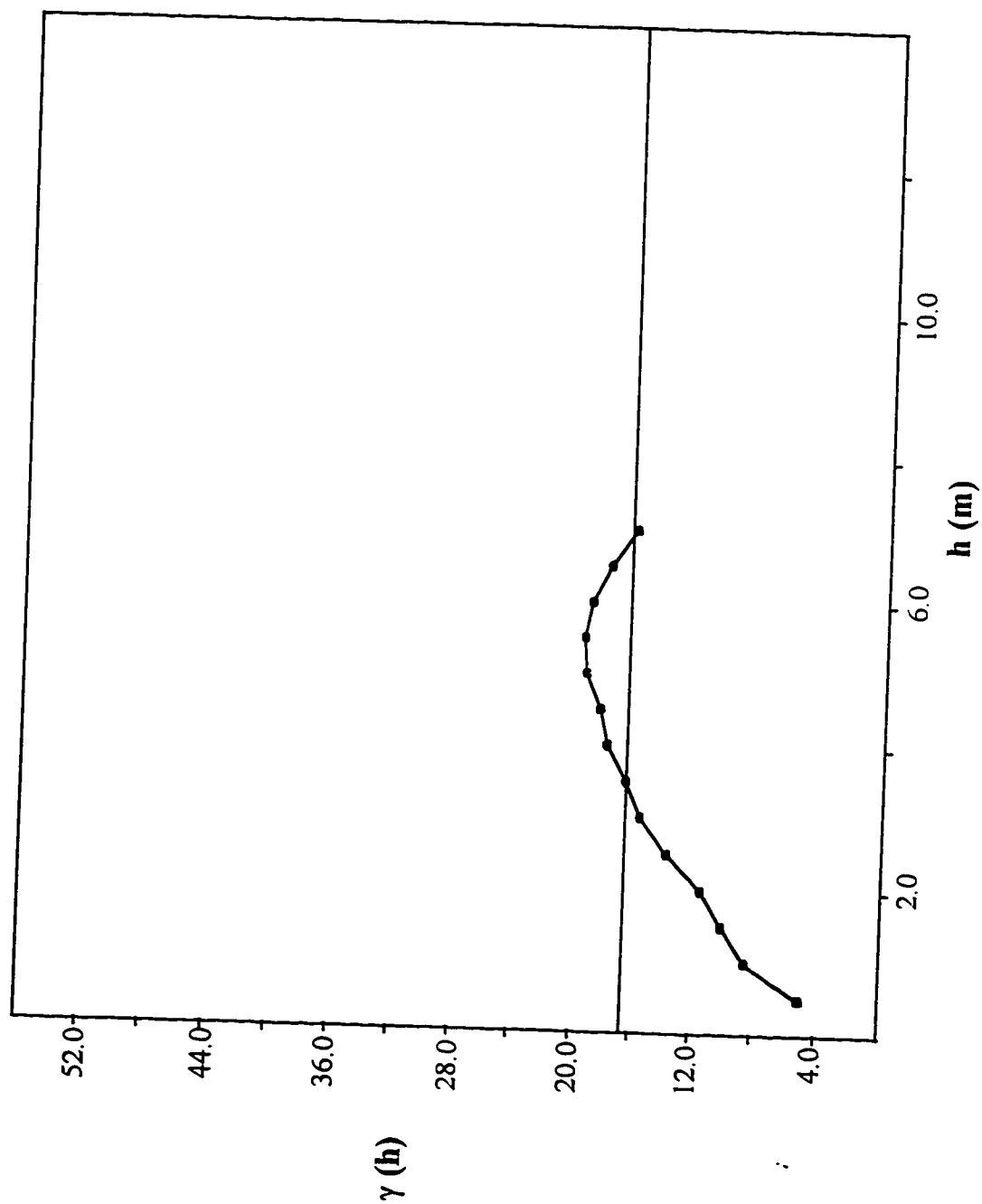


Figure 6.9 Vertical semivariogram for  $P_2O_5$  % in Horizon I



uniform spacing on these lines which have NE-SW and NW-SE orientations. The horizontal semivariograms of  $P_2O_5$  % from these drill-holes were calculated along the lines, and are illustrated in Figures 6.10 and 6.11.

Due to relatively high spacing between drill-holes, the experimental semivariograms for the data from the original drill-holes revealed poor spatial correlation (see Appendix E). Therefore, it was not possible to delineate the spatial structure and to fit models. To overcome this problem, infill drill-hole semivariograms were assumed to represent the whole study area. This assumption appears to be valid since all the phosphorites in the area are deposited in the same basin under the same structural control as a result of the same chemical processes. Moreover, the semivariograms for the original data revealed generally similar patterns with those of the infill drill-holes data (Appendix E).

Spherical models were fitted for the horizontal semivariograms along both directions and hence the geostatistical parameters were obtained. The parameters of these models are listed in Table 6.1. The semivariograms along both directions have the same values of nugget variance and the sills. However, they have revealed different ranges indicating strong geometric anisotropy with an anisotropy ratio of 4 ( $2000 \div 500$ ).

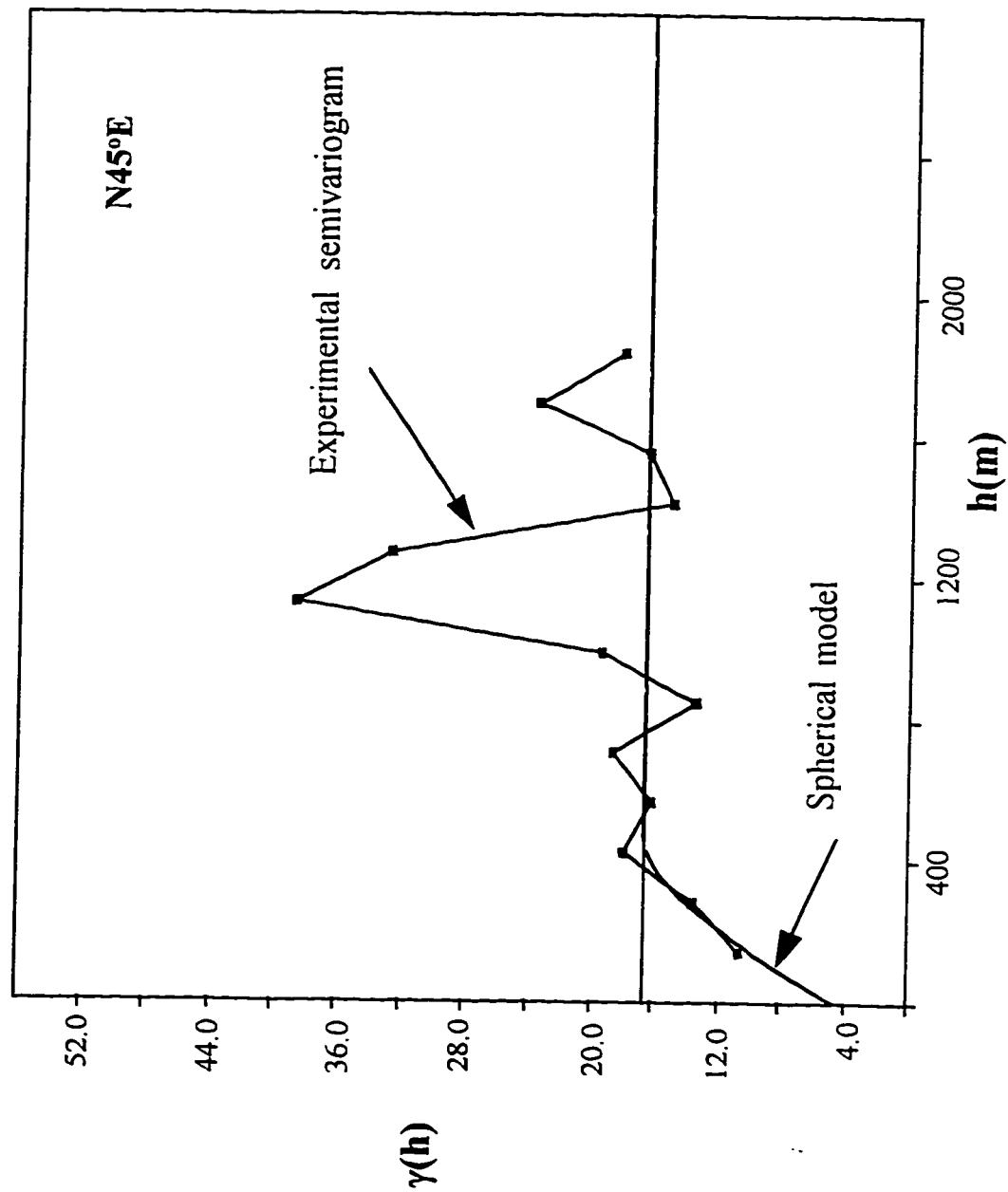


Figure 6.10 Horizontal semivariogram for  $P_2O_5$  % in Horizon 1 along N45°E direction and the fitted spherical model.

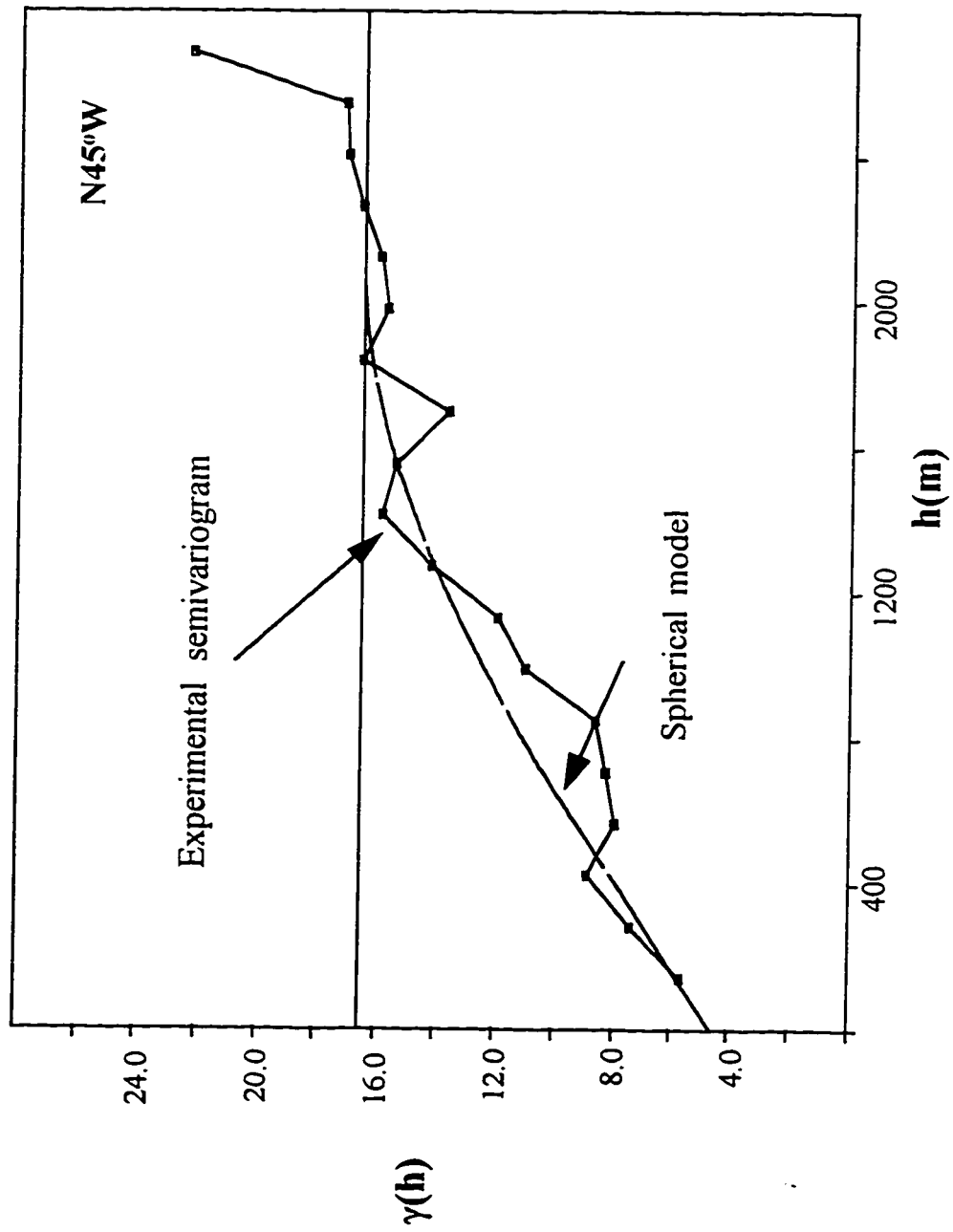


Figure 6.11 Horizontal semivariogram for  $P_2O_5$  % in Horizon 1 along N45°W direction and the fitted spherical model.

Table 6.1 Parameters of horizontal semivariograms for  $P_2O_5$  % in Horizon 1

| PARAMETERS | N45°E                 | N45°W                 |
|------------|-----------------------|-----------------------|
| $C_0$      | 4.2 (%) <sup>2</sup>  | 4.2 (%) <sup>2</sup>  |
| C          | 12.3 (%) <sup>2</sup> | 12.3 (%) <sup>2</sup> |
| a          | 500 m                 | 2000 m                |

### 6.3.2 Semivariogram for Horizon 3

#### *Vertical Semivariograms*

The vertical semivariograms of the data from the infill drill-holes and the original holes intersecting the Horizon 3 revealed a spatial correlation with a range of about 4 m (Figure 6.12). The sample support (i. e. 0.5 meter) was used as the minimum lag distance as in the case of Horizon 1. Simple spherical models appear to be appropriate to fit these semivariograms.

#### *Horizontal semivariograms for the infill drill-holes*

Semivariograms in different horizontal directions for the original drill-holes were calculated and are given in Appendix F. The same conclusions regarding the sample spacing of data from original drill-holes in Horizon 1 are also applicable to this horizon. Therefore, the infill drill-hole data provided the basis for semivariogram modeling. The horizontal semivariograms for the data from the infill drill-holes along N45°E and N45°W display same spatial correlation.

Spherical models were fitted to these semivariograms and hence the geostatistical parameters for the lower horizon have been obtained. It should be noted that the values of the ranges along both directions are the same. However, the values of the sills are different reflecting the behavior of zonal anisotropy. The experimental semivariograms and the fitted spherical models for the above-mentioned directions are illustrated in Figure 6.13 and Figure 6.14. The corresponding model parameters are listed in Table 6.2.

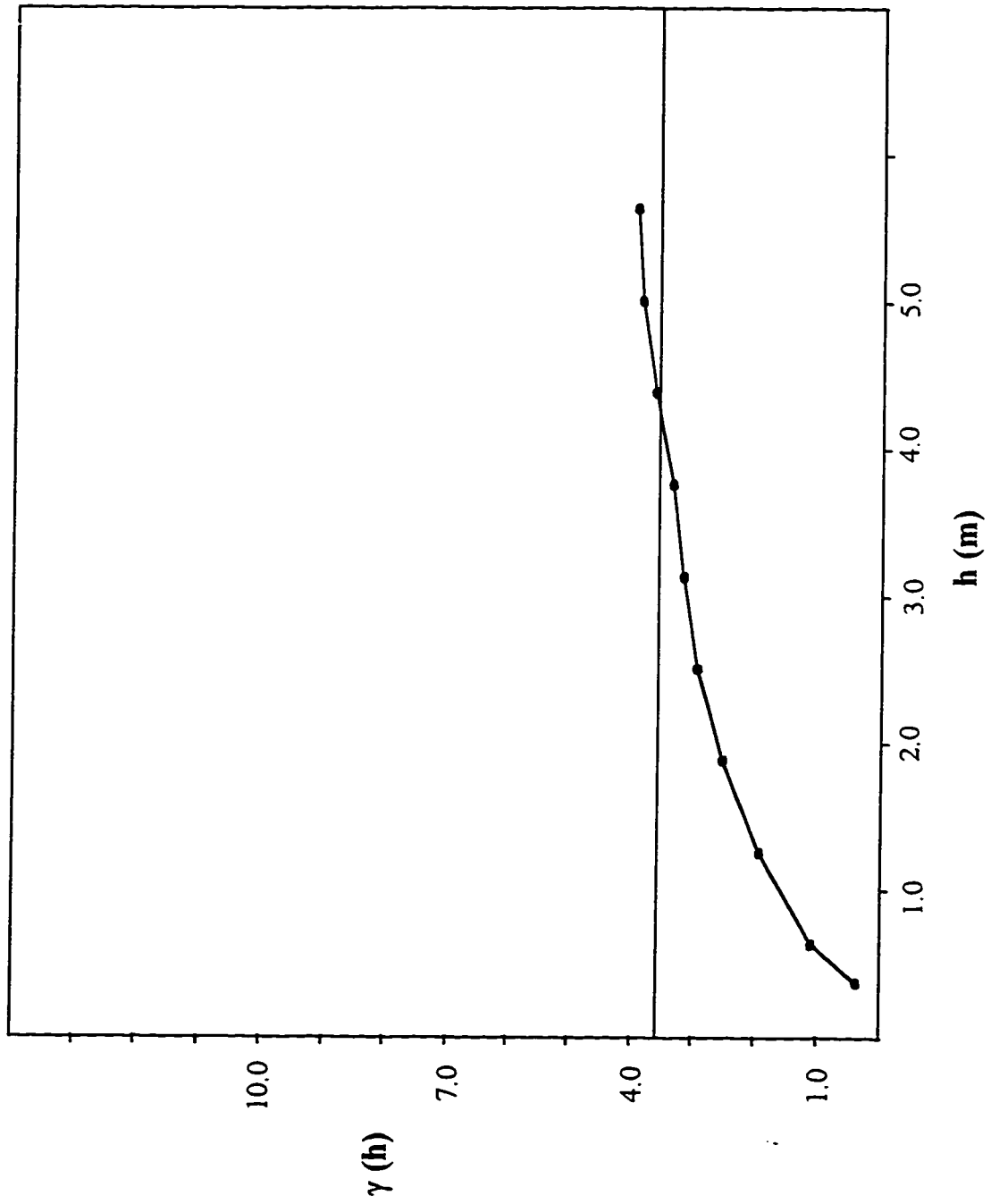


Figure 6.12 Vertical semivariogram for  $P_2O_5$  % in Horizon 3

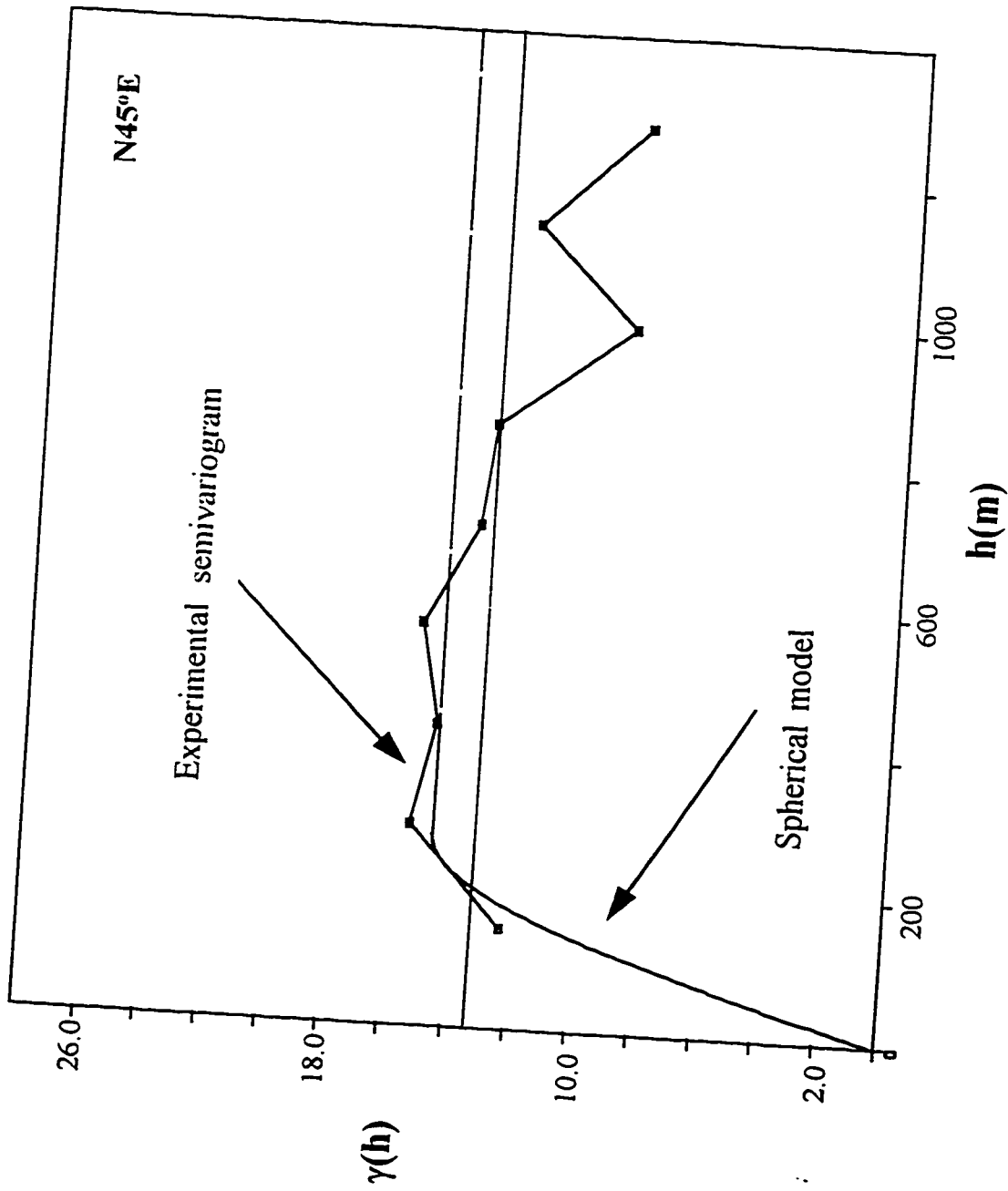


Figure 6.13 Horizontal semivariogram for  $P_2O_5$  % in Horizon 3 along N45°E direction and the fitted spherical model.

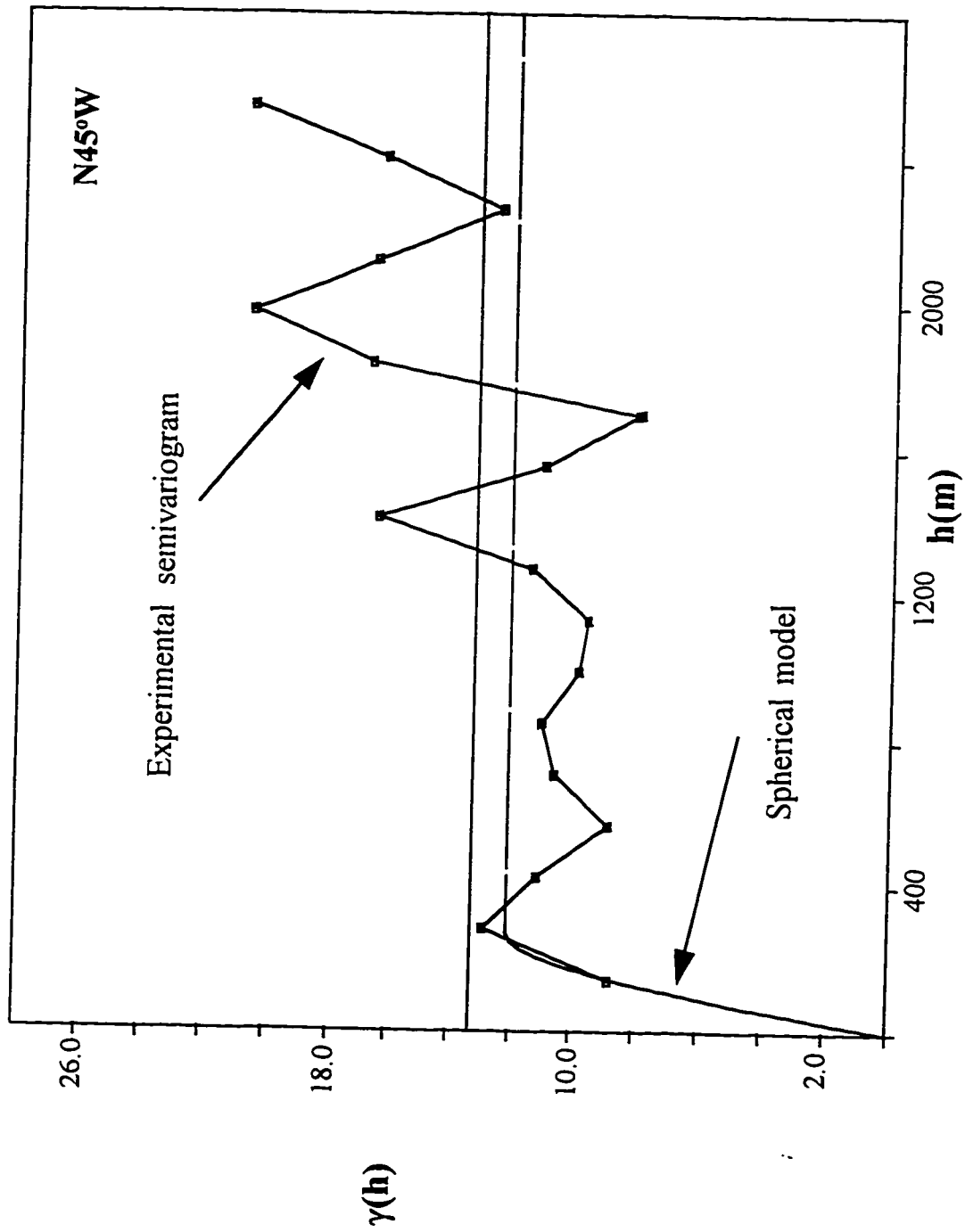


Figure 6.14 Horizontal semivariogram for  $P_2O_5$  % in Horizon 3 along N45°W direction and the fitted spherical model.



Table 6.2 Parameters of horizontal semivariograms for  $P_2O_3$  % in Horizon 3

| PARAMETERS | N45°E                 | N45°W                 |
|------------|-----------------------|-----------------------|
| a          | 230 m                 | 230 m                 |
| $C_0$      | 14.4 (%) <sup>2</sup> | 14.4 (%) <sup>2</sup> |
| C          | 12.0 (%) <sup>2</sup> | 12.0 (%) <sup>2</sup> |

## **CHAPTER 7**

# **LOCAL ESTIMATION AND GRADE-TONNAGE RELATIONSHIP**

### **7.1 Introduction**

Two types of geostatistical methods are commonly adopted for the estimation of mineral deposits. These are the global estimation and local estimation methods described in detail in geostatistical literature. Local estimation method has been employed to estimate  $P_2O_5$  % in this study. Based on the estimates derived from this method, the grade-tonnage relationship for the deposit has been determined.

Brief outline of the local estimation will be given in the following section. This will be followed by the application of this method to the Hazm Al-Jalamid phosphorite deposit, and the derivation of grade-tonnage curves.

## 7.2 Local Estimation

Geostatistical local estimation method is widely known as *kriging* after Dr. Krige who published the pioneering work in early 1960's. This method provides Minimum Variance Unbiased Estimate (MVUE) of the variable values. The estimate is referred to as the *kriged estimate*, while the variance is called *kriging variance*. The kriged estimate is derived by assigning weighting factors to the sample values. The magnitude of the factors depends on both the geostatistical characteristics of variable under consideration and the geometrical relationship between samples used in estimation and the point or block to be estimated. The kriging variance is used to measure the reliability of the estimate. The lower the kriging variance the more reliable the estimates (Sahin, 1994).

### 7.2.1 Block Kriging

Let  $x_1, x_2, \dots, x_n$  be sample grades to be used to estimate the grade of a block whose true and estimated values are  $Z$  and  $Z^*$  respectively. The estimate is given by:

$$Z^* = \sum_{i=1}^n \lambda_i x_i \quad (7.1)$$

where  $\lambda_i$ 's are the weighting coefficients assigned to the samples. The main problem in kriging is the calculation of  $\lambda_i$ 's under the following conditions:

1. The estimator,  $Z^*$ , must be unbiased, i.e.  $E[Z - Z^*] = 0$

This condition implies that the sum of the weights is equal to unity.

2. The estimation variance must to be minimum, i. e.  $E[Z-Z^*]^2$

The estimation variance can be expressed as follows:

$$E[Z-Z^*]^2 = E[Z]^2 - 2E[ZZ^*] + [Z^*]^2$$

Now, substituting the value of  $Z^*$  from Equation (7.1) leads to:

$$\begin{aligned} E[Z-Z^*]^2 &= E[Z]^2 - 2E[Z \sum \lambda_i x_i] + E[\sum \sum \lambda_i \lambda_j x_i x_j] \\ &= \sigma_z^2 - 2 \sum \lambda_i \sigma_{zx_i} + \sum \sum \lambda_i \lambda_j \sigma_{x_i x_j} \end{aligned} \quad (7.2)$$

Where  $\sigma_z^2$  represents the variance of sample within the block and  $\sigma_{x_i x_j}$  the average value of covariance function  $\sigma(h)$  when two extremities of the vector  $h$  is located at point  $x_i$  and  $x_j$  respectively.

According to Lagrange principle, the minimization of estimation variance under the constrain  $\sum \lambda_i = 1$ , amounts to minimization of

$$F = E[Z-Z^*]^2 - 2\mu(\sum \lambda_i - 1) \quad (7.3)$$

where  $\mu$  is the Lagrange multiplier.

Substituting the value of the first term given in Equation (7.2), the Equation (7.3) can be written as:

$$F = \sigma_z^2 - 2 \sum \lambda_i \sigma_{zx_i} + \sum \sum \lambda_i \lambda_j \sigma_{x_i x_j} - 2\mu(\sum \lambda_i - 1) \quad (7.4)$$

The unknowns (i.e.  $\lambda_i$ 's and  $\mu$ ) are determined by partial differentiation of Equation (7.4) as follows:

$$\delta F / \delta \sum \lambda_i = -2\sigma_{xx} + 2\sum \sigma_{xx_{ij}} - 2\mu = 0 \quad (7.5)$$

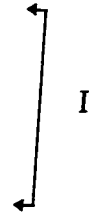
and

$$\delta F / \delta \mu = 2\sum \lambda_i - 2 = 0 \quad (7.6)$$

The Equations (7.5) and (7.6) can be arranged to give the following linear system of  $n + 1$  equations with  $n + 1$  unknowns referred as the *Kriging system*:

$$\sum \lambda_j \sigma_{xx_{ij}} - \mu = \sigma_{xx_i} \quad (i = 1, 2, 3, \dots, n)$$

$$\sum \lambda_i = 1$$



Multiplying the both sides of the first equation by the  $\sum \lambda_i$  gives

$$\sum \sum \lambda_i \lambda_j \sigma_{xx_{ij}} - \sum \lambda_i \mu = \sum \lambda_i \sigma_{xx_i} \quad (7.7)$$

However, as  $\sum \lambda_i = 1$ , the Equation (7.7) reduces to

$$\sum \sum \lambda_i \lambda_j \sigma_{xx_{ij}} = \sum \lambda_i \sigma_{xx_i} + \mu \quad (7.8)$$

Substituting this value in the Equation (7.3) will give the minimum estimation variance referred to as kriging variance (i. e.  $\sigma_k^2$ )

$$\begin{aligned}
 \sigma_k^2 &= \sigma_z^2 - 2 \sum \lambda_i \sigma_{z_{xi}} + \sum \lambda_i \sigma_{z_{xi}}^2 + \mu \\
 &= \sigma_z^2 - \sum \lambda_i \sigma_{z_{xi}}^2 - \mu
 \end{aligned}
 \tag{7.9}$$

The kriging system can be expressed in terms of the semivariogram function. This step requires substitution of semivariogram values for the covariance in the first expression in system I, i.e.

$$\sigma(h) = \gamma(\infty) - \gamma(h)
 \tag{7.10}$$

similarly,

$$\sum \lambda_j [\gamma(\infty) - \gamma_{xx_{ij}}] - \mu = \gamma(\infty) - \gamma_{xx_i}$$

$$\sum \lambda_j \gamma(\infty) - \sum \lambda_j \gamma_{xx_{ij}} - \mu - \gamma(\infty) = -\gamma_{xx_i}
 \quad (\text{where } \sum \lambda_j = 1)$$

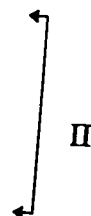
and,

$$\sum \lambda_j \gamma_{xx_{ij}} + \mu = \gamma_{xx_i}
 \tag{7.11}$$

Therefore, the kriging system, in terms of semivariogram, will be in the following form:

$$\sum \lambda_j \gamma_{xx_{ij}} + \mu = \gamma_{xx_i}
 \quad (i = 1, 2, 3, \dots, n)$$

$$\sum \lambda_i = 1$$



$$[P] [W] = [B]$$

where  $[P]$  is the matrix of semivariograms between samples

$[W]$  is the matrix of weights and Lagrange multiplier

$[B]$  is the matrix of semivariograms between samples and blocks.

i.e.

$$[P] = \begin{bmatrix} \gamma_{11} & \gamma_{12} & \dots & \gamma_{1n} & 1 \\ \gamma_{21} & \gamma_{22} & \dots & \gamma_{2n} & 1 \\ . & . & & . & . \\ . & . & & . & . \\ . & . & & . & . \\ \gamma_{n1} & \gamma_{n2} & \dots & \gamma_{nn} & 1 \\ 1 & 1 & \dots & 1 & 0 \end{bmatrix}$$

$$[W] = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ . \\ . \\ . \\ \lambda_n \\ \mu \end{bmatrix} \quad \text{and} \quad [B] = \begin{bmatrix} \gamma_{zx_1} \\ \gamma_{zx_2} \\ . \\ . \\ . \\ \gamma_{zx_n} \\ 1 \end{bmatrix}$$

The kriging variance, in terms of semivariograms, is expressed as follows:

$$\sigma_k^2 = -\gamma_z - \sum_{i=1}^n \lambda_i \gamma_{zx_i} - \mu \quad (7.12)$$

After computing the elements of matrices [P] and [B] from the model semivariogram, the linear system can be solved for  $\lambda_i$ s and  $\mu$ . Finally, the kriged estimate for the block value can be determined using expression 7.1 and the kriging variance using expression 7.12.

## 7.2.2 Application to the Hazm Al-Jalamid Deposit

### *Kriging for Horizon 1*

The block kriging was performed for  $P_2O_5$  % in Horizon 1 using a block dimension of 1000m x 500m x 0.5m (Figure 7.1). This provided both the kriged estimate of  $P_2O_5$  % within each block and the associated kriging standard deviation. Considering 33 meters maximum thickness, the horizon was divided into 66 levels each having 0.5 m thickness.

Based on the geostatistical parameters revealed from the semivariogram model, the block kriging was carried out using **KRIGE3** module (GEOSTAT package, 1992). The input data file used for the kriging program contains X, Y, and Z coordinates in meters



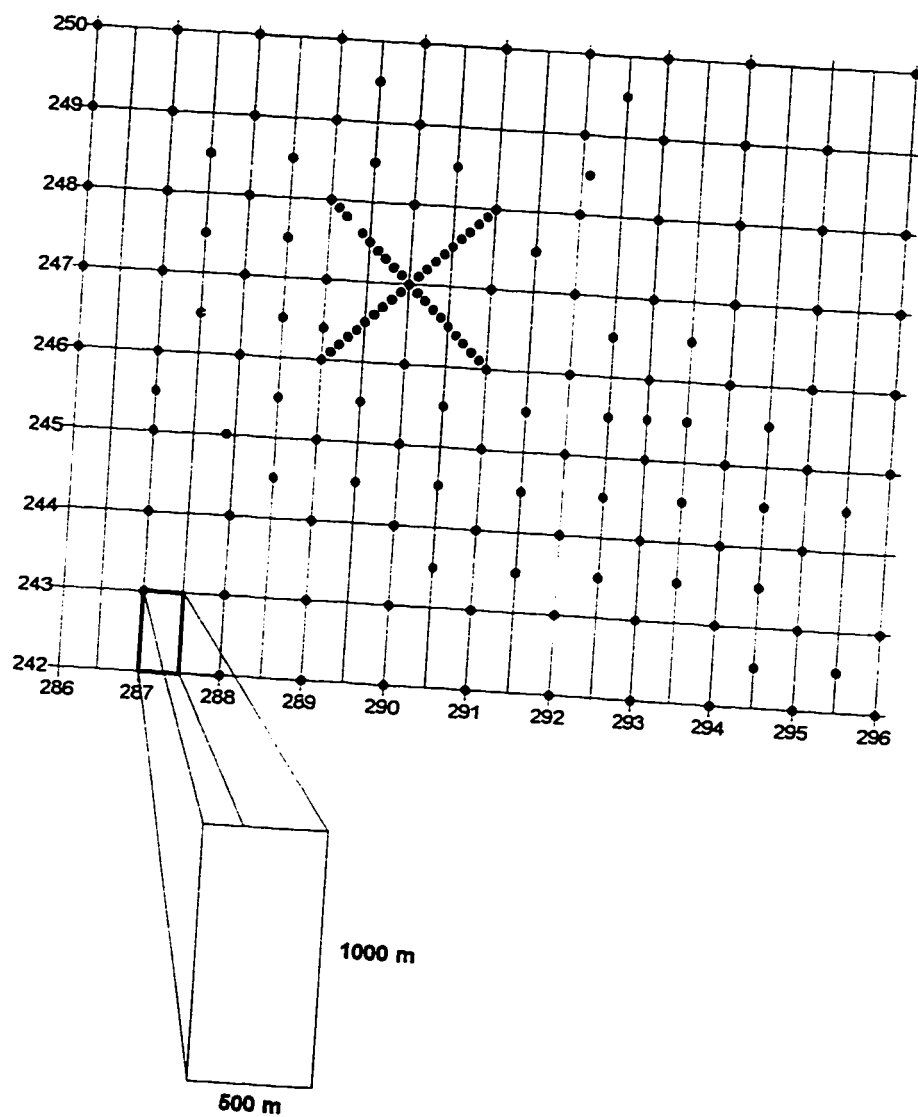


Figure 7.1 Kriging plan used for both horizons in the study area

and the variable (i.e.  $P_2O_5$ ) values, whereas the output file contains the indices representing block coordinates, number of the samples used to kriged each block, the kriged estimates and the kriging standard deviations. An excerpt from the kriging output file is given in Appendix G.

The output file from kriging program was processed using **BLKPLT** module (GEOSTAT package 1994) to produce kriging block maps. The map for the Level number 1 is illustrated in Figure 7.2 as an example, while the whole output maps are listed in Appendix H. Each block contains three numbers: the upper number represents the kriged estimate, the intermediate one indicates the kriging standard deviation, and the lower number indicates the number of samples used to krig the block

The kriging standard deviation generally reflects the accuracy and the precision of the associated kriged estimate. Assuming normal distribution of kriged estimate, the 95 % confidence limits for the actual block value will be  $Z^* \pm 2\sigma_k$  (where  $Z^*$  is the kriged estimate and  $\sigma_k$  is the associated kriging standard deviation). By reviewing the kriging output file for Horizon 1, we can see that the majority of kriging standard deviation values fall within a range of 1.97 to 3.79. Some values slightly higher than 3.79 observed in the eastern margin of the study area. Using these values and the corresponding kriged estimates, the confidence intervals for the actual block values can be estimated.

The kriged estimates for 66 levels resulted in 1716 kriged blocks in Horizon 1. These were combined to give the total tonnage using the following expression:

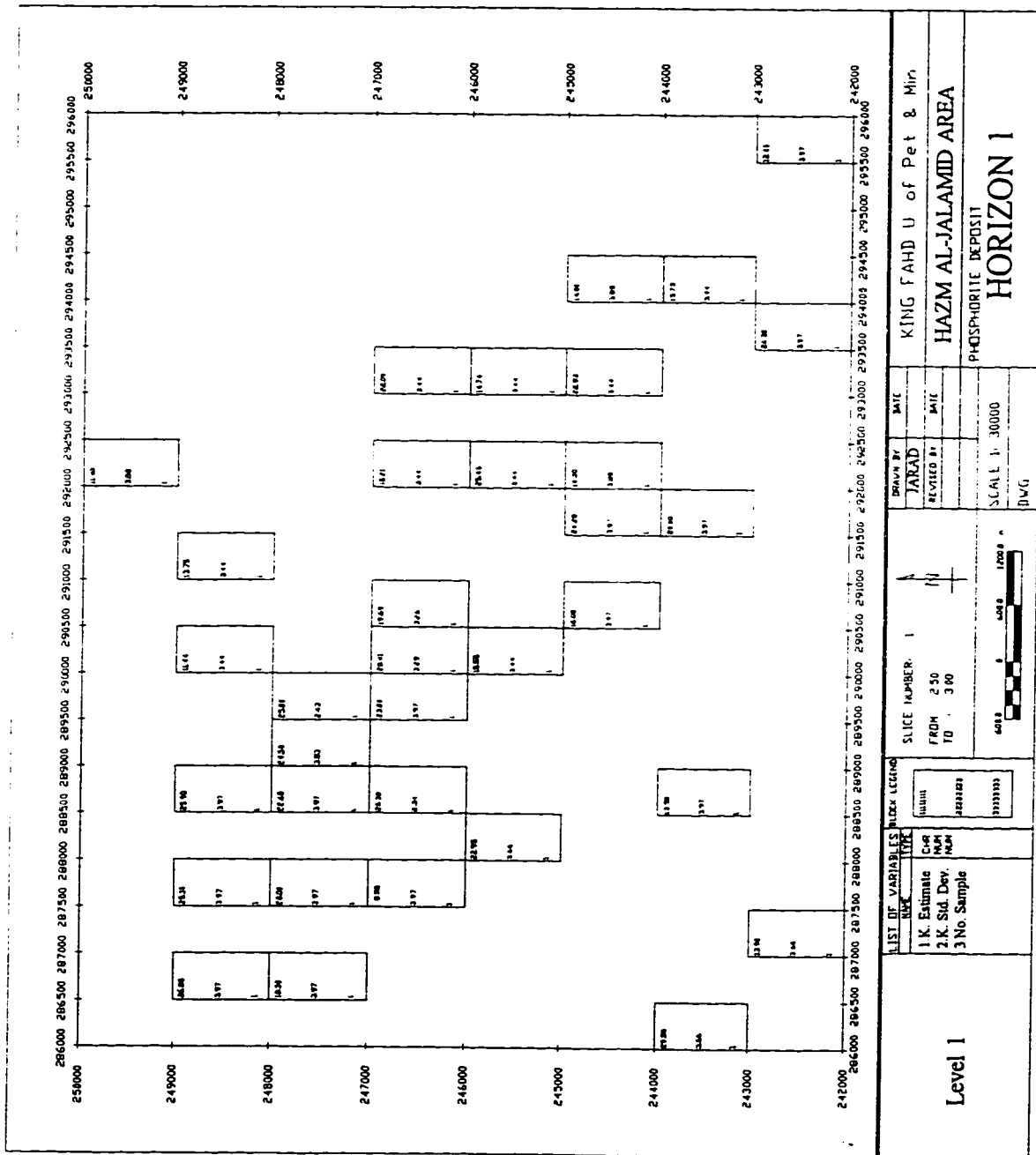


Figure 7.2 Kriging output for Level I in Horizon I

$$\text{Total tonnage} = N \times S \times T \times D, \text{ where} \quad (7.13)$$

$N$  = is the total number of kriged blocks in the 66 levels (i. e. 1716)

$S$  = is the surface area of each block (i. e. 1000m x 500m )

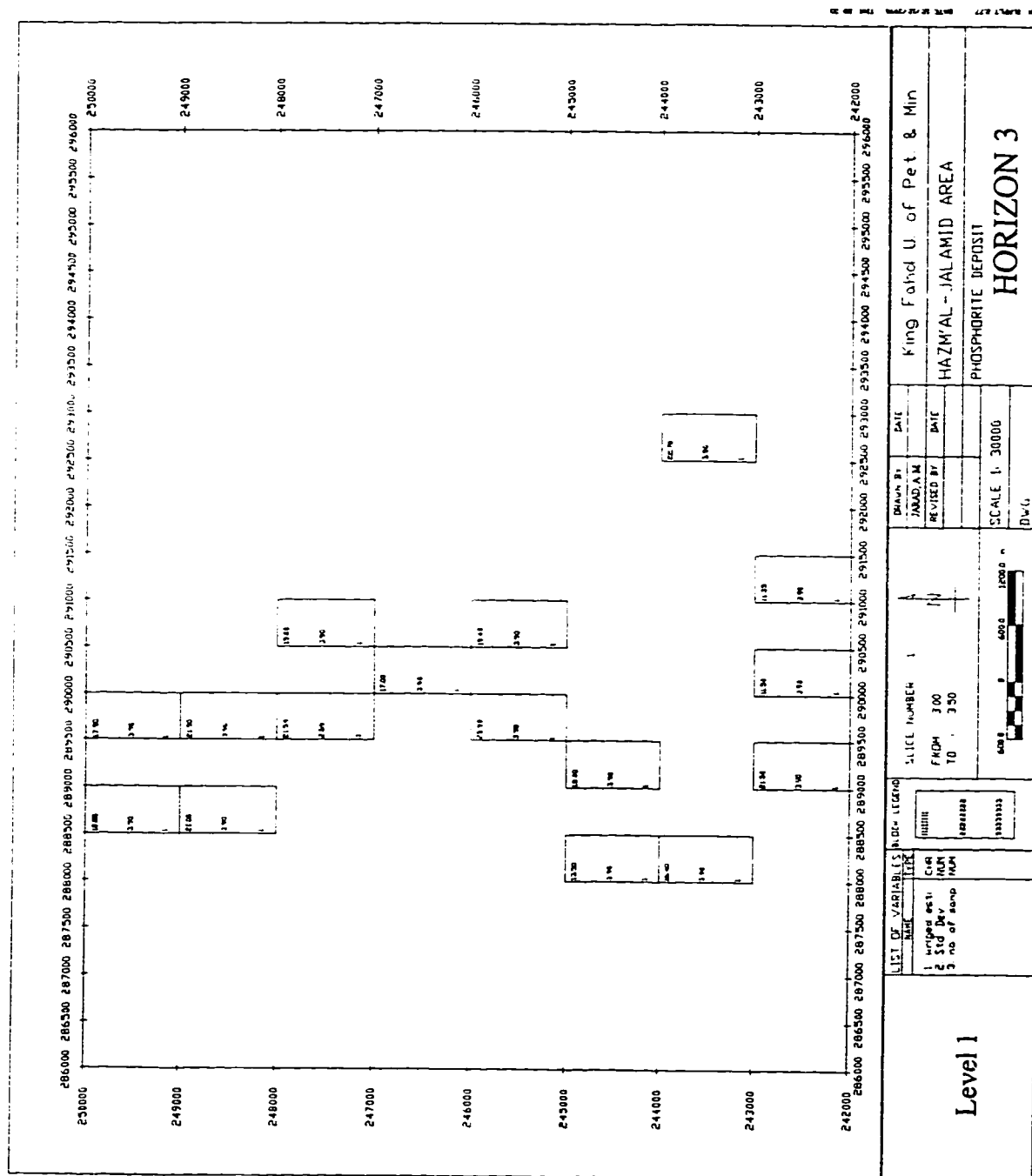
$T$  = is the thickness of each block (i. e. 0.5m)

$D$  = is the density of phosphorite (i. e. 2.35t/m<sup>3</sup>)

By substituting the above values in previous equation, the total tonnage for the phosphorite in Horizon 1 was calculated to be approximately  $1008 \times 10^6$  tonnes.

### *Kriging for Horizon 3*

The phosphorite in Horizon 3 is found within 28 meters, so this horizon was divided into 56 levels. The blocks in these levels were kriged using **KRIGE3** module and subsequently processed to produce block plots using **BLKPLT** module. The kriging output for Level 1 in Horizon 3 is illustrated in Figure 7.3, whereas the whole output maps are listed in Appendix I. A total number of 941 blocks was obtained as a result of kriging in Horizon 3. The kriging standard deviation values in this horizon fall within a range of 1.98 to 4.23. This range is almost the same as that observed in Horizon 1. However, the relatively higher values generally located randomly within the Horizon 3. This is may be due to the concentric occurrence of phosphorite in this horizon.



Using the Equation (7.13), the total tonnage of phosphorite in this horizon was found to be approximately  $553 \times 10^6$  tonnes.

### **7.3 Grade - Tonnage Relationship**

#### **7.3.1 General Introduction**

Due to the variations of grade from place to place, the mining operation are commonly performed in a selective manner. Therefore, it is more appropriate to derive a relationship between the cut-off grades and the corresponding tonnage of reserves. This relationship is called grade-tonnage relationship and expressed in a graphical form.

To derive the grade-tonnage relationship for any selective mining unit, it is essential to verify the type of distribution of the selective mining units and to determine both the mean and the variance of this distribution. The size of selective mining units depends on economical and technological conditions that vary with time and the nature of the deposit (Huijbregts, 1976).

The grade-tonnage relationship can provide the miners the tonnage of ore to be expected at different cut-off grades. Based on the forecasted tonnage derived from the curve, it is also possible to calculate returns from the mining operation (Huijbregts, 1976).

### 7.3.2 Grade-Tonnage Relationship for Hazm Al-Jalamid Deposit

Grade-tonnage relationship for both horizons were determined to reveal the tonnages of phosphorite at different cut off grades. To derive the grade-tonnage relationship for each horizon, the kriging output file for the corresponding horizon was processed using **REPORT** module (GEOSTAT package, 1994).

The results for Horizon 1 and Horizon 3 are listed in Table 7.1 and Table 7.2, respectively. The tonnage at different cut-off grades can be read directly from the tables. For example, there are  $1008 \times 10^6$  tonnes of phosphorite reserves corresponding to the  $P_2O_5$  grade of 19.62 % and  $420 \times 10^6$  tonnes of reserves corresponding to 23.75 % in Horizon 1. Table 7.1 and Table 7.2 also provide tonnages corresponding to various grade intervals with their mean grades.

The grade-tonnage curves for these horizons are illustrated in Figure 7.4 and 7.5 respectively. As it obvious from these curves, the tonnage is inversely proportional with the mean grade. The curve for Horizon 1 is almost straight line indicating relatively rapid increase in the tonnage with decrease in mean grade. In case of Horizon 3, the curve is more or less parabolic and changes in tonnage is significantly smaller at higher grades.

Table 7.1 Grade-tonnage relationship for Horizon 1

| GRADE INTERVAL |       | MEAN GRADE                      | TONNAGE                     | MEAN GRADE ABOVE LOWER LIMIT    | TONNAGE                     |
|----------------|-------|---------------------------------|-----------------------------|---------------------------------|-----------------------------|
| from           | to    | P <sub>2</sub> O <sub>5</sub> % | tonnes (x 10 <sup>6</sup> ) | P <sub>2</sub> O <sub>5</sub> % | tonnes (x 10 <sup>6</sup> ) |
| 0.00           | 10.00 | 8.59                            | 11.78                       | 19.62                           | 1008.15                     |
| 10.00          | 15.00 | 13.39                           | 162.88                      | 19.75                           | 996.37                      |
| 15.00          | 16.00 | 15.51                           | 62.90                       | 20.99                           | 833.49                      |
| 16.00          | 17.00 | 16.50                           | 68.47                       | 21.44                           | 770.58                      |
| 17.00          | 18.00 | 17.48                           | 59.47                       | 21.92                           | 702.11                      |
| 18.00          | 19.00 | 18.52                           | 57.96                       | 22.33                           | 642.65                      |
| 19.00          | 20.00 | 19.52                           | 77.22                       | 22.71                           | 584.69                      |
| 20.00          | 21.00 | 20.51                           | 87.03                       | 23.19                           | 507.47                      |
| 21.00          | 22.00 | 21.50                           | 89.35                       | 23.75                           | 420.45                      |
| 22.00          | 23.00 | 22.49                           | 82.98                       | 24.35                           | 331.10                      |
| 23.00          | 24.00 | 23.50                           | 76.62                       | 24.97                           | 248.11                      |
| 24.00          | 25.00 | 24.48                           | 65.65                       | 25.63                           | 171.50                      |
| 25.00          | 26.00 | 25.47                           | 78.62                       | 26.35                           | 105.85                      |
| 26.00          | 27.00 | 26.46                           | 31.40                       | 27.10                           | 57.23                       |
| 27.00          | 28.00 | 27.44                           | 17.05                       | 27.88                           | 25.82                       |
| 28.00          | ***** | 28.74                           | 8.77                        | 28.74                           | 8.77                        |



TABLE 7.2 Grade-tonnage relationship for Horizon 3

| GRADE INTERVAL<br>from to |       | MEAN GRADE<br>P <sub>2</sub> O <sub>5</sub> % | TONNAGE<br>tonnes (x 10 <sup>6</sup> ) | MEAN GRADE ABOVE LOWER LIMIT<br>P <sub>2</sub> O <sub>5</sub> % | TONNAGE<br>tonnes (x 10 <sup>6</sup> ) |
|---------------------------|-------|-----------------------------------------------|----------------------------------------|-----------------------------------------------------------------|----------------------------------------|
| 0.00                      | 10.00 | 8.35                                          | 0.91                                   | 17.93                                                           | 552.84                                 |
| 10.00                     | 15.00 | 13.36                                         | 102.22                                 | 17.95                                                           | 551.92                                 |
| 15.00                     | 16.00 | 15.52                                         | 56.36                                  | 18.93                                                           | 449.70                                 |
| 16.00                     | 17.00 | 16.51                                         | 65.59                                  | 19.42                                                           | 393.34                                 |
| 17.00                     | 18.00 | 17.50                                         | 73.13                                  | 20.00                                                           | 327.75                                 |
| 18.00                     | 19.00 | 18.48                                         | 65.29                                  | 20.72                                                           | 254.61                                 |
| 19.00                     | 20.00 | 19.49                                         | 53.44                                  | 21.49                                                           | 189.33                                 |
| 20.00                     | 21.00 | 20.48                                         | 43.50                                  | 22.28                                                           | 135.89                                 |
| 21.00                     | 22.00 | 21.47                                         | 32.27                                  | 23.13                                                           | 92.38                                  |
| 22.00                     | 23.00 | 22.46                                         | 19.42                                  | 24.02                                                           | 60.11                                  |
| 23.00                     | 24.00 | 23.49                                         | 14.40                                  | 24.76                                                           | 40.70                                  |
| 24.00                     | 25.00 | 27.47                                         | 11.70                                  | 25.46                                                           | 26.30                                  |
| 25.00                     | 26.00 | 25.45                                         | 7.22                                   | 26.25                                                           | 14.59                                  |
| 26.00                     | 27.00 | 26.47                                         | 4.72                                   | 27.04                                                           | 7.37                                   |
| 27.00                     | 28.00 | 27.36                                         | 1.82                                   | 28.04                                                           | 2.65                                   |
| 28.00                     | ***** | 29.51                                         | 0.83                                   | 29.51                                                           | 0.83                                   |

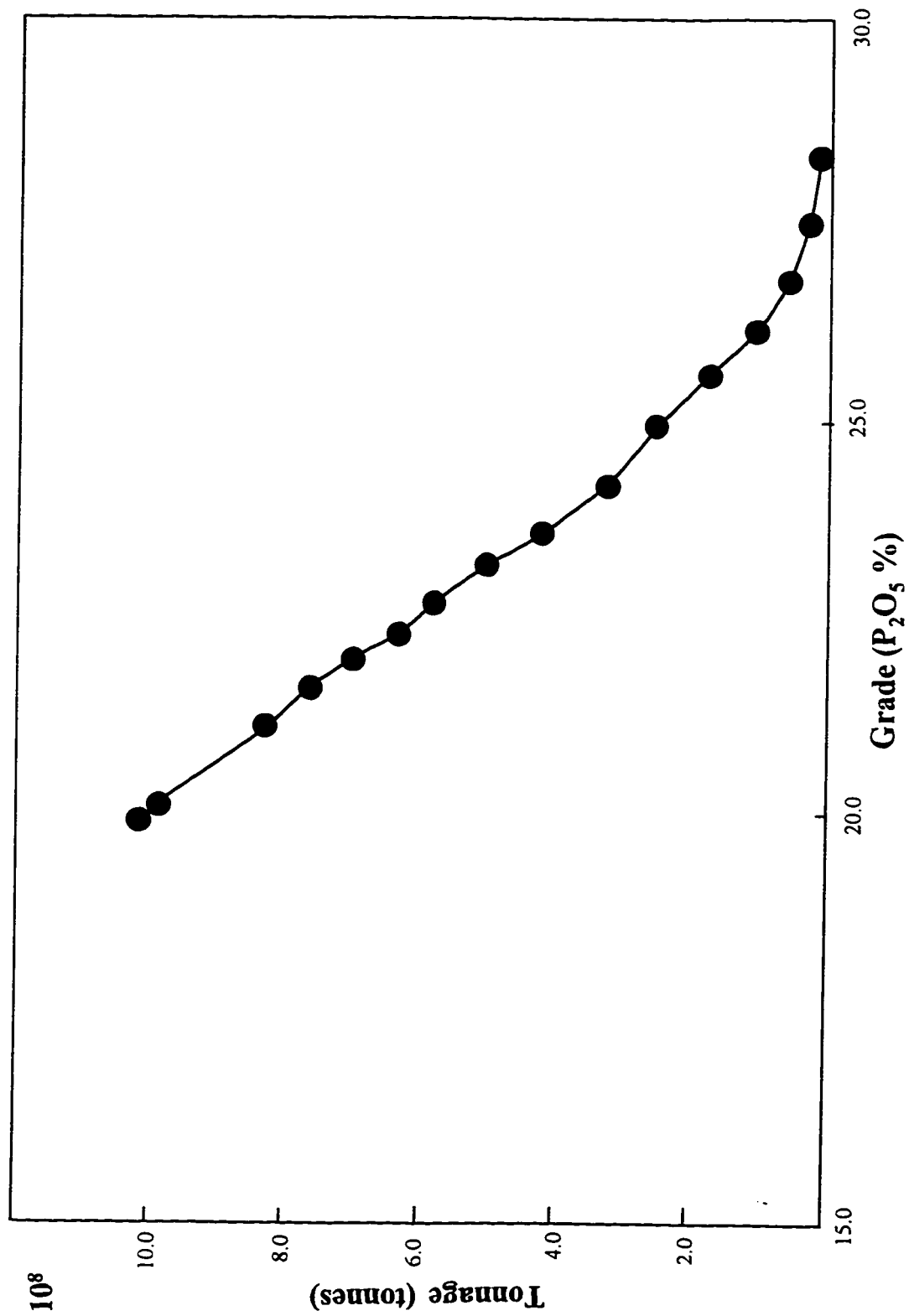


Figure 7.4 Grade-tonnage curve for Horizon 1

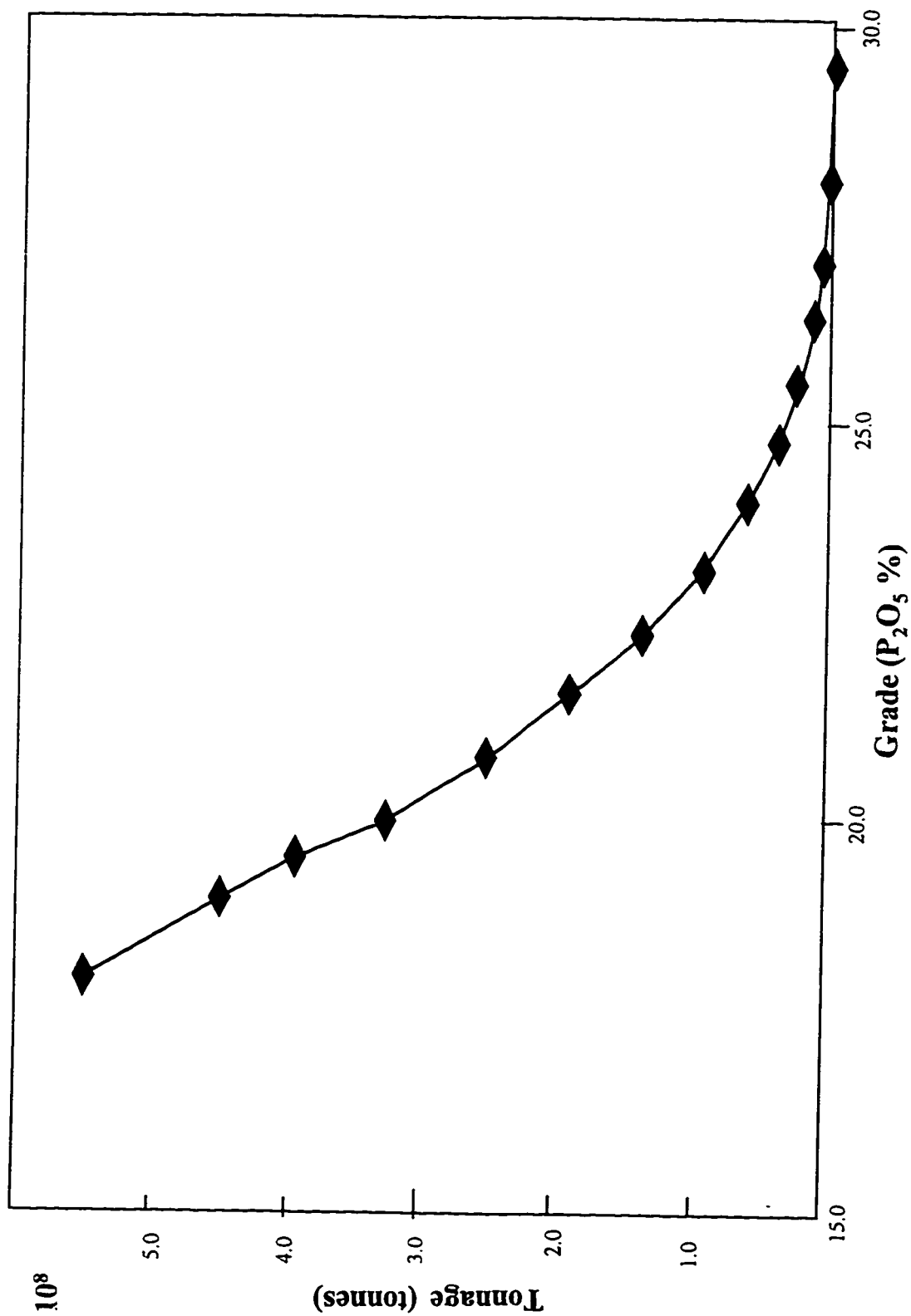


Figure 7.5 Grade-tonnage curve for Horizon 3

## **CHAPTER 8**

### **CONDITIONAL SIMULATION**

#### **8.1 Introduction**

It is essential for geologists or mining engineers to predict the fluctuations in the recoverable reserve characteristics at various stages during mining operation. This can not be completely achieved using the estimation methods such as kriging. Therefore, simulation techniques have been employed to predict such fluctuations.

In this chapter, Turning Band method of conditional simulation technique was employed to produce several realizations for the regionalized variable (i.e.  $P_2O_5$  %) in Horizon 1 and Horizon 3 individually. The results are going to be of great advantage in any planing and mining operation in the study area together with the kriging maps produced in the previous chapter.

#### **8.2 Review of Conditional Simulation Techniques**

Two types of geostatistical simulation techniques are available. These are non-conditional and conditional simulation techniques. The later differs from the former



Several techniques of conditional simulation have been described in the geostatistical literature (Dowd, 1992 and Srivastava, 1994). These include Turning Band (TB), Gaussian Sequential Simulation (GSS), Sequential Indicator Simulation (SIS), Fractal Simulation (FS) and Boolean Simulation (BS). A brief review of Turning Band method, which has been used in this study, is given in the following paragraphs.

### **8.3 Turning Band Method**

The Turning Band Method is one of the earliest efficient and popular simulation algorithms. It was introduced in the 1970's by Matheron and later modified by other geostatisticians. The idea behind the turning band method is to reduce all-two or three-dimensional simulations to the sum of several one dimensional simulations. This method originally consists of simulating a random function with a given one dimensional covariance along 15 lines which make a fixed size partition of the space. A systems of bands of constant thickness perpendicular to the line is defined along each line. Each node of 3-dimensional grid belongs to 15 bands of which the contributions are summed up.

Based on the work of Dowd (1994), the theoretical background of this method is summarized as follow:

Consider the line  $l$  in the three dimensional space  $R^3$  in Figure 8.1. Let  $x_l$  be the projection of any point  $x$  on the line  $l$  and let  $Y(x_l)$  be a one-dimensional, second order stationary, random function defined on  $l$  with zero expectation and dimensional covariance function  $C_l(h_l)$ .

The three-dimensional random function defined by  $Z(x) = Y(x_l) \forall x \in R^3$  is second order stationary with zero expectation and a three dimensional covariance function given by:

$$E[Z(x) Z(x+h)] = E[Y(x_l) Y(x_l+h)] = C_l(h_l)$$

The projection of points  $x$  on the line  $l$  is better shown in Figure 8.2.

Realizations  $y(x_l)$  of the random function  $Y(x_l)$  are generated along the line  $l$ . At all points  $x_l$  on  $l$ , a plane is constructed at right angles to  $l$  and all points  $x$  on this plane are assigned to value  $y(x_l)$ . In practice it is impossible to generate continuous realizations of  $y(x_l)$  on  $l$ , so instead the line is divided into a number of small intervals (b). Each interval is then assigned one realization and all points  $x$  falling within a band of  $b/2$  either side of the plane are assigned the value  $y(x_l)$ .

The procedure is illustrated in two dimensions in Figure 8.3. Values of  $y(x_l)$  are generated at each of the points  $x_i$  regularly spaced at interval  $b$  on the line  $l$ . The intervals (or bands) are projected at right angles into the two-dimensional space. Grid point 1 receives the value  $y(x_2)$ , grid points 2 and 7 receive the value  $y(x_3)$  and so on.

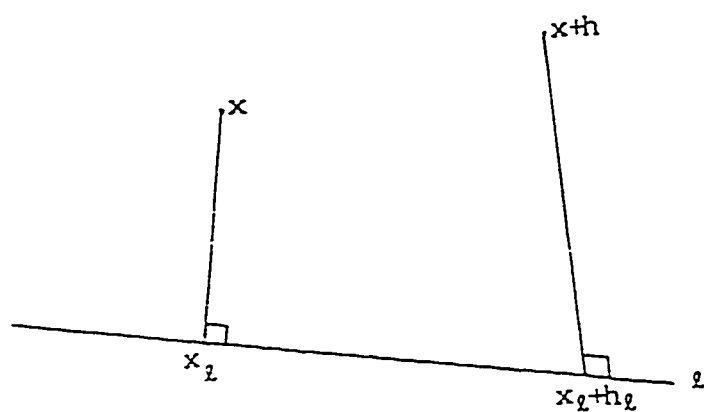


Figure 8.1 Line  $l$  in the three-dimensional space  $R^3$  (after Dowd, 1994)

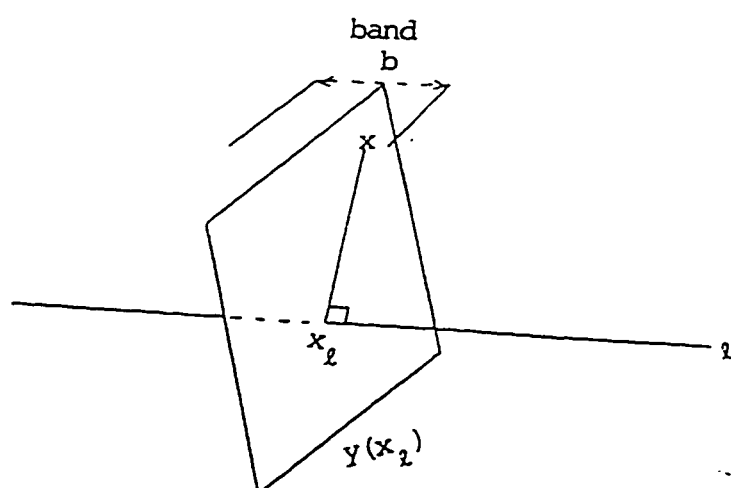


Figure 8.2 The projection of point  $x$  on the line  $l$  (after Dowd, 1994)





Figure 8.3 Diagram illustrating Turning Band Simulation in two-dimensions (after Dowd, 1994)

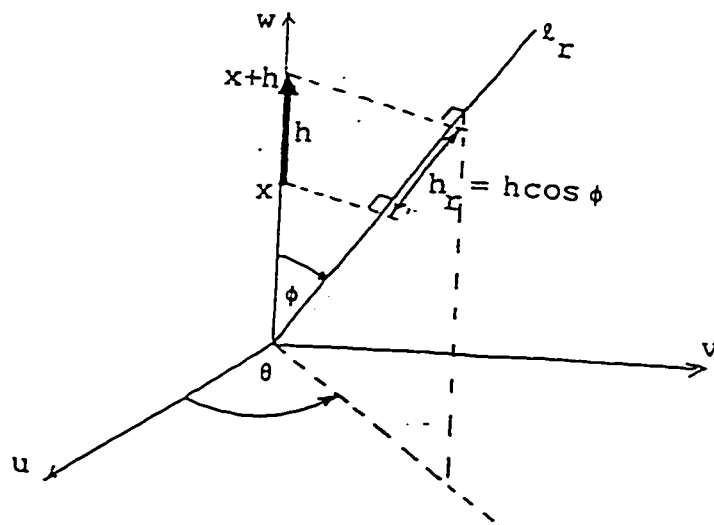


Figure 8.4 Diagram illustrating Turning Band Simulation in three-dimensions (after Dowd, 1994)

Let us consider  $n$  lines  $l_1, l_2, \dots, l_n$  which cover the three-dimensional space in a uniform manner, this can be achieved by defining the directions of the lines by a uniform selection of the radii of a unit sphere.

A one-dimensional random function  $Y(x_l)$  is defined on each line  $l_i$ ; the  $Y(x_l)$  all have zero expectation, the same covariance function  $C_l(h_{l_i})$  and are independent. Let  $x_{l_i}$  be the projection of any point  $x$  on the line  $l_i$  and  $z_i(x)$  the three-dimensional random function defined by  $Z_i(x) = Y(x_{l_i})$ ,  $\forall x \in R^3$ . There are then  $n$  random function  $z_i(x)$ ,  $i = 1, 2, \dots, n$  defined at each point  $x$  in the three dimensional space. These random functions can be summed to provide another random function  $z_s(x)$ ,  $x \in R^3$ :

$$z_s(x) = \sum_{i=1}^n z_i(x)$$

which is second order stationary. It has zero expectation and a covariance function given by:

$$C_3(h) = E[z_s(x) z_s(x+h)]$$

As  $n \rightarrow \infty$   $C_3(h)$  tends toward the isotropic covariance:

$$C_3(h) = \int_{1/2 \text{ unit sphere}} C_l(h_r) dr$$

In Figure 8.4 the axes have been chosen so that the vertical axis coincides with the vector  $h$ ; the line is defined by the angle  $\theta$  and  $\phi$  and all radii of a half unit sphere can be obtained by rotating the line  $l_i$  through  $360^\circ$  in  $u$ - $v$  plane ( $0 \leq \theta \leq 2\pi$ ) and through  $90^\circ$  in the vertical ( $0 \leq \phi \leq \pi/2$ ).  $C_3(h)$  can be then expressed as:

$$C_3(h) = \int_0^{2\pi} d\theta \int_0^{\pi/2} C_1(/h \cos \phi/) \sin \phi d\phi$$

putting  $u = /h \cos \phi/$  gives

$$C_3(h) = \int_0^{2\pi} d\phi \int_0^h C_1(u) du/h$$

$$= 2\pi/h \int_0^h C_1(u) du$$

which can be inverted to give:

$$C_1(h) = 1/2\pi d/dh h C_3(h) \quad (8.2)$$

It is impossible to generate an infinite number of lines  $l_i$ . A practical alternative is to define the lines as those joining the mid-points of the opposite edges of a regular polyhedron (Dowd, 1994). The regular polyhedron with the largest number of edges (and thus the number of such lines) is the icosahedron shown in Figure 8.5.

Since icosahedron has 30 edges, there are 15 lines joining the mid-points of these edges. Therefore, each point  $x$  in  $R^3$  is assigned the sum:

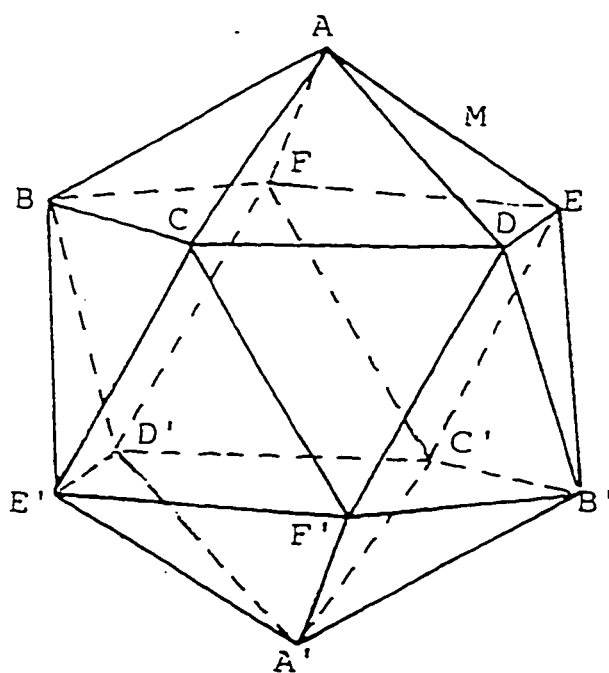


Figure 8.5 Icosahedron

$$z_s(x) = \sum_{i=1}^{15} z_i(x)$$

and the corresponding covariance is:

$$C^*(h) = \sum_{i=1}^{15} C_i(h_i)$$

instead of the theoretical covariance

$$C(h) = 2\pi h \int_0^h C_1(u) du$$

It is very difficult to determine a theoretical expression for  $C^*(h)$  and thus evaluate the bias due to the discrete approximation. However, a simple multiplicative correction can be made by comparing the two expressions for the case when  $C_1(h)$  is a constant (Dowd, 1994):

$$C^*(h) = 15t$$

$$C(h) = 2\pi t$$

$$\text{and thus } C^*(h) = 15 C(h) / 2\pi \quad (8.3)$$

## 8.4 Application to the Hazm Al-Jalamid Phosphorite Deposit

To perform a conditional simulation using Turning Band methods, several steps are necessary. The block kriging using the actual values is considered as the first step. This is followed by the non-conditional simulations for the kriged values. The blocks are then kriged using the simulated values produced from the non-conditional simulation process. This is followed by the derivation of conditional simulation using the basic expression given earlier. These steps were implemented to conduct the conditional simulation for both horizons in the study area.

To perform simulation, each horizon was divided into blocks with 50m x 50m x 0.5 dimensions. These blocks were non-conditionally simulated using **SIM3** module (GEOSTAT package, 1992). A huge output file containing the X, Y indices, level number and a simulated variable value for each block was generated. This file was subsequently processed using **SIMC3** module (GEOSTAT package, 1992) to produce conditionally simulated values. An excerpt for the final output file is given in Appendix J.

For Horizon 1, 66 levels were conditionally simulated producing a total  $2.2 \times 10^6$  blocks, while in Horizon 3, 56 levels were simulated producing  $1.79 \times 10^6$  blocks. Conditionally simulated values of  $P_2O_5$  % was derived for each of these blocks.

The output files obtained from the conditional simulation program contained huge data set (consist of 2.2 millions for Horizon 1 and 1.79 millions for Horizon 3).

Therefore, it was not possible to process these files using GEOSTAT utility programs so that it can be presented in the form of maps. To overcome this problem, the above - mentioned files were processed in the Remote Sensing Center (RSC) at the Research Institute (KFUPM) using the computer program employed for the processing of satellite images. Each block is assumed as a pixel and the simulated values assigned to the blocks are sorted in the color scale from 1 to 256. Finally, the simulation maps representing various levels for both horizons were prepared. The processing of the simulation output this way has other advantages including filtering of data before the construction of maps.

Examples of the conditional simulations for both levels are illustrated in Figure 8.6 and Figure 8.7, while the selected simulation maps representing the two horizons are presented in Appendices K and L. The conditional simulation maps for Horizon 1 show the general trend of the high grade phosphorite occurrence within the synclinal structure with NW-SE orientation. On the other hand, the simulation maps for Horizon 3 indicate more random distribution of high and low grade values with the same general trend. As it was expected, the variations in  $P_2O_5$  % are reproduced using the conditional simulation and are smoothed out using kriging. This can be seen by comparing the corresponding kriging and the simulation output maps presented in the appendices. It was also noticed in both horizons that some low concentrations of  $P_2O_5$  occur in the synclinal structure and exhibit the same trend with high  $P_2O_5$  concentrations. This confirms the presence of a paleo-highs and a paleo-lows within the syncline.

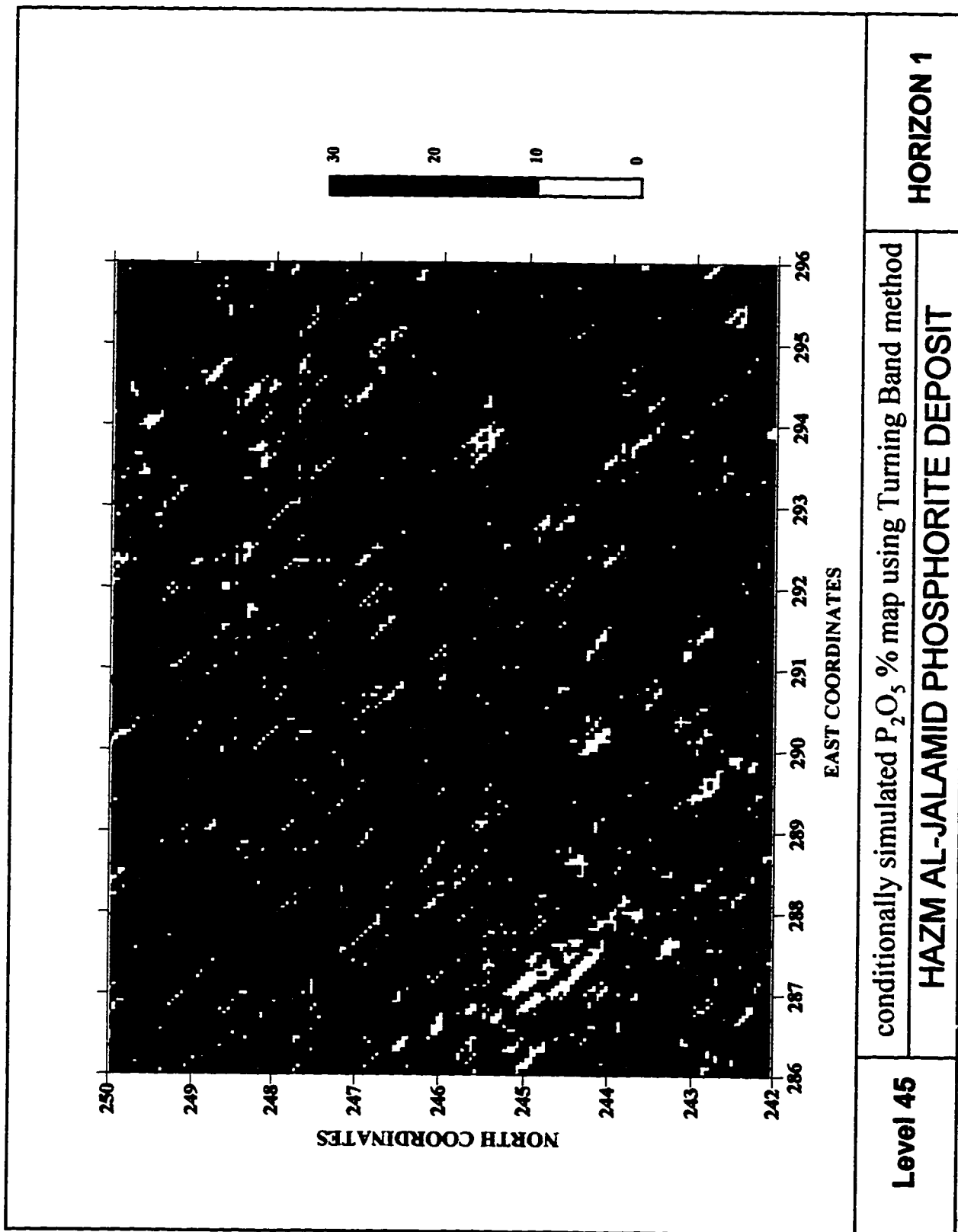


Figure 8.6 Conditionally simulated  $P_2O_5$  % map for Level 45 (Horizon 1)



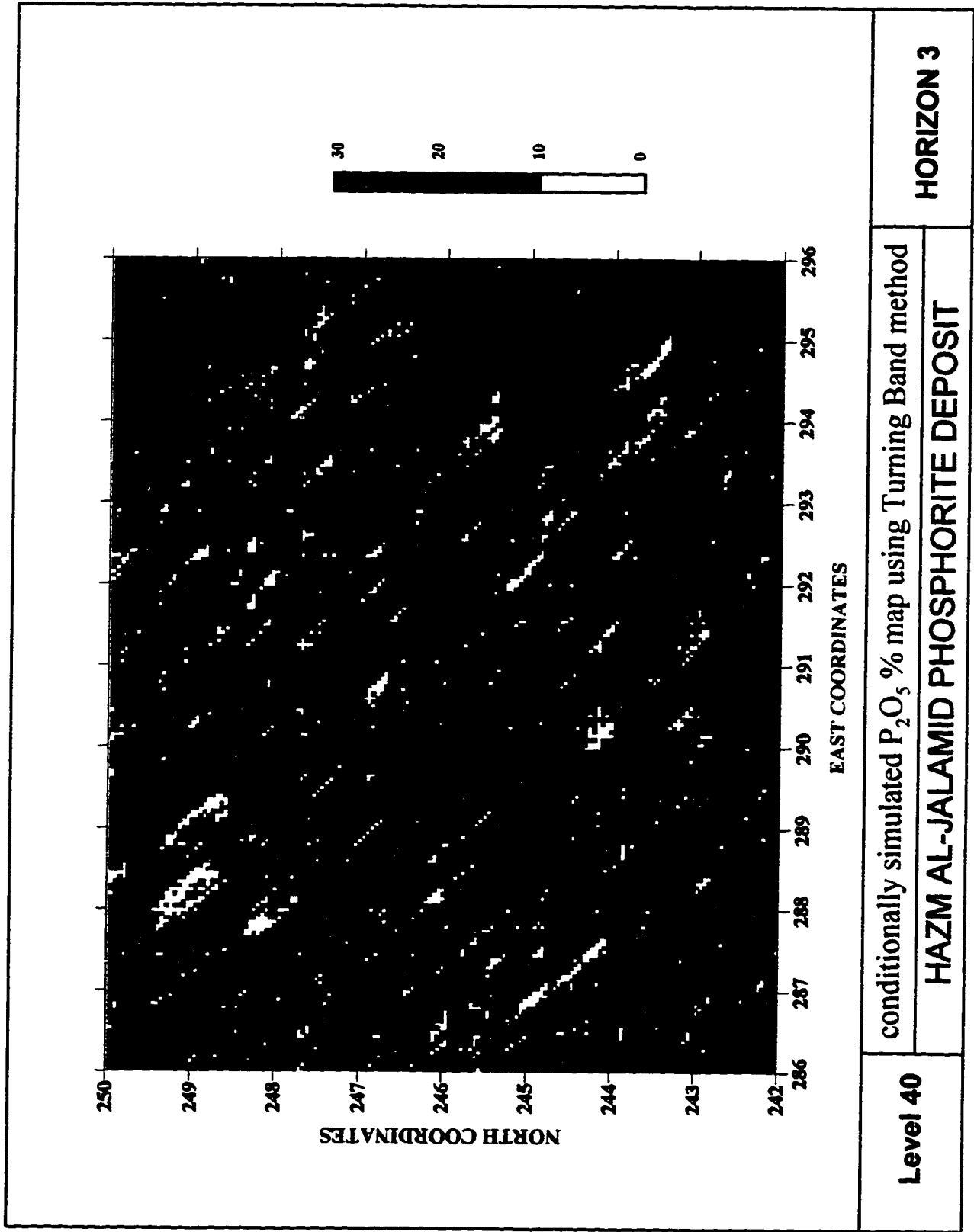


Figure 8.6 Conditionally simulated  $P_2O_5$  % map for Level 40 (Horizon 3)

## **CHAPTER 9**

### **SUMMARY AND CONCLUSIONS**

The phosphorite occurrences in the Sirhan-Turayf Basin are considered to be part of the Late Cretaceous-Early Paleogene phosphogenic province that extends from Morocco to Iraq. The restricted to semi-restricted shallow marine phosphorite deposit in the Hazm Al-Jalamid area has been dated as the Paleocene age (Heersian for Horizon 1 and Landenian for the Horizon 3). This deposit occurs in two horizons separated by a low grade phosphatic chalky limestone (Horizon 2). This study was essentially aimed to evaluate and to estimate the reserves in Horizon 1 and Horizon 3 using geostatistical techniques.

The main conclusions drawn from this study can be listed as follow:

1. Statistical analyses of  $P_2O_5$  % from two phosphorite horizons and the intermediate horizon were conducted to determine the statistical parameters and to construct the histograms and cumulative frequency curves. The histograms shows that  $P_2O_5$  % distribution for the three horizons are normal or approximately normal. The cumulative frequency curves for  $P_2O_5$  % confirm the normality of these distributions.

2. Histograms of the thickness and the accumulation for Horizon 1 show bimodal distributions, indicating the presence of two sets of thicknesses in the horizon. This is explained by the presence of lenticular structures giving rise to variable thickness values.
3. The highest mean  $P_2O_5$  grade (20.03%) is found in Horizon 1. This is followed by 17.82% and 9.72% in Horizon 3 and Horizon 2 respectively. The average thicknesses have been estimated to be 5.8m, 2.3m and 3.6m meters for Horizon 1, Horizon 2 and Horizon 3 respectively.
4. Horizontal semivariograms for Horizon 1 revealed a geometric anisotropy with the maximum range oriented  $N45^{\circ}W$  direction. This orientation is parallel to the main trend of the synclinal structure in the area.
5. Horizontal semivariogram for Horizon 3 revealed slight zonal anisotropy. The maximum sill was observed along  $N45^{\circ}E$  direction indicating greater variation in that direction. The same ranges observed in different directions are consistent with the circular to semi-circular structures appearing in this horizon.
6. Simple spherical models were found to provide best fits to the horizontal semivariograms of  $P_2O_5\%$  from both Horizon 1 and Horizon 3. Models based on

the infill drill-hole data were used in subsequent estimation and simulation of the study area.

7. Due to the large spacing between the drill-holes, it was difficult to detect the spatial structure from semivariograms based on the original drill-hole data. Therefore, the infill drilling data has been used. This suggests that further infill drilling data may prove useful in evaluation of the area. Suggested drilling program should take into consideration semivariogram ranges in different directions. Also, considering the fact that almost all the drill-holes located outside the syncline are generally worthless, it is advisable to restrict such drilling program to the synclinal structure present in the area
8. Simple kriging was adopted to estimate  $P_2O_5\%$  in both horizons. Each horizon was divided into blocks with 1000m x 500m x 0.5m dimensions. A total of 1716 blocks was kriged in Horizon 1 and 995 blocks in the Horizon 3. The total reserves were found to be  $1008 \times 10^6$  tonnes and  $553 \times 10^6$  tonnes in Horizon 1 and Horizon 3 respectively.
9. Kriging block maps for levels in Horizon 1 indicate the concentration of blocks in the synclinal structure with  $N45^\circ W$  trend. On the other hand, the kriging block maps for Horizon 3 generally match with the circular to semi-circular structures present in this horizon.

10. Turning Band technique was employed to derive conditionally simulated values of  $P_2O_5\%$  within both horizons. As it was expected, simulation results show more variability than the kriging results.

11. The simulation maps for Horizon 1 revealed relatively high grade phosphorite occurrence within the synclinal structure with NW-SE orientation. The simulation maps for Horizon 3 indicate more random distribution of high and low grade values with the same general trend.

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## **APPENDIX A**

An excerpt from the original data file

| From  | To    | Lithology | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | MgO   | CaO   | U <sub>3</sub> O <sub>8</sub> | P <sub>2</sub> O <sub>5</sub> | N-Coord | E-Coord | Elevation |
|-------|-------|-----------|------------------|--------------------------------|--------------------------------|-------|-------|-------------------------------|-------------------------------|---------|---------|-----------|
| 5.50  | 6.00  | Tjt       | 7.20             | 0.50                           | 0.06                           | 6.90  | 42.00 | 23.00                         | 17.30                         | 247.40  | 290.40  | 783.00    |
| 6.00  | 6.50  | Tjt       | 12.60            | 0.60                           | 0.08                           | 38.50 | 14.30 | 20.00                         | 14.30                         | 247.40  | 290.40  | 783.00    |
| 6.50  | 7.00  | Tjt       | 6.80             | 0.20                           | 0.07                           | 10.40 | 39.30 | 19.00                         | 14.40                         | 247.40  | 290.40  | 783.00    |
| 7.00  | 7.50  | Tjt       | 1.40             | 0.20                           | 0.04                           | 11.30 | 39.90 | 12.00                         | 15.50                         | 247.40  | 290.40  | 783.00    |
| 7.50  | 8.00  | Tjt       | 1.10             | 0.40                           | 0.04                           | 11.20 | 40.80 | 24.00                         | 16.70                         | 247.40  | 290.40  | 783.00    |
| 8.00  | 8.50  | Tjt       | 0.50             | 0.30                           | 0.04                           | 12.30 | 40.10 | 25.00                         | 15.70                         | 247.40  | 290.40  | 783.00    |
| 8.50  | 9.00  | Tjt       | 2.60             | 0.60                           | 0.14                           | 13.00 | 39.20 | 27.00                         | 12.60                         | 247.40  | 290.40  | 783.00    |
| 9.00  | 9.50  | Tjt       | 10.10            | 0.50                           | 0.07                           | 10.60 | 36.90 | 10.00                         | 9.10                          | 247.40  | 290.40  | 783.00    |
| 9.50  | 10.00 | Tjt       | 1.40             | 0.20                           | 0.09                           | 13.40 | 39.10 | 12.00                         | 13.30                         | 247.40  | 290.40  | 783.00    |
| 10.00 | 10.50 | Tjt       | 1.30             | 0.30                           | 0.11                           | 11.30 | 41.20 | 21.00                         | 14.00                         | 247.40  | 290.40  | 783.00    |
| 10.50 | 11.00 | Tjt       | 4.60             | 0.30                           | 0.03                           | 7.60  | 42.90 | 25.00                         | 19.10                         | 247.40  | 290.40  | 783.00    |
| 11.00 | 11.50 | Tjt       | 4.40             | 1.10                           | 0.10                           | 4.80  | 45.00 | 15.00                         | 14.40                         | 247.40  | 290.40  | 783.00    |
| 11.50 | 12.00 | Tjt       | 11.00            | 0.80                           | 0.11                           | 7.30  | 39.50 | 5.00                          | 10.70                         | 247.40  | 290.40  | 783.00    |
| 12.00 | 12.50 | Tjt       | 2.40             | 0.10                           | 0.15                           | 5.80  | 46.00 | 17.00                         | 18.60                         | 247.40  | 290.40  | 783.00    |
| 12.50 | 13.00 | Tjt       | 2.30             | 0.20                           | 0.12                           | 8.60  | 44.20 | 15.00                         | 15.60                         | 247.40  | 290.40  | 783.00    |
| 13.00 | 13.50 | Tjt       | 2.60             | 0.20                           | 0.11                           | 6.60  | 46.00 | 22.00                         | 18.70                         | 247.40  | 290.40  | 783.00    |
| 13.50 | 14.00 | Tjt       | 2.30             | 0.20                           | 0.11                           | 7.50  | 45.00 | 23.00                         | 17.30                         | 247.40  | 290.40  | 783.00    |
| 14.00 | 14.50 | Tjt       | 6.70             | 0.30                           | 0.11                           | 6.00  | 44.20 | 25.00                         | 17.20                         | 247.40  | 290.40  | 783.00    |
| 14.50 | 15.00 | Tjt       | 3.60             | 0.30                           | 0.10                           | 2.70  | 48.60 | 25.00                         | 19.20                         | 247.40  | 290.40  | 783.00    |
| 15.00 | 15.50 | Tjt       | 7.40             | 0.20                           | 0.11                           | 1.80  | 48.60 | 25.00                         | 18.80                         | 247.40  | 290.40  | 783.00    |
| 15.50 | 16.00 | Tjt       | 0.40             | 0.40                           | 0.10                           | 1.00  | 53.20 | 36.00                         | 25.70                         | 247.40  | 290.40  | 783.00    |
| 16.00 | 16.50 | Tjt       | 0.90             | 0.10                           | 0.10                           | 1.10  | 51.80 | 78.00                         | 24.70                         | 247.40  | 290.40  | 783.00    |
| 16.50 | 17.00 | Tjt       | 0.60             | 0.10                           | 0.09                           | 2.60  | 50.50 | 35.00                         | 23.90                         | 247.40  | 290.40  | 783.00    |
| 17.00 | 17.50 | Tjt       | 1.50             | 0.10                           | 0.09                           | 5.90  | 46.60 | 36.00                         | 21.20                         | 247.40  | 290.40  | 783.00    |
| 17.50 | 18.00 | Tjt       | 0.50             | 0.10                           | 0.06                           | 9.90  | 42.50 | 24.00                         | 15.60                         | 247.40  | 290.40  | 783.00    |
| 18.00 | 18.50 | Tjt       | 0.50             | 0.20                           | 0.09                           | 8.00  | 45.60 | 18.00                         | 15.60                         | 247.40  | 290.40  | 783.00    |
| 18.50 | 19.00 | Tjt       | 8.80             | 0.10                           | 0.10                           | 3.50  | 45.80 | 12.00                         | 19.00                         | 247.40  | 290.40  | 783.00    |
| 19.00 | 19.50 | Tjt       | 0.90             | 0.20                           | 0.13                           | 3.30  | 50.10 | 25.00                         | 23.30                         | 247.40  | 290.40  | 783.00    |
| 19.50 | 20.00 | Tjt       | 0.60             | 0.10                           | 0.10                           | 6.30  | 46.10 | 16.00                         | 20.90                         | 247.40  | 290.40  | 783.00    |
| 20.00 | 20.50 | Tjt       | 0.80             | 0.10                           | 0.07                           | 13.50 | 39.00 | 10.00                         | 12.10                         | 247.40  | 290.40  | 783.00    |
| 20.50 | 21.00 | Tjt       | 0.40             | 0.30                           | 0.06                           | 13.10 | 39.30 | 11.00                         | 12.80                         | 247.40  | 290.40  | 783.00    |
| 27.00 | 27.50 | Kab       | 0.60             | 0.20                           | 0.04                           | 15.90 | 36.90 | 0.00                          | 5.00                          | 247.40  | 290.40  | 783.00    |
| 27.50 | 28.00 | Kab       | 0.60             | 0.10                           | 0.04                           | 18.30 | 34.50 | 0.00                          | 4.50                          | 247.40  | 290.40  | 783.00    |

## **APPENDIX B**

An excerpt from the master data file

| E-coord | N-coord | Depth | P <sub>2</sub> O <sub>5</sub> % | Code |
|---------|---------|-------|---------------------------------|------|
| 295     | 242     | 18.75 | 18.9                            | 111  |
| 295     | 242     | 19.25 | 22                              | 111  |
| 295     | 242     | 19.75 | 22.8                            | 111  |
| 295     | 242     | 20.25 | 16.1                            | 111  |
| 295     | 244     | 3.75  | 15.9                            | 111  |
| 295     | 244     | 4.25  | 17.8                            | 111  |
| 295     | 244     | 4.75  | 17.1                            | 111  |
| 295     | 244     | 5.25  | 17.2                            | 111  |
| 295     | 244     | 5.75  | 17.8                            | 111  |
| 295     | 244     | 6.25  | 15.1                            | 111  |
| 295     | 244     | 6.75  | 20                              | 111  |
| 295     | 244     | 7.25  | 21.2                            | 111  |
| 295     | 244     | 7.75  | 23.1                            | 111  |
| 295     | 244     | 8.25  | 19.4                            | 111  |
| 295     | 244     | 8.75  | 23                              | 111  |
| 295     | 244     | 9.25  | 23.8                            | 111  |
| 295     | 244     | 9.75  | 24                              | 111  |
| 295     | 244     | 10.25 | 23.3                            | 111  |
| 295     | 244     | 10.75 | 23.3                            | 111  |
| 295     | 244     | 11.25 | 20                              | 111  |
| 294     | 250     | 2.75  | 13.3                            | 111  |
| 294     | 250     | 3.25  | 24.1                            | 111  |
| 294     | 250     | 3.75  | 16.1                            | 111  |
| 294     | 250     | 4.25  | 20                              | 111  |
| 294     | 250     | 4.75  | 16.8                            | 111  |
| 292     | 250     | 8.75  | 15.25                           | 111  |
| 292     | 250     | 9.25  | 15                              | 111  |
| 289     | 250     | 14.75 | 16.8                            | 111  |
| 289     | 250     | 15.25 | 16.9                            | 111  |
| 289     | 250     | 15.75 | 17.6                            | 111  |
| 288     | 250     | 13.75 | 14.95                           | 111  |
| 288     | 250     | 14.25 | 23.6                            | 111  |
| 288     | 250     | 14.75 | 14.2                            | 111  |
| 286     | 250     | 17.75 | 19.3                            | 111  |
| 286     | 250     | 18.25 | 17.1                            | 111  |
| 286     | 250     | 18.75 | 21.2                            | 111  |
| 286     | 250     | 19.25 | 22.1                            | 111  |
| 286     | 250     | 19.75 | 14                              | 111  |
| 290     | 249     | 10.25 | 13.6                            | 111  |
| 290     | 249     | 10.75 | 21.3                            | 111  |
| 290     | 249     | 11.25 | 25.5                            | 111  |
| 290     | 249     | 11.75 | 24.9                            | 111  |
| 290     | 249     | 12.25 | 23.6                            | 111  |
| 290     | 249     | 12.75 | 21.5                            | 111  |
| 290     | 249     | 13.25 | 21.7                            | 111  |
| 290     | 249     | 13.75 | 21                              | 111  |
| 290     | 249     | 14.25 | 17.4                            | 111  |
| 290     | 249     | 14.75 | 17.1                            | 111  |

## **APPENDIX C**

*An excerpt from the master data file used in the statistical analysis*



| Drill-hole | # Samples | Average P <sub>2</sub> O <sub>5</sub> | Thickness | Accumulation | Code |
|------------|-----------|---------------------------------------|-----------|--------------|------|
| JAL359     | 4         | 19.95                                 | 2.00      | 39.90        | 111  |
| JAL361     | 16        | 20.13                                 | 8.00      | 161.00       | 111  |
| JAL362     | 5         | 18.06                                 | 2.50      | 45.15        | 111  |
| JAL364     | 2         | 15.13                                 | 1.00      | 15.13        | 111  |
| JAL366     | 3         | 17.10                                 | 1.50      | 25.65        | 111  |
| JAL367     | 3         | 17.58                                 | 1.50      | 26.37        | 111  |
| JAL369     | 5         | 18.74                                 | 2.50      | 46.85        | 111  |
| JAL370     | 11        | 20.18                                 | 5.50      | 111.00       | 111  |
| JAL371     | 2         | 20.30                                 | 1.00      | 20.30        | 111  |
| JAL372     | 19        | 21.84                                 | 9.50      | 207.50       | 111  |
| JAL374     | 7         | 21.39                                 | 3.50      | 74.88        | 111  |
| JAL375     | 6         | 15.03                                 | 3.00      | 45.10        | 111  |
| JAL376     | 14        | 18.46                                 | 7.00      | 129.25       | 111  |
| JAL435     | 3         | 16.15                                 | 1.50      | 24.23        | 111  |
| JAL441     | 2         | 14.98                                 | 1.00      | 14.98        | 111  |
| JAL442     | 5         | 18.18                                 | 2.50      | 45.45        | 111  |
| JAL443     | 2         | 15.90                                 | 1.00      | 15.90        | 111  |
| JAL444     | 2         | 14.75                                 | 1.00      | 14.75        | 111  |
| JAL445     | 3         | 14.85                                 | 1.50      | 22.28        | 111  |
| JAL446     | 6         | 15.43                                 | 3.00      | 46.30        | 111  |
| JAL448     | 16        | 23.09                                 | 8.00      | 184.70       | 111  |
| JAL449     | 9         | 22.74                                 | 4.50      | 102.35       | 111  |
| JAL450     | 16        | 21.70                                 | 8.00      | 173.58       | 111  |
| JAL451     | 17        | 20.77                                 | 8.50      | 176.50       | 111  |
| JAL452     | 11        | 21.95                                 | 5.50      | 120.70       | 111  |
| JAL453     | 7         | 23.80                                 | 3.50      | 83.30        | 111  |
| JAL454     | 15        | 19.02                                 | 7.50      | 142.67       | 111  |
| JAL455     | 6         | 16.43                                 | 3.00      | 49.28        | 111  |
| JAL456     | 4         | 15.13                                 | 2.00      | 30.25        | 111  |
| JAL459     | 5         | 15.70                                 | 2.50      | 39.25        | 111  |
| JAL464     | 3         | 18.87                                 | 1.50      | 28.30        | 111  |
| JAL465     | 2         | 17.30                                 | 1.00      | 17.30        | 111  |
| JAL466     | 5         | 14.29                                 | 2.50      | 35.73        | 111  |
| JAL467     | 18        | 17.24                                 | 9.00      | 155.15       | 111  |
| JAL468     | 21        | 22.70                                 | 10.50     | 238.30       | 111  |
| JAL470     | 18        | 17.79                                 | 9.00      | 160.15       | 111  |
| JAL471     | 15        | 19.94                                 | 7.50      | 149.53       | 111  |
| JAL472     | 10        | 21.45                                 | 5.00      | 107.25       | 111  |
| JAL473     | 9         | 22.88                                 | 4.50      | 102.95       | 111  |
| JAL474     | 6         | 21.28                                 | 3.00      | 63.83        | 111  |
| JAL475     | 23        | 20.53                                 | 11.50     | 236.10       | 111  |
| JAL476     | 15        | 20.89                                 | 7.50      | 156.65       | 111  |
| JAL477     | 16        | 22.66                                 | 8.00      | 181.30       | 111  |
| JAL478     | 19        | 22.14                                 | 9.50      | 210.35       | 111  |
| JAL479     | 14        | 20.71                                 | 7.00      | 144.95       | 111  |
| JAL480     | 10        | 20.00                                 | 5.00      | 99.98        | 111  |
| JAL481     | 4         | 16.13                                 | 2.00      | 32.25        | 111  |
| JAL490     | 4         | 18.35                                 | 2.00      | 36.70        | 111  |

## **APPENDIX D**

Statistical parameters of  $P_2O_5$  % in individual drill-holes

## Appendix D1

**Statistical parameters for P<sub>2</sub>O<sub>5</sub> % in individual drill-holes within Horizon 1**

| HOLE NO. | NO.SAMPLES | MEAN  | VARIANCE | ST. DEV. | C. V. | SKEW. | KURT. | MIN.  | MAX.  |
|----------|------------|-------|----------|----------|-------|-------|-------|-------|-------|
| JAL359   | 4          | 19.95 | 7.06     | 2.66     | 0.13  | -0.35 | 1.53  | 16.10 | 22.80 |
| JAL361   | 16         | 20.13 | 8.70     | 2.95     | 0.15  | -0.14 | 1.60  | 15.10 | 24.00 |
| JAL362   | 5          | 18.06 | 13.67    | 3.70     | 0.21  | 0.44  | 2.01  | 13.30 | 24.10 |
| JAL364   | 2          | 15.13 | 0.02     | 0.13     | 0.01  | 0.00  | 1.00  | 15.00 | 15.25 |
| JAL366   | 3          | 17.10 | 0.13     | 0.36     | 0.02  | 0.67  | 1.50  | 16.80 | 17.60 |
| JAL367   | 3          | 17.58 | 18.19    | 4.27     | 0.24  | 0.69  | 1.50  | 14.20 | 23.60 |
| JAL369   | 5          | 18.74 | 8.56     | 2.93     | 0.16  | -0.46 | 1.85  | 14.00 | 22.10 |
| JAL370   | 11         | 20.18 | 14.75    | 3.84     | 0.19  | -0.36 | 1.92  | 13.60 | 25.50 |
| JAL371   | 2          | 20.30 | 0.64     | 0.80     | 0.04  | 0.00  | 1.00  | 19.50 | 21.10 |
| JAL372   | 19         | 21.84 | 11.92    | 3.45     | 0.16  | -0.01 | 2.05  | 15.70 | 28.00 |
| JAL374   | 7          | 21.39 | 26.02    | 5.10     | 0.24  | -0.41 | 1.53  | 14.05 | 27.10 |
| JAL375   | 6          | 15.03 | 13.67    | 3.70     | 0.25  | -0.46 | 2.46  | 8.40  | 20.30 |
| JAL376   | 14         | 18.46 | 22.94    | 4.79     | 0.26  | 0.23  | 1.73  | 11.15 | 26.20 |
| JAL435   | 3          | 16.15 | 6.16     | 2.48     | 0.15  | -0.21 | 1.50  | 12.95 | 19.00 |
| JAL441   | 2          | 14.98 | 14.63    | 3.83     | 0.26  | 0.00  | 1.00  | 11.15 | 18.80 |
| JAL442   | 5          | 18.18 | 5.66     | 2.38     | 0.13  | -0.90 | 2.69  | 13.80 | 21.00 |
| JAL443   | 2          | 15.90 | 10.89    | 3.30     | 0.21  | 0.00  | 1.00  | 12.60 | 19.20 |
| JAL444   | 2          | 14.75 | 2.40     | 1.55     | 0.11  | 0.00  | 1.00  | 13.20 | 16.30 |
| JAL445   | 3          | 14.85 | 8.20     | 2.86     | 0.19  | 0.71  | 1.50  | 12.80 | 18.90 |
| JAL446   | 6          | 15.43 | 0.56     | 0.75     | 0.05  | -0.70 | 2.33  | 14.05 | 16.30 |
| JAL448   | 16         | 23.09 | 19.19    | 4.38     | 0.19  | -0.76 | 2.49  | 14.05 | 28.10 |
| JAL449   | 9          | 22.74 | 12.35    | 3.51     | 0.16  | -0.72 | 2.06  | 16.00 | 26.40 |
| JAL450   | 16         | 21.70 | 21.80    | 4.67     | 0.22  | -0.65 | 2.55  | 12.20 | 28.30 |
| JAL451   | 17         | 20.77 | 25.70    | 5.07     | 0.24  | -0.65 | 2.52  | 8.95  | 27.60 |
| JAL452   | 11         | 21.95 | 2.39     | 1.55     | 0.07  | 0.36  | 1.82  | 20.00 | 24.50 |
| JAL453   | 7          | 23.80 | 8.92     | 2.99     | 0.13  | -0.12 | 1.61  | 19.50 | 27.70 |
| JAL454   | 15         | 19.02 | 16.99    | 4.12     | 0.22  | -0.27 | 2.17  | 11.95 | 25.80 |
| JAL455   | 6          | 16.43 | 8.73     | 2.95     | 0.18  | 0.26  | 2.20  | 12.40 | 21.50 |
| JAL456   | 4          | 15.13 | 4.93     | 2.22     | 0.15  | 0.86  | 2.13  | 12.95 | 18.80 |
| JAL459   | 5          | 15.70 | 0.71     | 0.84     | 0.05  | -0.02 | 1.41  | 14.55 | 16.70 |
| JAL464   | 3          | 18.87 | 3.09     | 1.76     | 0.09  | 0.14  | 1.50  | 16.80 | 21.10 |
| JAL465   | 2          | 17.30 | 0.25     | 0.50     | 0.03  | 0.00  | 1.00  | 16.80 | 17.80 |
| JAL466   | 5          | 14.29 | 5.01     | 2.24     | 0.16  | 0.50  | 1.47  | 12.10 | 17.70 |
| JAL467   | 18         | 17.24 | 34.46    | 5.87     | 0.34  | -0.54 | 2.33  | 5.20  | 26.20 |
| JAL468   | 21         | 22.70 | 25.78    | 5.08     | 0.22  | -0.48 | 1.74  | 14.40 | 28.70 |
| JAL470   | 18         | 17.79 | 29.44    | 5.43     | 0.31  | 0.22  | 1.83  | 8.70  | 26.40 |
| JAL471   | 15         | 19.94 | 29.24    | 5.41     | 0.27  | -0.31 | 2.12  | 8.55  | 27.00 |
| JAL472   | 10         | 21.45 | 20.23    | 4.50     | 0.21  | -0.45 | 2.09  | 13.80 | 27.80 |
| JAL473   | 9          | 22.88 | 15.71    | 3.96     | 0.17  | -0.31 | 1.93  | 15.90 | 28.00 |
| JAL474   | 6          | 21.28 | 14.72    | 3.84     | 0.18  | -0.73 | 2.61  | 14.05 | 26.30 |
| JAL475   | 23         | 20.53 | 14.69    | 3.83     | 0.19  | -0.18 | 1.66  | 14.00 | 26.60 |
| JAL476   | 15         | 20.89 | 14.95    | 3.87     | 0.19  | -0.23 | 1.93  | 13.80 | 26.30 |
| JAL477   | 16         | 22.66 | 25.44    | 5.04     | 0.22  | -0.67 | 1.93  | 13.90 | 28.20 |
| JAL478   | 19         | 22.14 | 6.22     | 2.49     | 0.11  | -0.03 | 1.85  | 18.00 | 26.60 |
| JAL479   | 14         | 20.71 | 18.18    | 4.26     | 0.21  | -0.81 | 3.63  | 9.90  | 26.80 |

**Statistical parameters for P<sub>2</sub>O<sub>5</sub> % in individual drill-holes within Horizon 1 (contd.)**

|        |    |       |       |      |      |       |      |       |       |
|--------|----|-------|-------|------|------|-------|------|-------|-------|
| JAL480 | 10 | 20.00 | 12.79 | 3.58 | 0.18 | 0.24  | 2.41 | 13.65 | 26.40 |
| JAL481 | 4  | 16.13 | 8.09  | 2.84 | 0.18 | 0.04  | 1.05 | 13.20 | 19.40 |
| JAL490 | 4  | 18.35 | 3.79  | 1.95 | 0.11 | 0.09  | 1.35 | 16.00 | 20.90 |
| JAL491 | 20 | 19.79 | 18.18 | 4.26 | 0.22 | -0.20 | 2.13 | 11.65 | 27.20 |
| JAL492 | 20 | 19.50 | 16.83 | 4.10 | 0.21 | -0.23 | 2.71 | 10.70 | 27.00 |
| JAL493 | 20 | 18.33 | 21.55 | 4.64 | 0.25 | -0.12 | 1.92 | 8.80  | 25.00 |
| JAL494 | 7  | 19.36 | 14.08 | 3.75 | 0.19 | -0.59 | 2.17 | 12.45 | 23.60 |
| JAL495 | 6  | 20.48 | 23.87 | 4.89 | 0.24 | 0.04  | 2.02 | 13.35 | 28.30 |
| JAL496 | 6  | 17.58 | 20.02 | 4.47 | 0.25 | -1.15 | 3.06 | 8.50  | 21.90 |
| JAL497 | 5  | 16.34 | 14.75 | 3.84 | 0.24 | -1.20 | 2.83 | 9.00  | 19.60 |
| JAL498 | 6  | 22.12 | 45.98 | 6.78 | 0.31 | -0.23 | 1.53 | 12.95 | 31.00 |
| JAL499 | 18 | 15.38 | 20.99 | 4.58 | 0.30 | 0.53  | 2.44 | 9.30  | 25.00 |
| JAL500 | 12 | 13.73 | 6.87  | 2.62 | 0.19 | -0.69 | 2.32 | 8.30  | 16.80 |
| JAL501 | 11 | 20.51 | 15.11 | 3.89 | 0.19 | 0.27  | 2.79 | 13.65 | 28.40 |
| JAL502 | 16 | 17.49 | 16.56 | 4.07 | 0.23 | -0.05 | 1.81 | 10.65 | 24.00 |
| JAL504 | 8  | 16.64 | 3.72  | 1.93 | 0.12 | -0.01 | 1.61 | 13.85 | 19.20 |
| JAL505 | 15 | 16.94 | 21.20 | 4.60 | 0.27 | 0.53  | 2.32 | 9.65  | 26.80 |
| JAL511 | 8  | 14.09 | 5.72  | 2.39 | 0.17 | 0.24  | 2.86 | 10.00 | 18.70 |
| JAL512 | 8  | 19.48 | 17.02 | 4.13 | 0.21 | 0.28  | 1.40 | 14.15 | 24.90 |
| JAL513 | 4  | 17.26 | 9.11  | 3.02 | 0.18 | 0.00  | 1.08 | 13.85 | 20.70 |
| JAL514 | 5  | 16.49 | 4.66  | 2.16 | 0.13 | 0.33  | 1.22 | 14.15 | 19.20 |
| JAL515 | 7  | 17.84 | 7.25  | 2.69 | 0.15 | -0.09 | 2.11 | 13.25 | 21.70 |
| JAL542 | 12 | 22.83 | 15.00 | 3.87 | 0.17 | -0.60 | 2.18 | 15.70 | 28.60 |
| JAL550 | 16 | 19.68 | 26.57 | 5.16 | 0.26 | 0.19  | 1.83 | 11.95 | 29.00 |
| JAL551 | 16 | 22.66 | 14.29 | 3.78 | 0.17 | -0.65 | 2.25 | 14.55 | 27.00 |
| JAL552 | 15 | 21.07 | 15.23 | 3.90 | 0.19 | -0.32 | 2.27 | 13.25 | 26.60 |
| JAL554 | 16 | 21.79 | 11.87 | 3.45 | 0.16 | -1.03 | 3.45 | 13.25 | 26.40 |
| JAL555 | 17 | 21.44 | 11.00 | 3.32 | 0.16 | -1.08 | 3.51 | 13.25 | 26.50 |
| JAL556 | 16 | 24.59 | 7.77  | 2.79 | 0.11 | -1.66 | 6.06 | 16.00 | 28.40 |
| JAL557 | 17 | 20.64 | 12.29 | 3.51 | 0.17 | -0.22 | 1.54 | 15.00 | 25.00 |
| JAL558 | 17 | 21.65 | 10.83 | 3.29 | 0.15 | -0.35 | 1.86 | 15.25 | 26.00 |
| JAL559 | 18 | 21.75 | 21.34 | 4.62 | 0.21 | -0.09 | 1.70 | 14.30 | 29.00 |
| JAL560 | 21 | 22.40 | 13.85 | 3.72 | 0.17 | -0.43 | 2.59 | 13.70 | 29.00 |
| JAL561 | 20 | 22.25 | 7.78  | 2.79 | 0.13 | -0.34 | 2.89 | 15.50 | 27.00 |
| JAL562 | 21 | 21.10 | 10.43 | 3.23 | 0.15 | 0.04  | 2.38 | 15.70 | 28.20 |
| JAL563 | 23 | 20.96 | 18.43 | 4.29 | 0.21 | -0.15 | 1.71 | 14.20 | 27.80 |
| JAL564 | 22 | 23.41 | 16.13 | 4.02 | 0.17 | -0.52 | 2.63 | 13.40 | 29.50 |
| JAL565 | 20 | 21.82 | 10.17 | 3.19 | 0.15 | -0.11 | 2.15 | 16.00 | 27.00 |
| JAL566 | 23 | 21.32 | 8.83  | 2.97 | 0.14 | -0.77 | 3.30 | 13.90 | 26.00 |
| JAL567 | 23 | 20.98 | 7.63  | 2.76 | 0.13 | -0.83 | 3.45 | 14.50 | 25.50 |
| JAL568 | 17 | 20.25 | 6.14  | 2.48 | 0.12 | -0.19 | 1.69 | 16.40 | 23.60 |
| JAL570 | 16 | 19.18 | 13.68 | 3.70 | 0.19 | -0.51 | 1.80 | 12.30 | 24.00 |
| JAL571 | 2  | 14.10 | 7.29  | 2.70 | 0.19 | 0.00  | 1.00 | 11.40 | 16.80 |
| JAL572 | 4  | 12.63 | 1.33  | 1.15 | 0.09 | 0.00  | 1.18 | 11.25 | 14.00 |
| JAL573 | 7  | 14.98 | 30.76 | 5.55 | 0.37 | -0.07 | 1.54 | 6.55  | 22.50 |
| JAL574 | 11 | 16.10 | 8.05  | 2.84 | 0.18 | -0.68 | 3.36 | 9.50  | 20.40 |
| JAL576 | 7  | 14.91 | 3.09  | 1.76 | 0.12 | 0.07  | 1.65 | 12.50 | 17.60 |
| JAL578 | 7  | 16.70 | 2.06  | 1.43 | 0.09 | 0.24  | 1.56 | 14.90 | 18.80 |

Statistical parameters for P<sub>2</sub>O<sub>5</sub> % in individual drill-holes within Horizon 1 (contd.)

|        |    |       |       |      |      |       |      |       |       |
|--------|----|-------|-------|------|------|-------|------|-------|-------|
| JAL579 | 10 | 19.60 | 5.84  | 2.42 | 0.12 | -0.74 | 2.07 | 14.90 | 22.00 |
| JAL580 | 18 | 19.46 | 11.08 | 3.33 | 0.17 | -0.46 | 2.00 | 12.80 | 23.50 |
| JAL581 | 18 | 22.24 | 7.80  | 2.79 | 0.13 | -0.05 | 1.68 | 17.60 | 26.70 |
| JAL582 | 19 | 22.61 | 8.95  | 2.99 | 0.13 | -0.75 | 2.57 | 16.20 | 26.30 |
| JAL583 | 18 | 25.42 | 16.05 | 4.01 | 0.16 | -1.02 | 2.83 | 16.40 | 30.80 |
| JAL584 | 16 | 21.46 | 15.03 | 3.88 | 0.18 | -0.62 | 2.13 | 13.20 | 25.90 |
| JAL585 | 13 | 19.87 | 6.36  | 2.52 | 0.13 | -0.36 | 1.77 | 15.80 | 23.50 |
| JAL586 | 10 | 20.69 | 9.11  | 3.02 | 0.15 | -0.38 | 1.92 | 15.00 | 24.20 |
| JAL587 | 9  | 23.09 | 11.91 | 3.45 | 0.15 | -0.94 | 4.38 | 14.90 | 28.80 |
| JAL588 | 11 | 22.05 | 21.45 | 4.63 | 0.21 | -0.58 | 2.23 | 12.50 | 27.20 |
| JAL589 | 9  | 24.88 | 4.89  | 2.21 | 0.09 | 0.23  | 2.48 | 21.10 | 29.00 |
| JAL590 | 9  | 24.66 | 10.98 | 3.31 | 0.13 | -1.02 | 3.39 | 17.10 | 28.40 |
| JAL591 | 15 | 21.89 | 21.49 | 4.64 | 0.21 | -0.16 | 1.67 | 14.30 | 28.40 |
| JAL597 | 10 | 18.70 | 29.96 | 5.47 | 0.29 | -1.13 | 3.50 | 5.70  | 24.20 |
| JAL598 | 10 | 24.68 | 18.05 | 4.25 | 0.17 | -0.55 | 3.89 | 15.00 | 32.50 |
| JAL599 | 17 | 21.15 | 29.45 | 5.43 | 0.26 | -0.27 | 1.76 | 11.40 | 28.40 |
| JAL600 | 14 | 21.70 | 30.66 | 5.54 | 0.26 | -0.63 | 2.16 | 11.00 | 28.80 |
| JAL601 | 15 | 20.91 | 13.48 | 3.67 | 0.18 | 0.41  | 3.79 | 13.60 | 30.00 |
| JAL602 | 13 | 19.68 | 6.38  | 2.53 | 0.13 | -1.44 | 3.74 | 13.60 | 22.40 |
| JAL603 | 16 | 16.10 | 26.87 | 5.18 | 0.32 | -0.41 | 2.90 | 5.10  | 24.50 |
| JAL604 | 24 | 20.45 | 22.34 | 4.73 | 0.23 | -1.27 | 4.59 | 6.00  | 26.00 |
| JAL605 | 12 | 21.62 | 9.46  | 3.08 | 0.14 | -0.94 | 3.07 | 14.30 | 25.00 |
| JAL606 | 17 | 21.10 | 12.41 | 3.52 | 0.17 | -0.96 | 2.76 | 13.00 | 25.40 |
| JAL607 | 26 | 21.14 | 33.05 | 5.75 | 0.27 | -0.88 | 2.53 | 8.40  | 27.50 |
| JAL608 | 14 | 15.68 | 15.10 | 3.89 | 0.25 | -1.15 | 4.63 | 5.00  | 21.50 |
| JAL609 | 20 | 19.02 | 29.77 | 5.46 | 0.29 | 0.12  | 2.19 | 10.00 | 30.40 |
| JAL610 | 15 | 17.71 | 10.02 | 3.17 | 0.18 | 0.04  | 1.87 | 12.30 | 22.80 |
| JAL612 | 12 | 16.99 | 5.10  | 2.26 | 0.13 | 0.19  | 2.32 | 13.00 | 21.30 |
| JAL613 | 17 | 18.77 | 8.04  | 2.84 | 0.15 | 0.03  | 1.81 | 14.30 | 23.00 |
| JAL617 | 7  | 17.33 | 6.95  | 2.64 | 0.15 | -0.35 | 1.48 | 13.60 | 20.50 |
| JAL619 | 16 | 20.48 | 19.05 | 4.37 | 0.21 | -0.12 | 2.21 | 12.10 | 26.90 |
| JAL620 | 19 | 17.52 | 25.66 | 5.07 | 0.29 | -0.56 | 2.80 | 4.90  | 24.60 |
| JAL621 | 7  | 14.83 | 9.02  | 3.00 | 0.20 | 1.05  | 3.27 | 11.10 | 21.20 |
| JAL623 | 7  | 23.26 | 8.59  | 2.93 | 0.13 | -0.76 | 2.52 | 17.50 | 26.70 |
| JAL624 | 9  | 14.99 | 5.07  | 2.25 | 0.15 | -0.60 | 2.55 | 10.50 | 18.30 |
| JAL625 | 3  | 15.77 | 2.21  | 1.49 | 0.09 | -0.33 | 1.50 | 13.80 | 17.40 |
| JAL655 | 9  | 15.63 | 5.46  | 2.34 | 0.15 | 1.20  | 3.23 | 13.20 | 20.90 |
| JAL656 | 9  | 17.78 | 2.56  | 1.60 | 0.09 | -0.57 | 2.88 | 14.40 | 20.10 |
| JAL659 | 10 | 16.96 | 14.84 | 3.85 | 0.23 | -0.92 | 3.84 | 7.80  | 22.20 |
| JAL667 | 11 | 23.08 | 15.33 | 3.92 | 0.17 | -1.15 | 3.27 | 14.16 | 27.74 |
| JAL668 | 15 | 21.53 | 29.27 | 5.41 | 0.25 | -0.80 | 2.21 | 10.10 | 27.70 |
| JAL669 | 13 | 21.13 | 30.61 | 5.53 | 0.26 | -0.94 | 2.48 | 10.41 | 27.38 |
| JAL670 | 14 | 20.39 | 24.60 | 4.96 | 0.24 | -0.34 | 1.87 | 11.29 | 26.94 |
| JAL671 | 5  | 21.77 | 7.72  | 2.78 | 0.13 | 0.65  | 1.76 | 19.14 | 26.35 |
| JAL672 | 20 | 18.52 | 16.67 | 4.08 | 0.22 | 0.27  | 1.73 | 12.90 | 26.03 |
| JAL673 | 3  | 18.24 | 5.98  | 2.45 | 0.13 | -0.64 | 1.50 | 14.82 | 20.40 |
| JAL712 | 3  | 18.10 | 11.29 | 3.36 | 0.19 | -0.18 | 1.50 | 13.80 | 22.00 |
| JAL754 | 7  | 16.59 | 12.20 | 3.49 | 0.21 | -0.03 | 1.48 | 11.58 | 21.29 |

## Appendix D2

154

**Statistical parameters for P<sub>2</sub>O<sub>5</sub> % in individual drill-holes within Horizon 2**

| HOLE NO. | NO. SAMPLES | MEAN  | VARIANCE | ST. DEV. | C.V. | SKEW. | KURT. | MIN.  | MAX   |
|----------|-------------|-------|----------|----------|------|-------|-------|-------|-------|
| JAL359   | 3           | 9.40  | 0.21     | 0.46     | 0.05 | 0.32  | 1.50  | 8.90  | 10.00 |
| JAL362   | 2           | 3.68  | 0.02     | 0.13     | 0.03 | 0.00  | 1.00  | 3.55  | 3.80  |
| JAL364   | 3           | 2.15  | 0.23     | 0.48     | 0.22 | 0.45  | 1.50  | 1.66  | 2.80  |
| JAL366   | 3           | 5.85  | 3.45     | 1.86     | 0.32 | 0.42  | 1.50  | 3.90  | 8.35  |
| JAL367   | 7           | 5.52  | 2.27     | 1.51     | 0.27 | 0.12  | 2.01  | 3.25  | 8.00  |
| JAL369   | 8           | 6.08  | 6.85     | 2.62     | 0.43 | 0.76  | 2.45  | 3.50  | 11.30 |
| JAL370   | 6           | 9.72  | 4.64     | 2.15     | 0.22 | 0.38  | 1.51  | 7.30  | 13.00 |
| JAL371   | 10          | 12.20 | 6.49     | 2.55     | 0.21 | -0.97 | 2.75  | 7.10  | 15.50 |
| JAL372   | 5           | 12.47 | 0.65     | 0.81     | 0.07 | -1.31 | 2.98  | 10.90 | 13.10 |
| JAL374   | 2           | 10.68 | 6.89     | 2.63     | 0.25 | 0.00  | 1.00  | 8.05  | 13.30 |
| JAL375   | 5           | 8.92  | 3.47     | 1.86     | 0.21 | 1.23  | 2.88  | 7.30  | 12.50 |
| JAL376   | 4           | 6.74  | 13.28    | 3.64     | 0.54 | 0.62  | 1.95  | 2.75  | 12.50 |
| JAL435   | 12          | 8.03  | 12.10    | 3.48     | 0.43 | 0.54  | 2.28  | 3.35  | 15.25 |
| JAL442   | 5           | 10.50 | 2.52     | 1.59     | 0.15 | 0.20  | 2.00  | 8.30  | 13.00 |
| JAL443   | 3           | 9.21  | 10.56    | 3.25     | 0.35 | -0.59 | 1.50  | 4.70  | 12.23 |
| JAL444   | 4           | 9.04  | 6.74     | 2.60     | 0.29 | -0.43 | 1.68  | 5.15  | 11.90 |
| JAL445   | 3           | 8.02  | 4.93     | 2.22     | 0.28 | 0.50  | 1.50  | 5.80  | 11.05 |
| JAL446   | 10          | 11.77 | 12.15    | 3.49     | 0.30 | 0.67  | 3.58  | 6.15  | 19.70 |
| JAL448   | 5           | 10.29 | 3.81     | 1.95     | 0.19 | 0.28  | 1.26  | 8.05  | 12.75 |
| JAL449   | 7           | 8.31  | 9.06     | 3.01     | 0.36 | 0.35  | 1.56  | 4.75  | 12.70 |
| JAL450   | 5           | 6.66  | 3.40     | 1.85     | 0.28 | 0.39  | 2.54  | 4.00  | 9.80  |
| JAL451   | 5           | 11.23 | 1.52     | 1.23     | 0.11 | -0.55 | 2.11  | 9.15  | 12.75 |
| JAL452   | 6           | 8.93  | 3.55     | 1.88     | 0.21 | 1.35  | 3.46  | 7.20  | 12.90 |
| JAL453   | 7           | 10.07 | 3.81     | 1.95     | 0.19 | -0.32 | 1.70  | 7.20  | 12.60 |
| JAL454   | 7           | 11.47 | 1.75     | 1.32     | 0.12 | -1.15 | 3.22  | 8.65  | 12.85 |
| JAL455   | 4           | 11.78 | 0.59     | 0.77     | 0.07 | 0.00  | 1.38  | 10.80 | 12.75 |
| JAL456   | 2           | 8.45  | 4.41     | 2.10     | 0.25 | 0.00  | 1.00  | 6.35  | 10.55 |
| JAL459   | 8           | 11.54 | 1.83     | 1.35     | 0.12 | 0.44  | 2.51  | 9.75  | 14.20 |
| JAL464   | 4           | 9.89  | 4.22     | 2.06     | 0.21 | -1.11 | 2.30  | 6.35  | 11.40 |
| JAL465   | 10          | 10.81 | 9.16     | 3.03     | 0.28 | 0.48  | 3.03  | 5.80  | 17.30 |
| JAL466   | 4           | 10.09 | 0.92     | 0.96     | 0.10 | 0.03  | 1.49  | 8.85  | 11.35 |
| JAL468   | 5           | 10.68 | 3.32     | 1.82     | 0.17 | -0.40 | 1.65  | 7.85  | 12.70 |
| JAL470   | 4           | 10.14 | 2.52     | 1.59     | 0.16 | 0.80  | 2.15  | 8.45  | 12.75 |
| JAL471   | 3           | 9.05  | 0.83     | 0.91     | 0.10 | 0.52  | 1.50  | 8.15  | 10.30 |
| JAL472   | 6           | 10.82 | 4.57     | 2.14     | 0.20 | -0.50 | 1.50  | 7.80  | 13.10 |
| JAL473   | 7           | 9.07  | 7.39     | 2.72     | 0.30 | -0.23 | 1.82  | 4.53  | 12.75 |
| JAL474   | 8           | 9.68  | 8.54     | 2.92     | 0.30 | 0.76  | 2.94  | 5.75  | 15.80 |
| JAL476   | 4           | 12.28 | 3.29     | 1.81     | 0.15 | -1.02 | 2.21  | 9.20  | 13.60 |
| JAL477   | 2           | 7.43  | 11.06    | 3.33     | 0.45 | 0.00  | 1.00  | 4.10  | 10.75 |
| JAL478   | 3           | 13.15 | 0.37     | 0.61     | 0.05 | 0.00  | 1.50  | 12.40 | 13.90 |
| JAL479   | 9           | 9.36  | 6.40     | 2.53     | 0.27 | 0.40  | 3.17  | 5.00  | 14.65 |
| JAL480   | 3           | 9.53  | 0.70     | 0.84     | 0.09 | -0.45 | 1.50  | 8.40  | 10.40 |
| JAL481   | 5           | 9.46  | 4.51     | 2.12     | 0.23 | -0.06 | 1.54  | 6.40  | 12.00 |
| JAL494   | 2           | 10.75 | 1.69     | 1.30     | 0.12 | 0.00  | 1.00  | 9.45  | 12.05 |
| JAL495   | 3           | 5.80  | 5.76     | 2.40     | 0.41 | 0.63  | 1.50  | 3.65  | 9.15  |

Statistical parameters for P<sub>2</sub>O<sub>5</sub>% in individual drill-holes within Horizon2 (contd.)

|        |    |       |       |      |      |       |      |       |       |
|--------|----|-------|-------|------|------|-------|------|-------|-------|
| JAL496 | 9  | 9.64  | 3.54  | 1.88 | 0.20 | -0.61 | 2.47 | 5.85  | 12.05 |
| JAL497 | 11 | 8.24  | 12.55 | 3.54 | 0.43 | 0.21  | 1.72 | 3.50  | 13.90 |
| JAL498 | 4  | 9.91  | 4.33  | 2.08 | 0.21 | 0.49  | 2.00 | 7.40  | 13.15 |
| JAL499 | 7  | 5.99  | 5.90  | 2.43 | 0.41 | 0.38  | 1.79 | 3.10  | 9.85  |
| JAL500 | 12 | 9.83  | 18.82 | 4.34 | 0.44 | 0.24  | 2.64 | 2.45  | 18.80 |
| JAL501 | 3  | 12.30 | 3.81  | 1.95 | 0.16 | -0.57 | 1.50 | 9.60  | 14.15 |
| JAL505 | 3  | 7.80  | 3.71  | 1.93 | 0.25 | -0.44 | 1.50 | 5.20  | 9.80  |
| JAL512 | 2  | 11.48 | 5.64  | 2.38 | 0.21 | 0.00  | 1.00 | 9.10  | 13.85 |
| JAL513 | 3  | 8.38  | 1.78  | 1.34 | 0.16 | 0.63  | 1.50 | 7.20  | 10.25 |
| JAL514 | 3  | 10.28 | 0.23  | 0.48 | 0.05 | -0.35 | 1.50 | 9.65  | 10.80 |
| JAL515 | 6  | 8.63  | 7.33  | 2.71 | 0.31 | 0.26  | 1.43 | 5.75  | 12.80 |
| JAL542 | 9  | 7.60  | 6.62  | 2.57 | 0.34 | -0.39 | 1.97 | 2.80  | 11.00 |
| JAL550 | 4  | 10.68 | 5.09  | 2.26 | 0.21 | -0.11 | 1.27 | 7.75  | 13.25 |
| JAL551 | 4  | 9.88  | 1.64  | 1.28 | 0.13 | 0.73  | 2.08 | 8.50  | 11.95 |
| JAL552 | 5  | 10.46 | 4.13  | 2.03 | 0.19 | 0.41  | 1.17 | 8.75  | 12.95 |
| JAL554 | 5  | 10.24 | 1.94  | 1.39 | 0.14 | -0.01 | 1.54 | 8.25  | 11.95 |
| JAL555 | 4  | 10.03 | 2.02  | 1.42 | 0.14 | -0.53 | 1.99 | 7.80  | 11.70 |
| JAL556 | 4  | 10.79 | 0.68  | 0.83 | 0.08 | -0.25 | 1.66 | 9.60  | 11.80 |
| JAL557 | 5  | 11.74 | 1.07  | 1.03 | 0.09 | -1.26 | 2.89 | 9.75  | 12.50 |
| JAL558 | 5  | 12.24 | 1.04  | 1.02 | 0.08 | 0.64  | 2.17 | 11.10 | 14.00 |
| JAL559 | 4  | 12.94 | 0.06  | 0.25 | 0.02 | 0.14  | 1.84 | 12.60 | 13.30 |
| JAL560 | 4  | 11.88 | 0.45  | 0.67 | 0.06 | 0.15  | 1.24 | 11.15 | 12.75 |
| JAL561 | 5  | 11.97 | 1.62  | 1.27 | 0.11 | -0.28 | 1.37 | 10.20 | 13.45 |
| JAL562 | 5  | 11.70 | 1.21  | 1.10 | 0.09 | -0.07 | 1.77 | 10.10 | 13.25 |
| JAL563 | 5  | 12.63 | 4.02  | 2.01 | 0.16 | 1.26  | 2.90 | 11.00 | 16.50 |
| JAL564 | 6  | 13.24 | 1.94  | 1.39 | 0.11 | 0.89  | 3.09 | 11.40 | 16.00 |
| JAL565 | 5  | 12.38 | 1.16  | 1.08 | 0.09 | 0.70  | 1.93 | 11.30 | 14.20 |
| JAL566 | 3  | 11.75 | 0.61  | 0.78 | 0.07 | 0.71  | 1.50 | 11.20 | 12.85 |
| JAL567 | 4  | 12.28 | 0.12  | 0.34 | 0.03 | -0.95 | 2.21 | 11.70 | 12.60 |
| JAL568 | 9  | 11.78 | 1.82  | 1.35 | 0.12 | -0.46 | 1.85 | 9.65  | 13.60 |
| JAL570 | 2  | 11.63 | 0.05  | 0.23 | 0.02 | 0.00  | 1.00 | 11.40 | 11.85 |
| JAL571 | 3  | 4.17  | 4.30  | 2.07 | 0.50 | 0.50  | 1.50 | 2.10  | 7.00  |
| JAL572 | 6  | 9.09  | 7.08  | 2.66 | 0.29 | -0.07 | 1.80 | 5.00  | 13.00 |
| JAL573 | 5  | 10.76 | 14.11 | 3.76 | 0.35 | -0.04 | 2.28 | 4.90  | 16.50 |
| JAL574 | 2  | 8.15  | 26.52 | 5.15 | 0.63 | 0.00  | 1.00 | 3.00  | 13.30 |
| JAL576 | 3  | 10.85 | 1.71  | 1.31 | 0.12 | 0.71  | 1.50 | 9.90  | 12.70 |
| JAL578 | 2  | 11.65 | 3.42  | 1.85 | 0.16 | 0.00  | 1.00 | 9.80  | 13.50 |
| JAL579 | 2  | 11.80 | 3.61  | 1.90 | 0.16 | 0.00  | 1.00 | 9.90  | 13.70 |
| JAL580 | 4  | 12.51 | 1.20  | 1.10 | 0.09 | -0.43 | 1.82 | 10.85 | 13.80 |
| JAL581 | 4  | 12.16 | 0.42  | 0.65 | 0.05 | -0.26 | 1.88 | 11.20 | 13.00 |
| JAL582 | 5  | 11.48 | 0.91  | 0.95 | 0.08 | -0.41 | 1.67 | 10.00 | 12.60 |
| JAL583 | 9  | 11.28 | 2.98  | 1.73 | 0.15 | -0.49 | 2.31 | 8.00  | 13.80 |
| JAL584 | 7  | 10.62 | 3.93  | 1.98 | 0.19 | 0.02  | 2.03 | 7.40  | 13.65 |
| JAL585 | 7  | 9.11  | 5.23  | 2.29 | 0.25 | -0.61 | 2.08 | 5.00  | 11.60 |
| JAL586 | 7  | 7.90  | 4.96  | 2.23 | 0.28 | -0.52 | 3.47 | 3.40  | 11.60 |
| JAL587 | 7  | 9.93  | 3.37  | 1.84 | 0.19 | -1.34 | 3.94 | 5.80  | 12.00 |
| JAL588 | 7  | 9.23  | 8.77  | 2.96 | 0.32 | -0.72 | 1.85 | 4.30  | 12.30 |
| JAL589 | 7  | 9.56  | 6.58  | 2.57 | 0.27 | -1.01 | 3.04 | 4.20  | 12.30 |

Statistical parameters for P<sub>2</sub>O<sub>5</sub>% in individual drill-holes within Horizon2 (contd.)

|        |    |       |       |      |      |       |      |       |       |
|--------|----|-------|-------|------|------|-------|------|-------|-------|
| JAL591 | 2  | 12.35 | 2.40  | 1.55 | 0.13 | 0.00  | 1.00 | 10.80 | 13.90 |
| JAL597 | 6  | 8.57  | 4.61  | 2.15 | 0.25 | 0.94  | 2.56 | 6.50  | 12.70 |
| JAL598 | 4  | 9.25  | 0.94  | 0.97 | 0.11 | 0.00  | 1.87 | 7.90  | 10.60 |
| JAL599 | 5  | 8.28  | 3.71  | 1.93 | 0.23 | 0.55  | 2.02 | 6.00  | 11.50 |
| JAL600 | 7  | 7.56  | 3.87  | 1.97 | 0.26 | -0.44 | 3.17 | 3.70  | 10.80 |
| JAL601 | 8  | 11.41 | 5.34  | 2.31 | 0.20 | -0.12 | 1.52 | 8.20  | 14.60 |
| JAL603 | 7  | 6.39  | 6.84  | 2.62 | 0.41 | 0.52  | 2.96 | 2.30  | 11.50 |
| JAL605 | 6  | 11.40 | 9.29  | 3.05 | 0.27 | 0.24  | 1.60 | 7.80  | 16.20 |
| JAL606 | 8  | 12.08 | 1.74  | 1.32 | 0.11 | -0.35 | 1.81 | 9.80  | 13.70 |
| JAL607 | 4  | 8.55  | 0.71  | 0.84 | 0.10 | 0.20  | 1.37 | 7.60  | 9.70  |
| JAL608 | 9  | 8.96  | 10.67 | 3.27 | 0.37 | 0.63  | 2.20 | 5.10  | 15.30 |
| JAL609 | 7  | 11.93 | 0.98  | 0.99 | 0.08 | -0.60 | 2.66 | 10.00 | 13.30 |
| JAL612 | 2  | 9.35  | 4.62  | 2.15 | 0.23 | 0.00  | 1.00 | 7.20  | 11.50 |
| JAL617 | 6  | 8.10  | 3.84  | 1.96 | 0.24 | 0.24  | 1.76 | 5.60  | 11.20 |
| JAL619 | 4  | 11.75 | 0.95  | 0.97 | 0.08 | -0.14 | 1.18 | 10.50 | 12.70 |
| JAL620 | 3  | 10.50 | 0.83  | 0.91 | 0.09 | 0.32  | 1.50 | 9.50  | 11.70 |
| JAL621 | 7  | 11.09 | 2.39  | 1.55 | 0.14 | 1.29  | 3.60 | 9.70  | 14.50 |
| JAL623 | 8  | 8.89  | 5.05  | 2.25 | 0.25 | -0.02 | 2.03 | 5.40  | 12.50 |
| JAL624 | 6  | 7.97  | 3.53  | 1.88 | 0.24 | 0.62  | 1.82 | 5.80  | 11.10 |
| JAL625 | 3  | 6.37  | 5.24  | 2.29 | 0.36 | 0.70  | 1.50 | 4.60  | 9.60  |
| JAL655 | 3  | 10.23 | 0.68  | 0.83 | 0.08 | 0.70  | 1.50 | 9.60  | 11.40 |
| JAL656 | 2  | 5.95  | 0.56  | 0.75 | 0.13 | 0.00  | 1.00 | 5.20  | 6.70  |
| JAL659 | 11 | 8.03  | 7.72  | 2.78 | 0.35 | 0.78  | 3.12 | 4.20  | 14.40 |
| JAL667 | 6  | 8.48  | 7.95  | 2.82 | 0.33 | 0.53  | 1.84 | 5.06  | 13.17 |
| JAL668 | 6  | 8.00  | 7.00  | 2.65 | 0.33 | 0.88  | 2.69 | 4.80  | 13.10 |
| JAL669 | 2  | 10.47 | 0.40  | 0.63 | 0.06 | 0.00  | 1.00 | 9.84  | 11.10 |
| JAL670 | 8  | 9.38  | 3.02  | 1.74 | 0.19 | 0.19  | 1.89 | 7.07  | 12.26 |
| JAL671 | 9  | 10.48 | 9.78  | 3.13 | 0.30 | 0.11  | 2.61 | 5.08  | 16.36 |
| JAL673 | 2  | 8.52  | 1.65  | 1.29 | 0.15 | 0.00  | 1.00 | 7.23  | 9.80  |
| JAL754 | 7  | 10.67 | 2.99  | 1.73 | 0.16 | -0.29 | 1.22 | 8.27  | 12.52 |



## Appendix D3

**Statistical parameters for P<sub>2</sub>O<sub>5</sub> % in individual drill-holes within Horizon 3**

| HOLE NO. | NO.SAMPLES | MEAN  | VARIANCE | ST. DEV. | C.V. | SKEW. | KURT. | MIN.  | MAX.  |
|----------|------------|-------|----------|----------|------|-------|-------|-------|-------|
| JAL269   | 21         | 21.02 | 30.78    | 5.55     | 0.26 | -0.25 | 1.83  | 10.65 | 30.00 |
| JAL345   | 10         | 15.94 | 4.92     | 2.22     | 0.14 | -0.91 | 2.32  | 11.40 | 18.10 |
| JAL359   | 2          | 17.20 | 0.01     | 0.10     | 0.01 | 0.00  | 1.00  | 17.10 | 17.30 |
| JAL360   | 16         | 20.62 | 10.86    | 3.30     | 0.16 | -0.80 | 3.55  | 13.20 | 26.20 |
| JAL362   | 8          | 20.04 | 10.61    | 3.26     | 0.16 | -0.75 | 2.15  | 14.00 | 23.80 |
| JAL363   | 10         | 18.84 | 13.00    | 3.61     | 0.19 | -0.48 | 1.62  | 13.10 | 22.70 |
| JAL364   | 6          | 15.95 | 7.40     | 2.72     | 0.17 | 0.03  | 2.24  | 11.60 | 20.30 |
| JAL365   | 10         | 17.52 | 4.12     | 2.03     | 0.12 | -0.38 | 2.04  | 14.10 | 20.20 |
| JAL366   | 9          | 16.82 | 21.75    | 4.66     | 0.28 | 0.15  | 2.35  | 9.40  | 25.60 |
| JAL367   | 6          | 21.83 | 24.74    | 4.97     | 0.23 | -0.67 | 1.72  | 13.60 | 26.70 |
| JAL368   | 5          | 17.57 | 25.56    | 5.06     | 0.29 | 0.43  | 1.32  | 12.65 | 24.80 |
| JAL369   | 3          | 19.20 | 3.21     | 1.79     | 0.09 | 0.63  | 1.50  | 17.60 | 21.70 |
| JAL370   | 10         | 18.78 | 3.10     | 1.76     | 0.09 | 0.92  | 3.38  | 16.20 | 22.80 |
| JAL371   | 14         | 19.70 | 8.64     | 2.94     | 0.15 | -0.48 | 1.90  | 14.10 | 23.60 |
| JAL372   | 8          | 18.93 | 10.86    | 3.30     | 0.17 | -0.30 | 2.61  | 12.75 | 24.40 |
| JAL374   | 12         | 18.03 | 10.41    | 3.23     | 0.18 | -0.43 | 2.46  | 11.20 | 22.50 |
| JAL375   | 7          | 16.40 | 5.75     | 2.40     | 0.15 | 0.16  | 1.79  | 13.25 | 20.30 |
| JAL376   | 7          | 17.14 | 6.16     | 2.48     | 0.15 | 0.71  | 1.84  | 15.00 | 21.50 |
| JAL434   | 6          | 19.13 | 12.21    | 3.49     | 0.18 | 0.26  | 1.43  | 15.40 | 24.50 |
| JAL435   | 7          | 18.00 | 8.36     | 2.89     | 0.16 | 0.31  | 1.65  | 14.70 | 22.70 |
| JAL436   | 12         | 17.69 | 14.23    | 3.77     | 0.21 | -0.51 | 2.25  | 10.80 | 23.40 |
| JAL437   | 12         | 17.80 | 11.94    | 3.46     | 0.19 | 0.64  | 2.67  | 12.75 | 25.30 |
| JAL438   | 14         | 19.96 | 8.83     | 2.97     | 0.15 | -0.67 | 2.14  | 14.40 | 23.50 |
| JAL439   | 15         | 14.82 | 25.57    | 5.06     | 0.34 | -0.87 | 3.18  | 3.88  | 21.70 |
| JAL440   | 16         | 17.20 | 12.27    | 3.50     | 0.20 | 0.15  | 2.52  | 10.50 | 24.20 |
| JAL442   | 3          | 19.40 | 0.75     | 0.86     | 0.05 | 0.60  | 1.50  | 18.60 | 20.60 |
| JAL443   | 9          | 14.58 | 2.98     | 1.73     | 0.12 | 0.23  | 1.78  | 11.95 | 17.40 |
| JAL444   | 7          | 15.39 | 2.12     | 1.46     | 0.10 | 0.84  | 1.85  | 14.05 | 17.70 |
| JAL445   | 9          | 16.66 | 5.23     | 2.29     | 0.14 | -1.10 | 4.48  | 11.15 | 20.30 |
| JAL446   | 9          | 17.61 | 8.84     | 2.97     | 0.17 | 0.97  | 3.57  | 13.55 | 24.40 |
| JAL447   | 10         | 17.37 | 10.84    | 3.29     | 0.19 | 0.00  | 1.76  | 12.40 | 22.70 |
| JAL448   | 9          | 20.58 | 11.81    | 3.44     | 0.17 | -0.39 | 1.70  | 14.65 | 24.90 |
| JAL449   | 4          | 21.93 | 10.63    | 3.26     | 0.15 | -0.47 | 1.92  | 16.90 | 25.80 |
| JAL450   | 5          | 18.08 | 22.07    | 4.70     | 0.26 | 0.42  | 1.64  | 13.00 | 25.40 |
| JAL451   | 8          | 17.45 | 15.52    | 3.94     | 0.23 | 0.06  | 1.91  | 11.65 | 23.80 |
| JAL452   | 4          | 18.51 | 15.21    | 3.90     | 0.21 | -1.06 | 2.27  | 11.85 | 21.70 |
| JAL453   | 5          | 20.44 | 10.10    | 3.18     | 0.16 | 0.75  | 2.22  | 16.90 | 26.00 |
| JAL454   | 3          | 17.67 | 8.60     | 2.93     | 0.17 | -0.59 | 1.50  | 13.60 | 20.40 |
| JAL455   | 5          | 17.76 | 9.98     | 3.16     | 0.18 | -1.11 | 2.74  | 11.80 | 20.70 |
| JAL456   | 8          | 15.13 | 8.04     | 2.84     | 0.19 | 1.05  | 2.55  | 12.50 | 20.80 |
| JAL457   | 4          | 17.26 | 1.70     | 1.31     | 0.08 | -0.19 | 1.94  | 15.35 | 19.00 |
| JAL458   | 5          | 16.09 | 2.48     | 1.58     | 0.10 | -0.32 | 1.93  | 13.60 | 18.20 |
| JAL459   | 4          | 17.48 | 2.32     | 1.52     | 0.09 | 0.41  | 1.94  | 15.60 | 19.80 |
| JAL460   | 2          | 15.58 | 1.05     | 1.03     | 0.07 | 0.00  | 1.00  | 14.55 | 16.60 |
| JAL464   | 2          | 17.77 | 8.61     | 2.94     | 0.17 | 0.00  | 1.00  | 14.83 | 20.70 |

Statistical parameters for P<sub>2</sub>O<sub>5</sub> % in individual drill-holes within Horizon 3 (contd.)

|        |    |       |       |      |      |       |      |       |       |
|--------|----|-------|-------|------|------|-------|------|-------|-------|
| JAL465 | 4  | 17.68 | 4.75  | 2.18 | 0.12 | -0.79 | 2.14 | 14.10 | 20.00 |
| JAL466 | 10 | 14.31 | 14.49 | 3.81 | 0.27 | 0.05  | 1.45 | 9.15  | 19.50 |
| JAL468 | 3  | 20.23 | 10.91 | 3.30 | 0.16 | 0.57  | 1.50 | 17.10 | 24.80 |
| JAL470 | 5  | 16.67 | 4.38  | 2.09 | 0.13 | 1.04  | 2.80 | 14.35 | 20.60 |
| JAL471 | 6  | 17.90 | 6.34  | 2.52 | 0.14 | 0.05  | 1.93 | 14.40 | 21.90 |
| JAL472 | 6  | 20.07 | 11.68 | 3.42 | 0.17 | -0.07 | 2.60 | 14.30 | 25.70 |
| JAL473 | 4  | 18.35 | 8.75  | 2.96 | 0.16 | -0.19 | 1.27 | 14.40 | 21.40 |
| JAL474 | 2  | 15.73 | 10.73 | 3.28 | 0.21 | 0.00  | 1.00 | 12.45 | 19.00 |
| JAL476 | 11 | 16.20 | 10.54 | 3.25 | 0.20 | 0.01  | 1.99 | 11.30 | 22.00 |
| JAL477 | 10 | 18.40 | 14.86 | 3.86 | 0.21 | 0.08  | 2.24 | 11.65 | 25.10 |
| JAL478 | 3  | 16.52 | 2.41  | 1.55 | 0.09 | -0.63 | 1.50 | 14.35 | 17.90 |
| JAL479 | 2  | 16.08 | 5.88  | 2.43 | 0.15 | 0.00  | 1.00 | 13.65 | 18.50 |
| JAL480 | 3  | 18.30 | 1.93  | 1.39 | 0.08 | 0.00  | 1.50 | 16.60 | 20.00 |
| JAL481 | 3  | 15.17 | 6.62  | 2.57 | 0.17 | 0.70  | 1.50 | 13.20 | 18.80 |
| JAL494 | 13 | 16.79 | 14.16 | 3.76 | 0.22 | 0.74  | 2.34 | 11.90 | 23.70 |
| JAL495 | 9  | 15.54 | 13.14 | 3.63 | 0.23 | 1.12  | 2.56 | 12.45 | 22.60 |
| JAL496 | 5  | 13.21 | 1.23  | 1.11 | 0.08 | 0.95  | 2.60 | 12.00 | 15.25 |
| JAL497 | 6  | 15.86 | 3.15  | 1.78 | 0.11 | 0.59  | 1.61 | 13.90 | 18.60 |
| JAL498 | 9  | 18.19 | 10.15 | 3.19 | 0.18 | 0.43  | 1.93 | 14.05 | 23.90 |
| JAL499 | 4  | 15.10 | 1.89  | 1.37 | 0.09 | 0.72  | 1.92 | 13.80 | 17.30 |
| JAL500 | 7  | 17.02 | 8.86  | 2.98 | 0.18 | 0.25  | 1.46 | 13.65 | 21.60 |
| JAL501 | 3  | 18.63 | 2.28  | 1.51 | 0.08 | -0.70 | 1.50 | 16.50 | 19.80 |
| JAL503 | 8  | 17.39 | 15.81 | 3.98 | 0.23 | 0.37  | 2.07 | 11.35 | 24.00 |
| JAL505 | 2  | 17.60 | 0.64  | 0.80 | 0.05 | 0.00  | 1.00 | 16.80 | 18.40 |
| JAL512 | 3  | 14.13 | 0.42  | 0.65 | 0.05 | 0.40  | 1.50 | 13.45 | 15.00 |
| JAL513 | 7  | 17.04 | 4.64  | 2.15 | 0.13 | -0.37 | 1.91 | 13.30 | 19.60 |
| JAL514 | 8  | 15.38 | 5.71  | 2.39 | 0.16 | -0.28 | 1.79 | 11.35 | 18.50 |
| JAL515 | 7  | 16.44 | 15.02 | 3.88 | 0.24 | -0.35 | 2.07 | 10.25 | 22.30 |
| JAL542 | 6  | 18.90 | 11.69 | 3.42 | 0.18 | 0.17  | 1.60 | 14.20 | 23.30 |
| JAL550 | 8  | 20.58 | 8.42  | 2.90 | 0.14 | -0.27 | 1.32 | 16.80 | 24.00 |
| JAL551 | 10 | 19.73 | 12.09 | 3.48 | 0.18 | -0.28 | 2.22 | 13.45 | 24.80 |
| JAL552 | 9  | 18.63 | 11.85 | 3.44 | 0.19 | -0.42 | 1.65 | 13.00 | 23.00 |
| JAL554 | 8  | 18.88 | 5.45  | 2.34 | 0.12 | 0.69  | 2.42 | 16.10 | 23.50 |
| JAL555 | 9  | 19.30 | 10.34 | 3.22 | 0.17 | -0.05 | 1.88 | 13.90 | 24.00 |
| JAL556 | 9  | 18.91 | 7.72  | 2.78 | 0.15 | -0.08 | 1.82 | 14.70 | 23.20 |
| JAL557 | 7  | 19.83 | 6.35  | 2.52 | 0.13 | 0.24  | 2.71 | 15.80 | 24.50 |
| JAL558 | 7  | 19.87 | 8.50  | 2.92 | 0.15 | -0.17 | 2.17 | 15.00 | 24.50 |
| JAL559 | 9  | 18.44 | 14.12 | 3.76 | 0.20 | 0.51  | 1.63 | 14.15 | 24.30 |
| JAL560 | 7  | 17.11 | 5.95  | 2.44 | 0.14 | 0.16  | 3.18 | 12.80 | 21.70 |
| JAL561 | 7  | 18.41 | 9.57  | 3.09 | 0.17 | 0.03  | 1.59 | 14.25 | 23.00 |
| JAL562 | 7  | 17.55 | 11.84 | 3.44 | 0.20 | 0.81  | 2.45 | 14.25 | 24.30 |
| JAL563 | 4  | 18.58 | 11.49 | 3.39 | 0.18 | -0.05 | 1.58 | 14.00 | 23.00 |
| JAL564 | 5  | 20.38 | 10.41 | 3.23 | 0.16 | -0.38 | 1.19 | 16.40 | 23.60 |
| JAL565 | 4  | 18.93 | 5.91  | 2.43 | 0.13 | 0.49  | 1.98 | 16.00 | 22.70 |
| JAL566 | 5  | 18.04 | 18.30 | 4.28 | 0.24 | 1.01  | 2.67 | 13.50 | 26.00 |
| JAL567 | 5  | 17.66 | 12.10 | 3.48 | 0.20 | 0.77  | 2.25 | 14.30 | 23.80 |
| JAL568 | 5  | 17.66 | 9.22  | 3.04 | 0.17 | 0.50  | 1.88 | 14.00 | 22.60 |
| JAL570 | 5  | 22.14 | 29.51 | 5.43 | 0.25 | -1.06 | 2.62 | 12.00 | 26.80 |

**Statistical parameters for P<sub>2</sub>O<sub>5</sub> % in individual drill holes within Horizon 3 (contd.)**

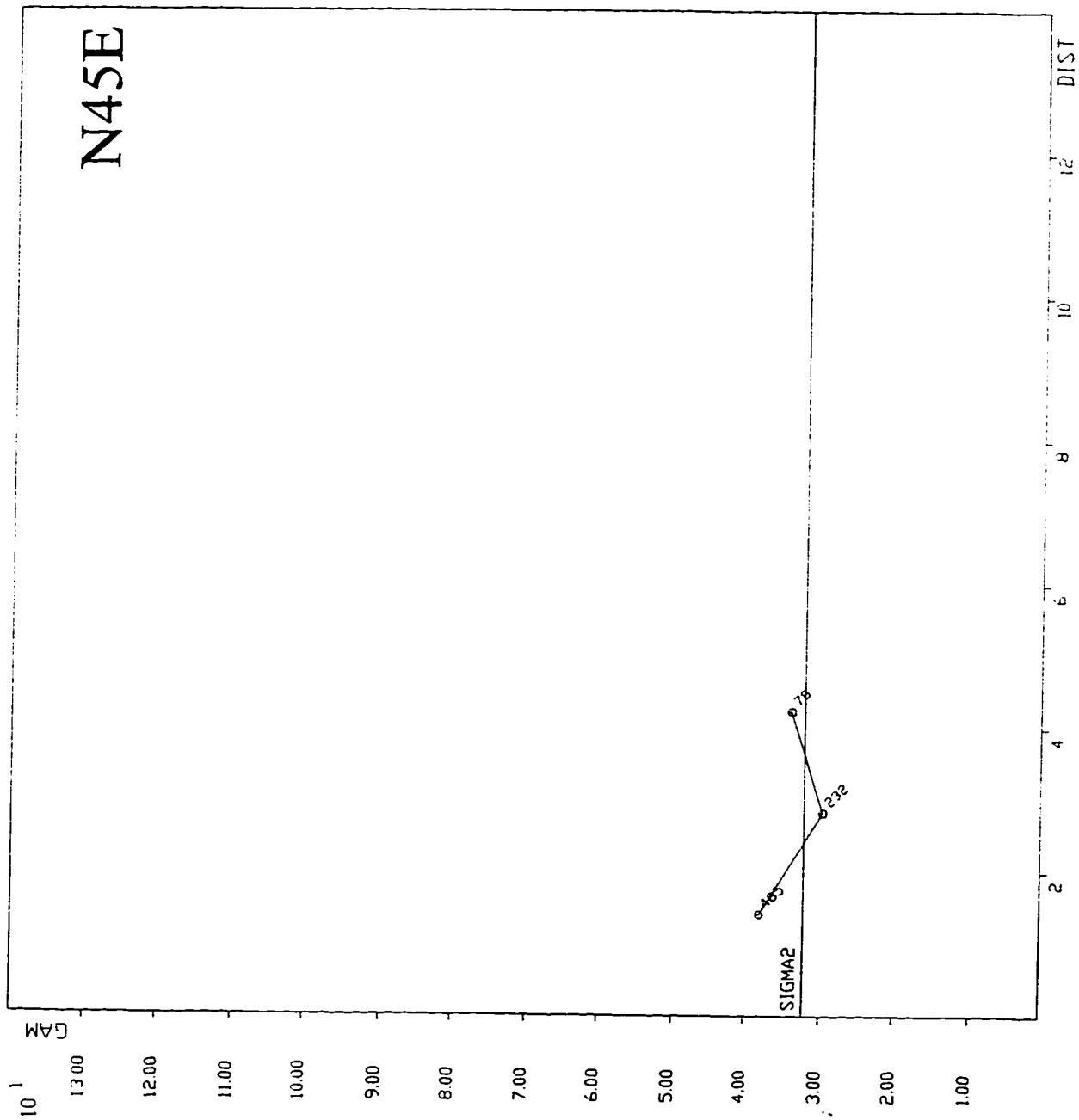
|        |    |       |       |      |      |       |      |       |       |
|--------|----|-------|-------|------|------|-------|------|-------|-------|
| JAL572 | 10 | 19.38 | 8.09  | 2.84 | 0.15 | -0.60 | 2.61 | 13.50 | 23.50 |
| JAL573 | 13 | 17.64 | 8.66  | 2.94 | 0.17 | -0.07 | 1.68 | 13.45 | 22.50 |
| JAL574 | 15 | 16.54 | 9.52  | 3.09 | 0.19 | -0.19 | 1.94 | 10.50 | 21.00 |
| JAL575 | 32 | 16.12 | 13.05 | 3.61 | 0.22 | -1.01 | 5.07 | 4.15  | 22.00 |
| JAL576 | 26 | 16.03 | 17.45 | 4.18 | 0.26 | -1.00 | 3.90 | 4.45  | 22.00 |
| JAL577 | 20 | 16.91 | 14.61 | 3.82 | 0.23 | 0.07  | 1.78 | 10.00 | 23.70 |
| JAL578 | 32 | 18.81 | 15.56 | 3.94 | 0.21 | 0.20  | 2.18 | 11.90 | 26.80 |
| JAL579 | 14 | 17.51 | 8.74  | 2.96 | 0.17 | 0.44  | 1.89 | 13.80 | 23.20 |
| JAL580 | 7  | 15.65 | 7.30  | 2.70 | 0.17 | -0.21 | 2.27 | 10.95 | 19.90 |
| JAL581 | 6  | 20.20 | 17.61 | 4.20 | 0.21 | -0.92 | 2.78 | 12.00 | 25.00 |
| JAL582 | 8  | 17.93 | 16.49 | 4.06 | 0.23 | 0.69  | 2.05 | 12.90 | 24.60 |
| JAL583 | 4  | 19.68 | 8.43  | 2.90 | 0.15 | 0.15  | 1.42 | 16.20 | 23.60 |
| JAL584 | 5  | 19.26 | 12.69 | 3.56 | 0.19 | -0.37 | 1.91 | 13.50 | 23.50 |
| JAL585 | 4  | 16.55 | 4.94  | 2.22 | 0.13 | 0.19  | 1.25 | 14.40 | 19.50 |
| JAL586 | 5  | 20.06 | 18.76 | 4.33 | 0.22 | 0.42  | 1.20 | 16.30 | 25.80 |
| JAL587 | 6  | 18.22 | 5.36  | 2.32 | 0.13 | -0.20 | 2.25 | 14.40 | 21.80 |
| JAL588 | 5  | 17.02 | 2.59  | 1.61 | 0.10 | 0.09  | 2.03 | 14.70 | 19.50 |
| JAL589 | 6  | 16.53 | 3.54  | 1.88 | 0.11 | 0.12  | 1.74 | 14.00 | 19.40 |
| JAL590 | 5  | 16.16 | 2.85  | 1.69 | 0.11 | -0.36 | 1.82 | 13.50 | 18.30 |
| JAL591 | 7  | 18.91 | 7.65  | 2.77 | 0.15 | -0.34 | 2.14 | 14.00 | 22.80 |
| JAL597 | 7  | 16.83 | 6.00  | 2.45 | 0.15 | 0.11  | 1.59 | 13.20 | 20.20 |
| JAL598 | 8  | 17.46 | 2.75  | 1.66 | 0.10 | -0.29 | 2.04 | 14.50 | 19.80 |
| JAL599 | 6  | 16.98 | 4.77  | 2.18 | 0.13 | 1.06  | 2.77 | 14.90 | 21.30 |
| JAL600 | 7  | 15.96 | 1.43  | 1.20 | 0.08 | 0.16  | 2.03 | 14.20 | 18.00 |
| JAL601 | 5  | 16.26 | 5.30  | 2.30 | 0.14 | 0.75  | 2.23 | 13.90 | 20.30 |
| JAL603 | 2  | 14.60 | 0.49  | 0.70 | 0.05 | 0.00  | 1.00 | 13.90 | 15.30 |
| JAL605 | 5  | 16.04 | 8.13  | 2.85 | 0.18 | 1.44  | 3.18 | 14.00 | 21.70 |
| JAL606 | 4  | 17.60 | 5.22  | 2.28 | 0.13 | 0.39  | 2.03 | 14.70 | 21.10 |
| JAL607 | 3  | 17.27 | 8.00  | 2.83 | 0.16 | -0.65 | 1.50 | 13.30 | 19.70 |
| JAL608 | 2  | 16.10 | 0.00  | 0.00 | 0.00 | 0.00  | 0.00 | 16.10 | 16.10 |
| JAL609 | 3  | 19.87 | 8.17  | 2.86 | 0.14 | -0.07 | 1.50 | 16.30 | 23.30 |
| JAL611 | 4  | 18.13 | 6.51  | 2.55 | 0.14 | -0.34 | 1.87 | 14.30 | 21.30 |
| JAL612 | 6  | 18.87 | 11.10 | 3.33 | 0.18 | 0.48  | 1.76 | 14.70 | 24.20 |
| JAL614 | 16 | 18.51 | 15.38 | 3.92 | 0.21 | -0.17 | 3.18 | 9.30  | 25.10 |
| JAL616 | 22 | 20.24 | 23.28 | 4.83 | 0.24 | -0.27 | 1.79 | 11.40 | 28.50 |
| JAL617 | 2  | 14.95 | 0.12  | 0.35 | 0.02 | 0.00  | 1.00 | 14.60 | 15.30 |
| JAL619 | 4  | 18.40 | 15.06 | 3.88 | 0.21 | -0.17 | 1.33 | 13.20 | 22.80 |
| JAL620 | 5  | 16.50 | 7.94  | 2.82 | 0.17 | 0.28  | 1.34 | 13.40 | 20.40 |
| JAL621 | 4  | 17.35 | 1.95  | 1.40 | 0.08 | -0.97 | 2.17 | 15.00 | 18.50 |
| JAL622 | 8  | 15.44 | 7.32  | 2.71 | 0.18 | 0.13  | 1.57 | 11.40 | 19.10 |
| JAL623 | 4  | 21.68 | 11.60 | 3.41 | 0.16 | 0.36  | 1.68 | 17.70 | 26.70 |
| JAL624 | 12 | 18.78 | 8.36  | 2.89 | 0.15 | 0.15  | 2.28 | 13.90 | 24.00 |
| JAL625 | 13 | 17.55 | 7.29  | 2.70 | 0.15 | -0.25 | 2.38 | 12.10 | 21.70 |
| JAL655 | 13 | 18.03 | 6.72  | 2.59 | 0.14 | -0.17 | 1.79 | 13.50 | 22.00 |
| JAL656 | 5  | 18.58 | 2.35  | 1.53 | 0.08 | -0.28 | 2.14 | 16.10 | 20.70 |
| JAL659 | 2  | 15.60 | 0.09  | 0.30 | 0.02 | 0.00  | 1.00 | 15.30 | 15.90 |
| JAL667 | 6  | 19.21 | 20.90 | 4.57 | 0.24 | 0.45  | 1.83 | 14.18 | 26.94 |

**Statistical parameters for P<sub>2</sub>O<sub>5</sub> % in individual drill holes within Horizon 3 (contd.)**

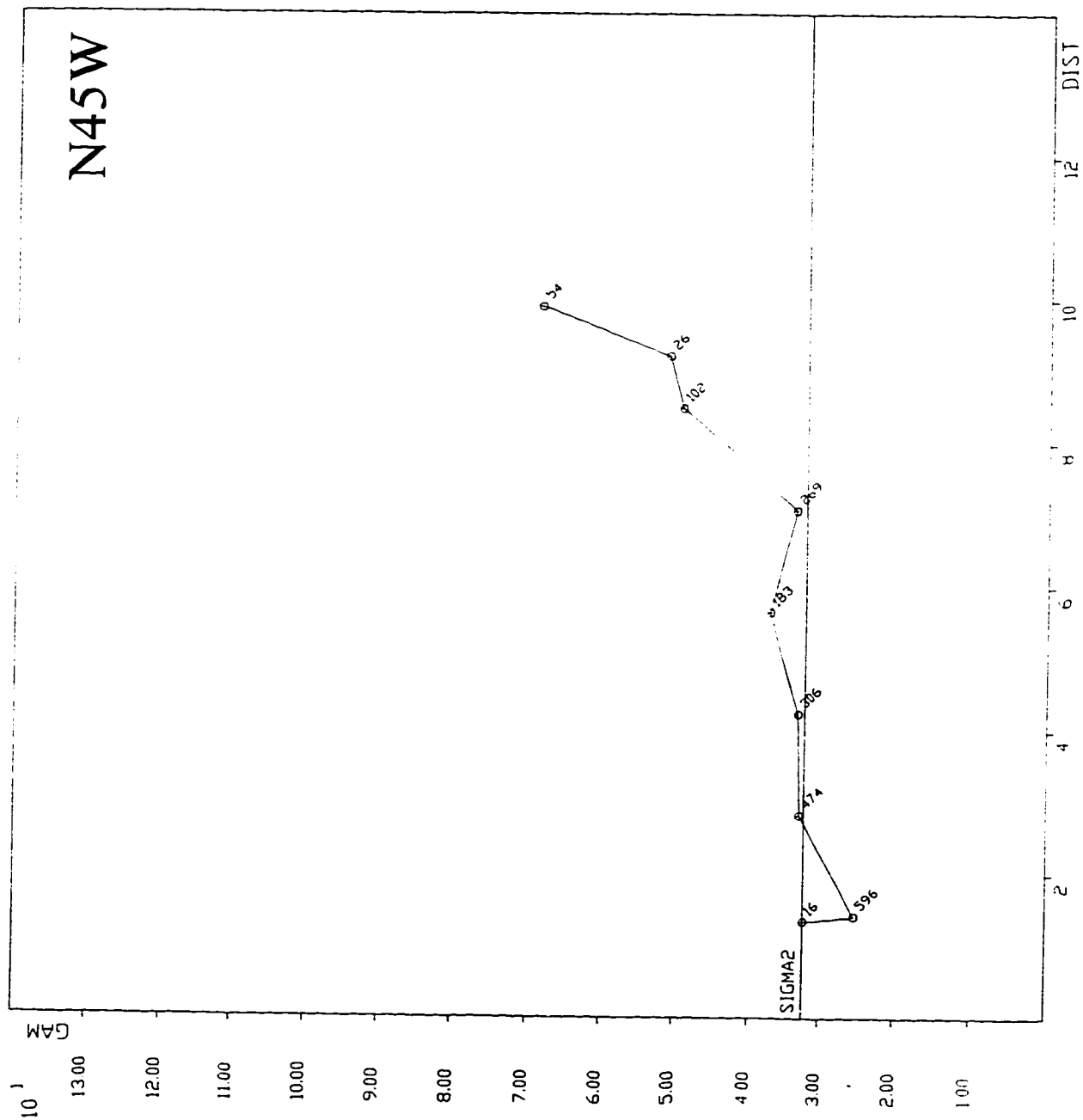
|        |    |       |       |      |      |       |      |       |       |
|--------|----|-------|-------|------|------|-------|------|-------|-------|
| JAL668 | 4  | 19.05 | 17.48 | 4.18 | 0.22 | 0.07  | 1.45 | 13.80 | 24.60 |
| JAL669 | 7  | 16.55 | 14.27 | 3.78 | 0.23 | -0.29 | 1.55 | 10.46 | 20.72 |
| JAL670 | 3  | 19.68 | 2.55  | 1.60 | 0.08 | -0.33 | 1.50 | 17.57 | 21.43 |
| JAL671 | 4  | 16.69 | 3.83  | 1.96 | 0.12 | 0.40  | 1.77 | 14.39 | 19.63 |
| JAL673 | 11 | 17.13 | 7.11  | 2.67 | 0.16 | -0.80 | 2.28 | 11.82 | 20.13 |
| JAL674 | 12 | 17.23 | 14.71 | 3.84 | 0.22 | 0.05  | 1.46 | 11.72 | 22.68 |
| JAL754 | 5  | 17.28 | 0.53  | 0.73 | 0.04 | -0.44 | 1.92 | 16.10 | 18.20 |

## **APPENDIX E**

Experimental semivariograms for the original drill-holes data in Horizon 1



VARIABLE P205  
 (Horizon 1) Horizontal Semivariogram (logarithmic scale)



VARIABLE P205  
(Horizon 1)

ARBITRARY

Horizontal distance in feet

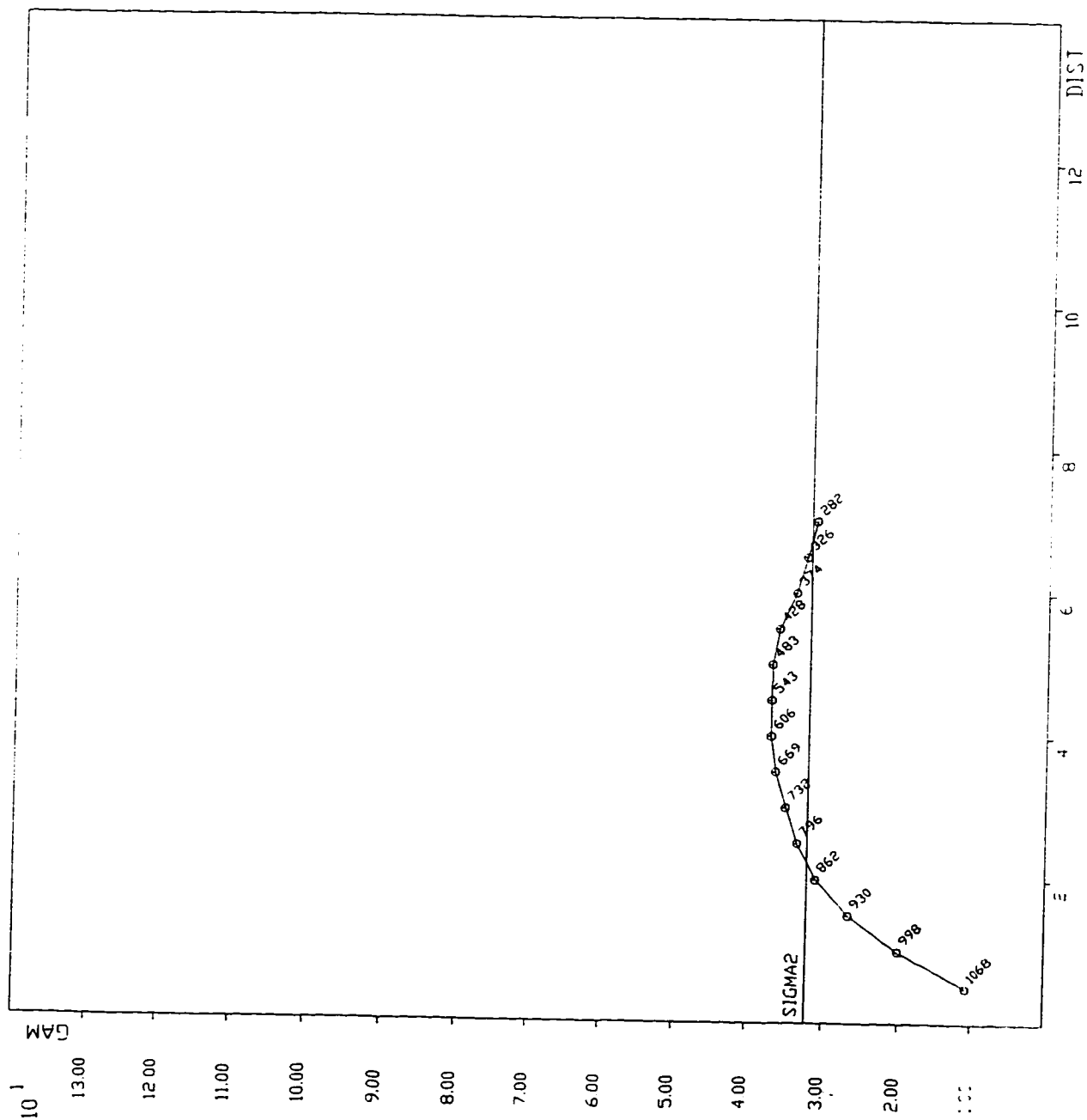
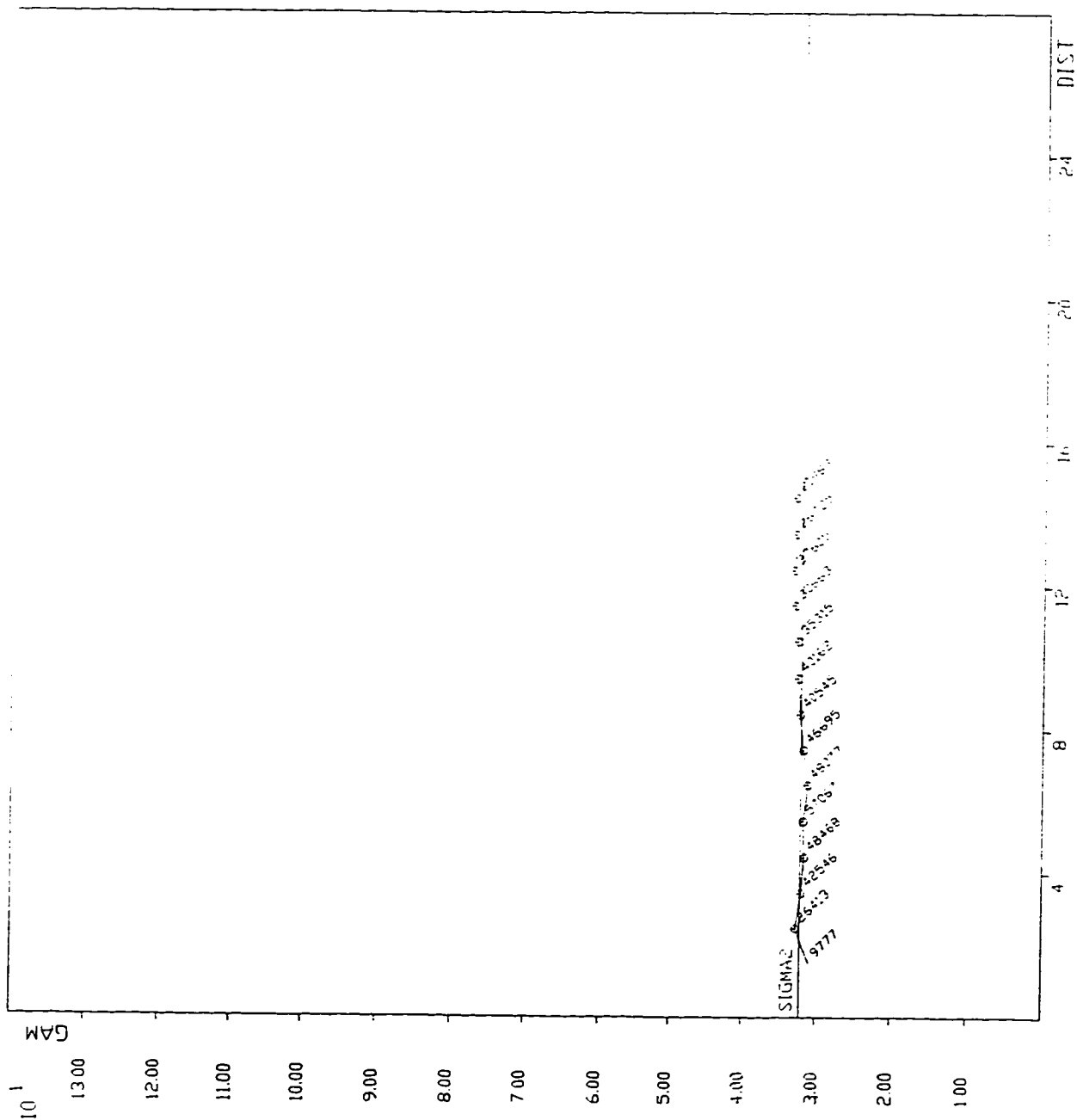


TABLE 1. GAMMA vs. DISTANCE. (See text for details.)



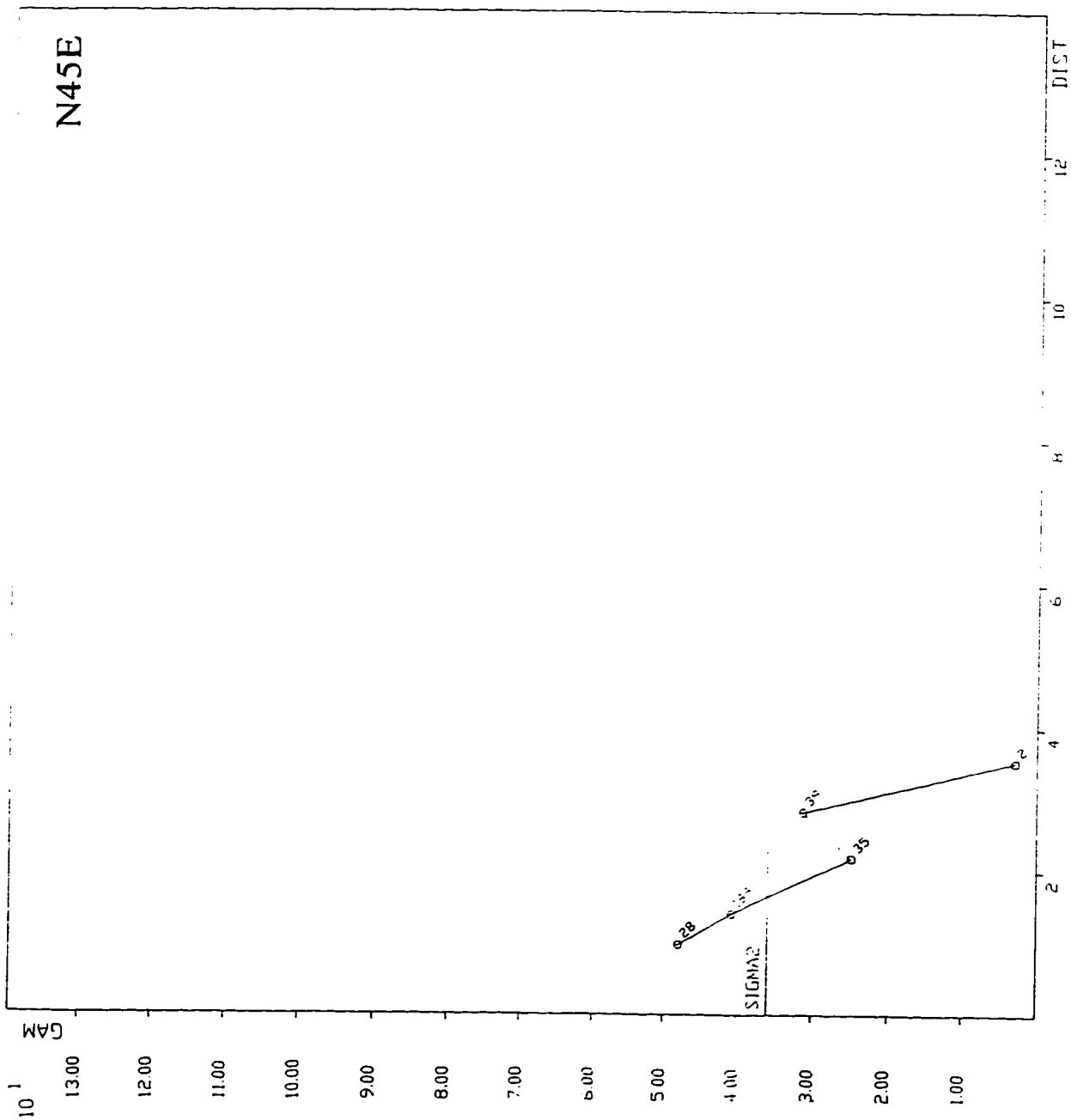


VARIABLE PEDS  
(Horizon 1)      ABILITY      GAM

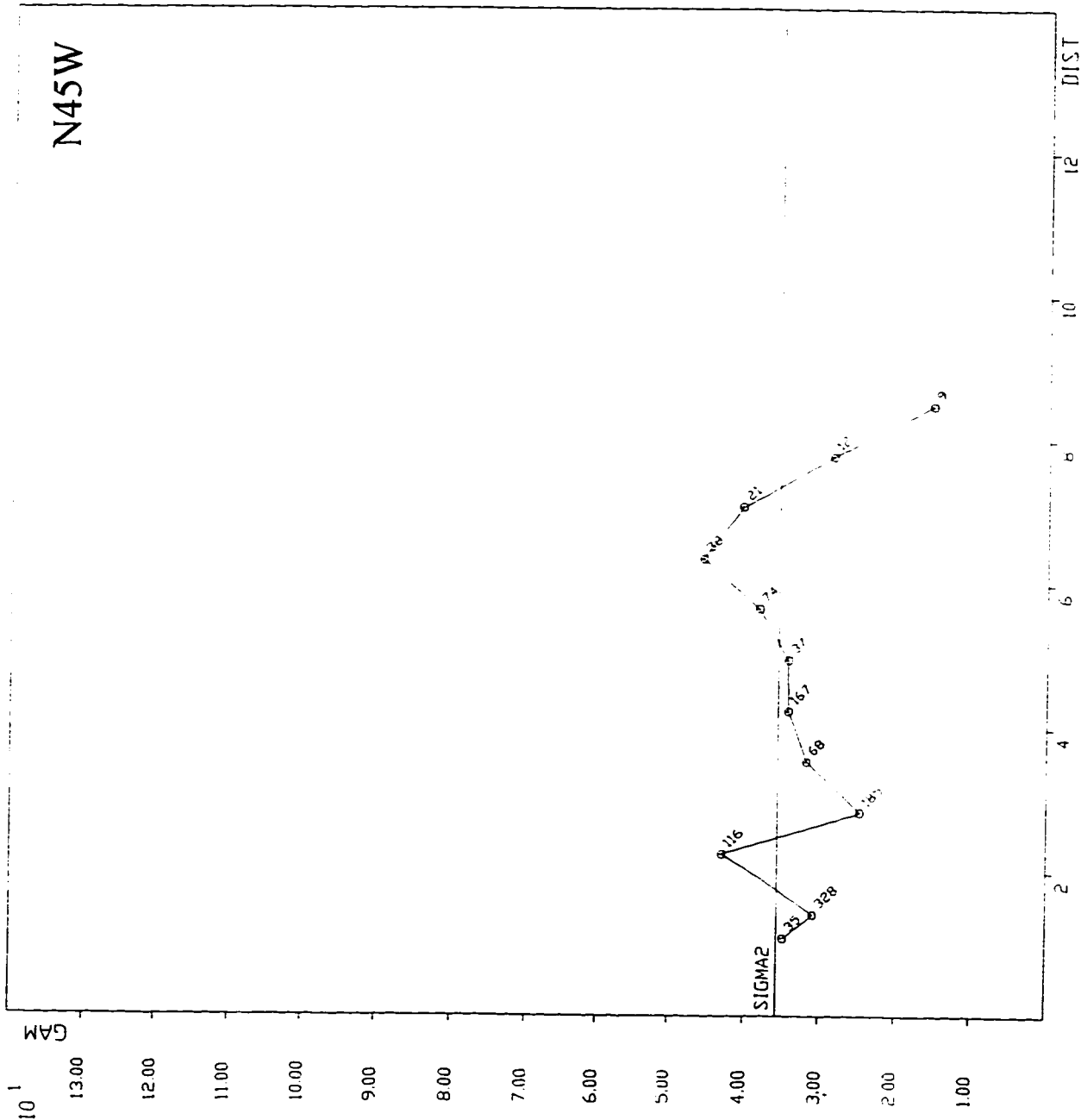
Isotropy (original data table)

## **APPENDIX F**

Experimental semivariograms for the original drill-holes data in Horizon 3

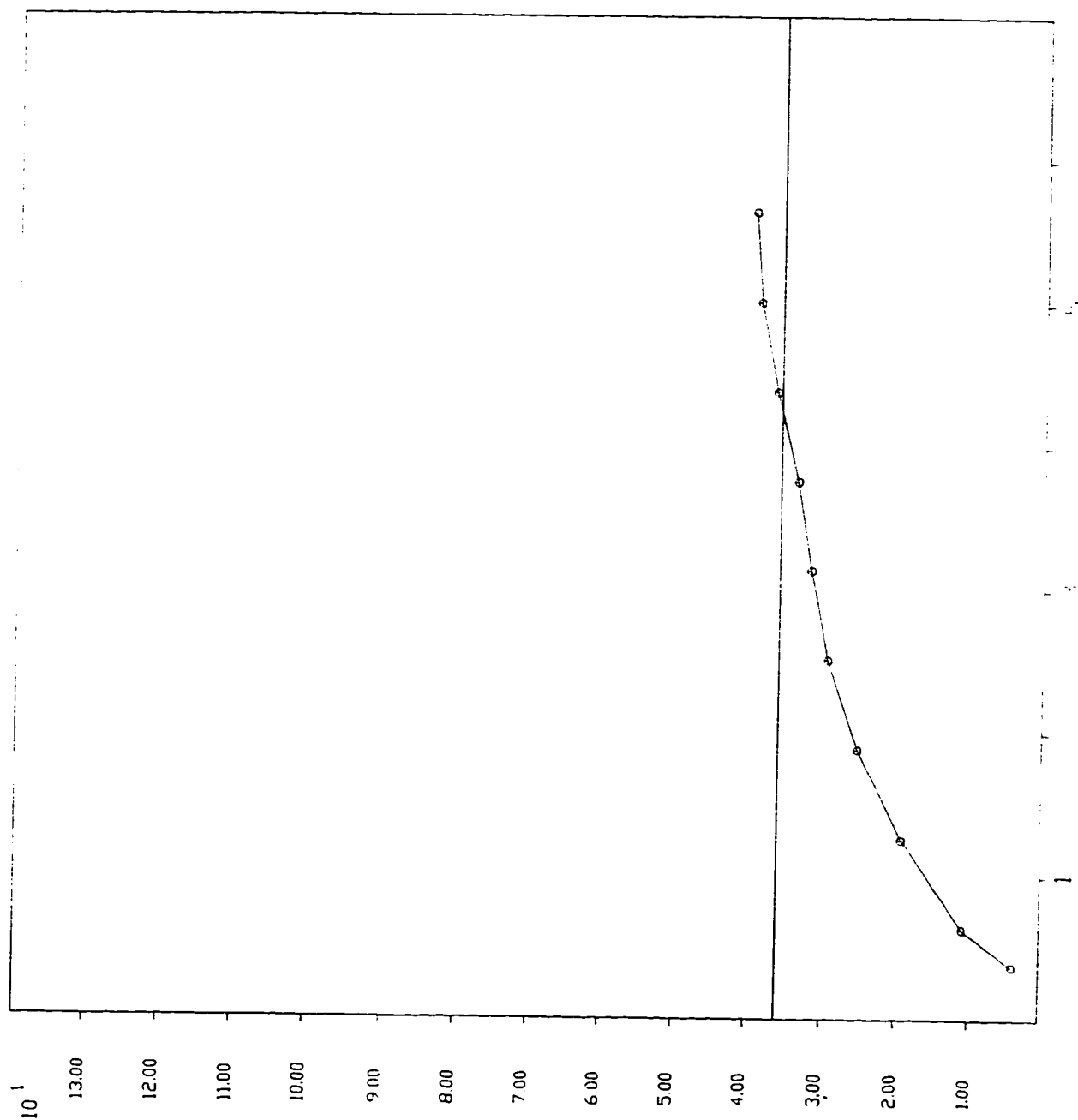


VARIABLE P205  
 CHDR12/10  
 ABSOLUTE CAP116GAM

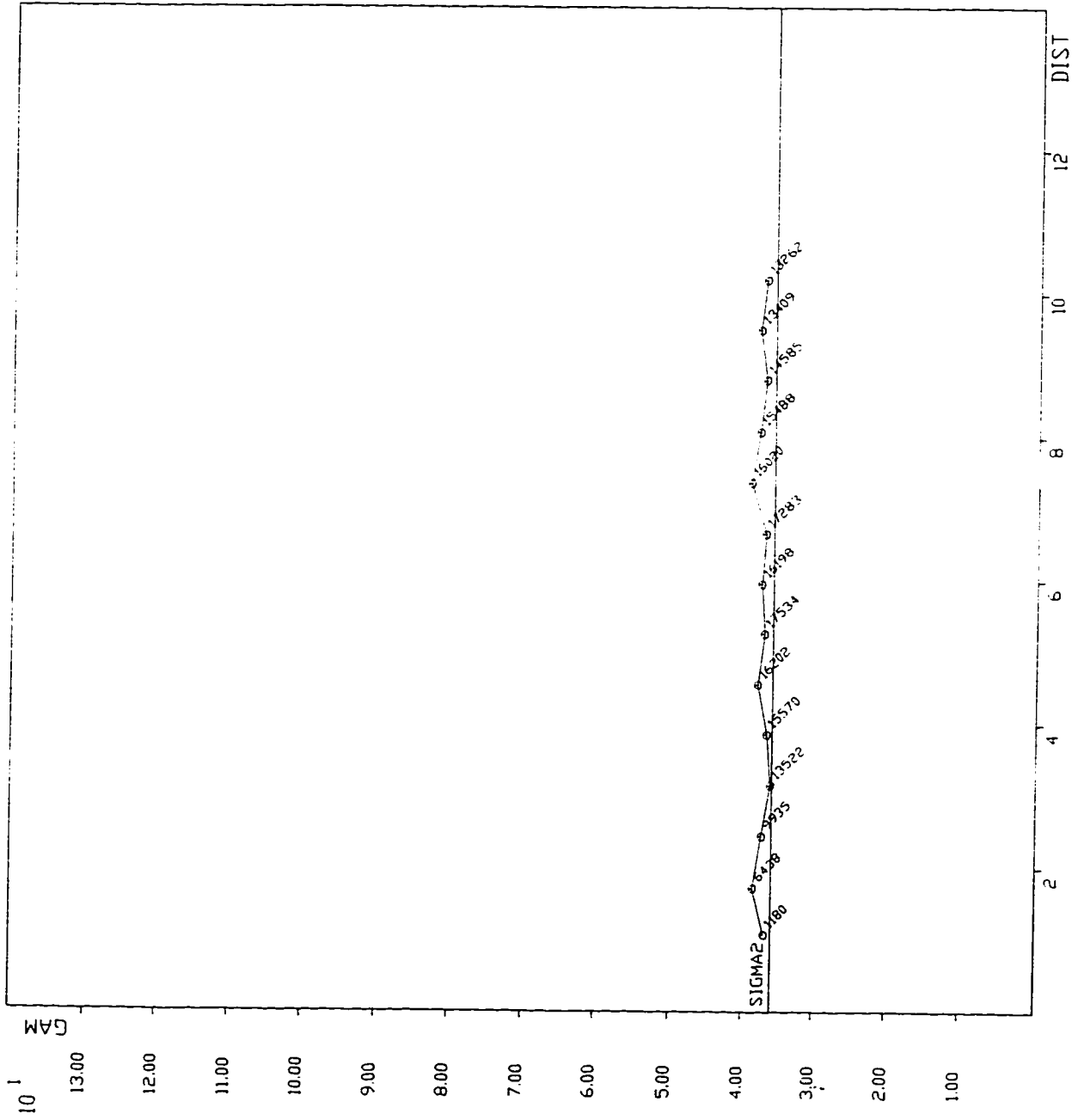


VARIABLE P205  
(HORIZON 3)

ABSOLUTE VARIOGRAM  
Horizontal Semivariogram for signal (drill-holes)



VARIABLE FIELD (HORIZON) 30  
Vertical Distance (Feet) 1000



VARIABLE P205  
(HORIZON 3)  
ABJ1111  
isotropy (corrected for holes)  
VARIDIGRAM

## **APPENDIX G**

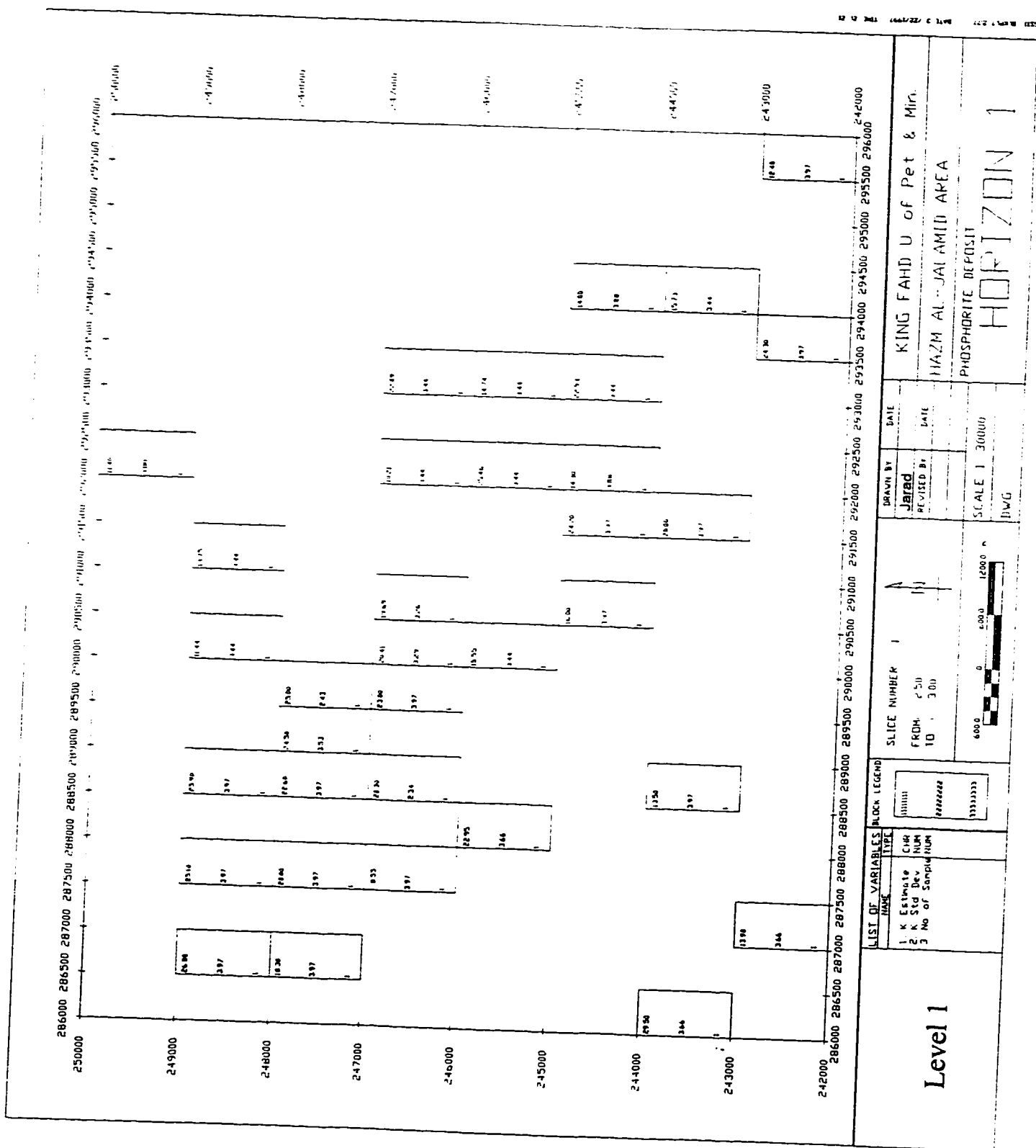
An excerpt from the kriging output file

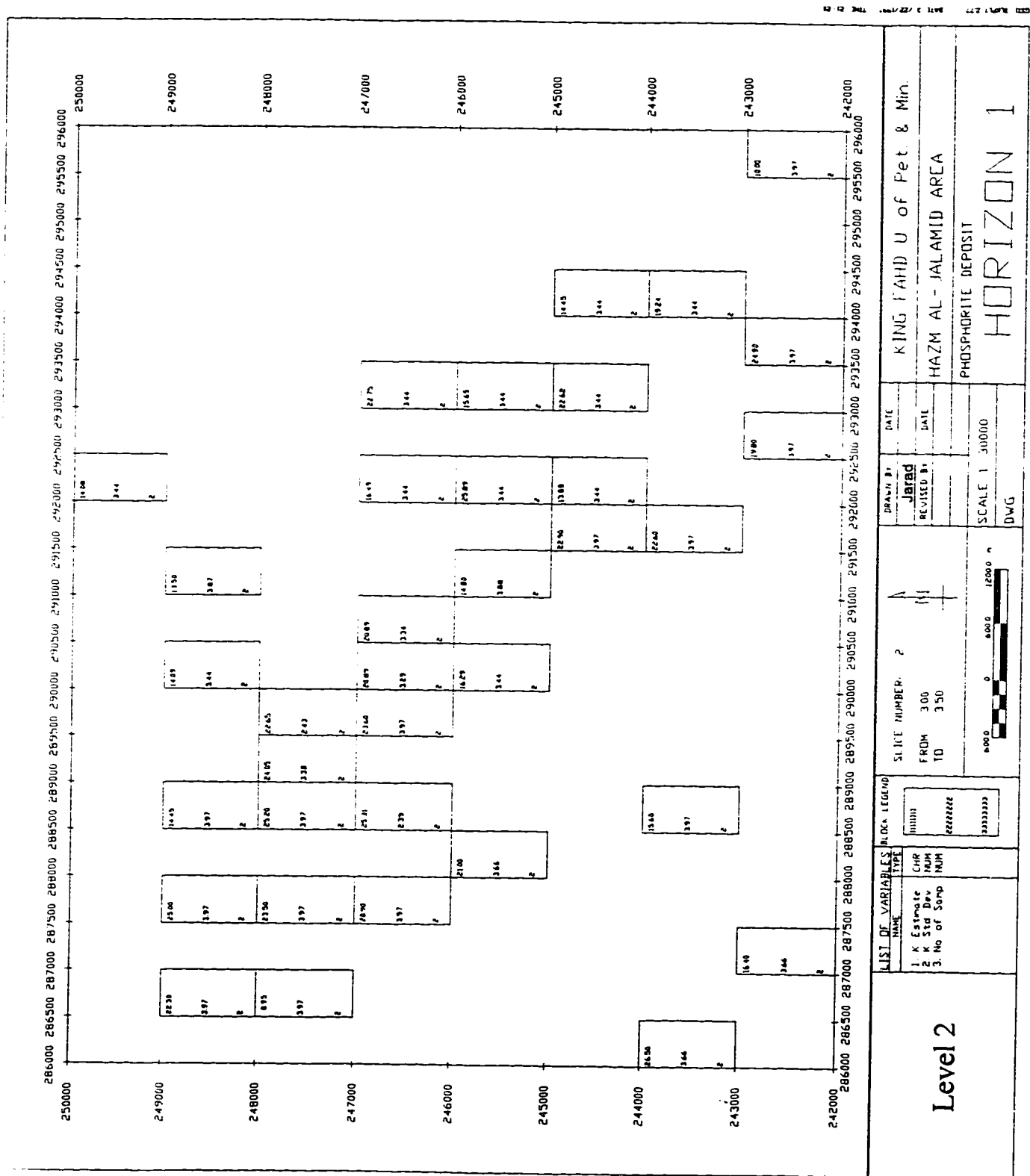
| X-index | Y-index | Z-index | No. of Samples | Kriged Estimate | Kriging Standard Deviation |
|---------|---------|---------|----------------|-----------------|----------------------------|
| 3       | 1       | 1       | 2              | 13.90           | 3.66                       |
| 16      | 1       | 1       | 1              | 24.30           | 3.97                       |
| 20      | 1       | 1       | 1              | 12.40           | 3.97                       |
| 1       | 2       | 1       | 2              | 29.50           | 3.66                       |
| 6       | 2       | 1       | 1              | 13.50           | 3.97                       |
| 12      | 2       | 1       | 1              | 20.00           | 3.97                       |
| 17      | 2       | 1       | 2              | 15.73           | 3.44                       |
| 10      | 3       | 1       | 1              | 16.00           | 3.97                       |
| 12      | 3       | 1       | 1              | 24.20           | 3.97                       |
| 13      | 3       | 1       | 1              | 14.30           | 3.88                       |
| 15      | 3       | 1       | 2              | 22.93           | 3.44                       |
| 17      | 3       | 1       | 1              | 14.00           | 3.88                       |
| 5       | 4       | 1       | 2              | 22.95           | 3.66                       |
| 9       | 4       | 1       | 2              | 15.55           | 3.44                       |
| 13      | 4       | 1       | 2              | 25.46           | 3.44                       |
| 15      | 4       | 1       | 2              | 14.74           | 3.44                       |
| 4       | 5       | 1       | 1              | 8.55            | 3.97                       |
| 6       | 5       | 1       | 8              | 20.30           | 2.34                       |
| 8       | 5       | 1       | 1              | 23.00           | 3.97                       |
| 9       | 5       | 1       | 4              | 20.41           | 3.29                       |
| 10      | 5       | 1       | 4              | 19.69           | 3.26                       |
| 13      | 5       | 1       | 2              | 10.21           | 3.44                       |
| 15      | 5       | 1       | 4              | 22.09           | 3.44                       |
| 2       | 6       | 1       | 1              | 18.30           | 3.97                       |
| 4       | 6       | 1       | 1              | 20.00           | 3.97                       |
| 6       | 6       | 1       | 1              | 22.60           | 3.97                       |
| 7       | 6       | 1       | 2              | 24.50           | 3.53                       |
| 8       | 6       | 1       | 6              | 25.00           | 2.43                       |
| 2       | 7       | 1       | 1              | 26.80           | 3.97                       |
| 4       | 7       | 1       | 1              | 25.10           | 3.97                       |
| 6       | 7       | 1       | 1              | 25.90           | 3.97                       |
| 9       | 7       | 1       | 2              | 11.44           | 3.44                       |
| 11      | 7       | 1       | 2              | 13.75           | 3.44                       |
| 13      | 8       | 1       | 1              | 11.40           | 3.88                       |
| 3       | 1       | 2       | 2              | 16.40           | 3.66                       |
| 14      | 1       | 2       | 1              | 19.80           | 3.97                       |
| 16      | 1       | 2       | 1              | 24.90           | 3.97                       |
| 20      | 1       | 2       | 1              | 10.00           | 3.97                       |
| 1       | 2       | 2       | 2              | 26.50           | 3.66                       |
| 6       | 2       | 2       | 1              | 15.60           | 3.97                       |
| 12      | 2       | 2       | 1              | 22.60           | 3.97                       |
| 17      | 2       | 2       | 2              | 19.24           | 3.44                       |
| 12      | 3       | 2       | 1              | 22.90           | 3.97                       |
| 13      | 3       | 2       | 2              | 13.88           | 3.44                       |
| 15      | 3       | 2       | 2              | 22.62           | 3.44                       |
| 17      | 3       | 2       | 2              | 14.45           | 3.44                       |
| 5       | 4       | 2       | 2              | 21.00           | 3.66                       |
| 9       | 4       | 2       | 2              | 16.29           | 3.44                       |

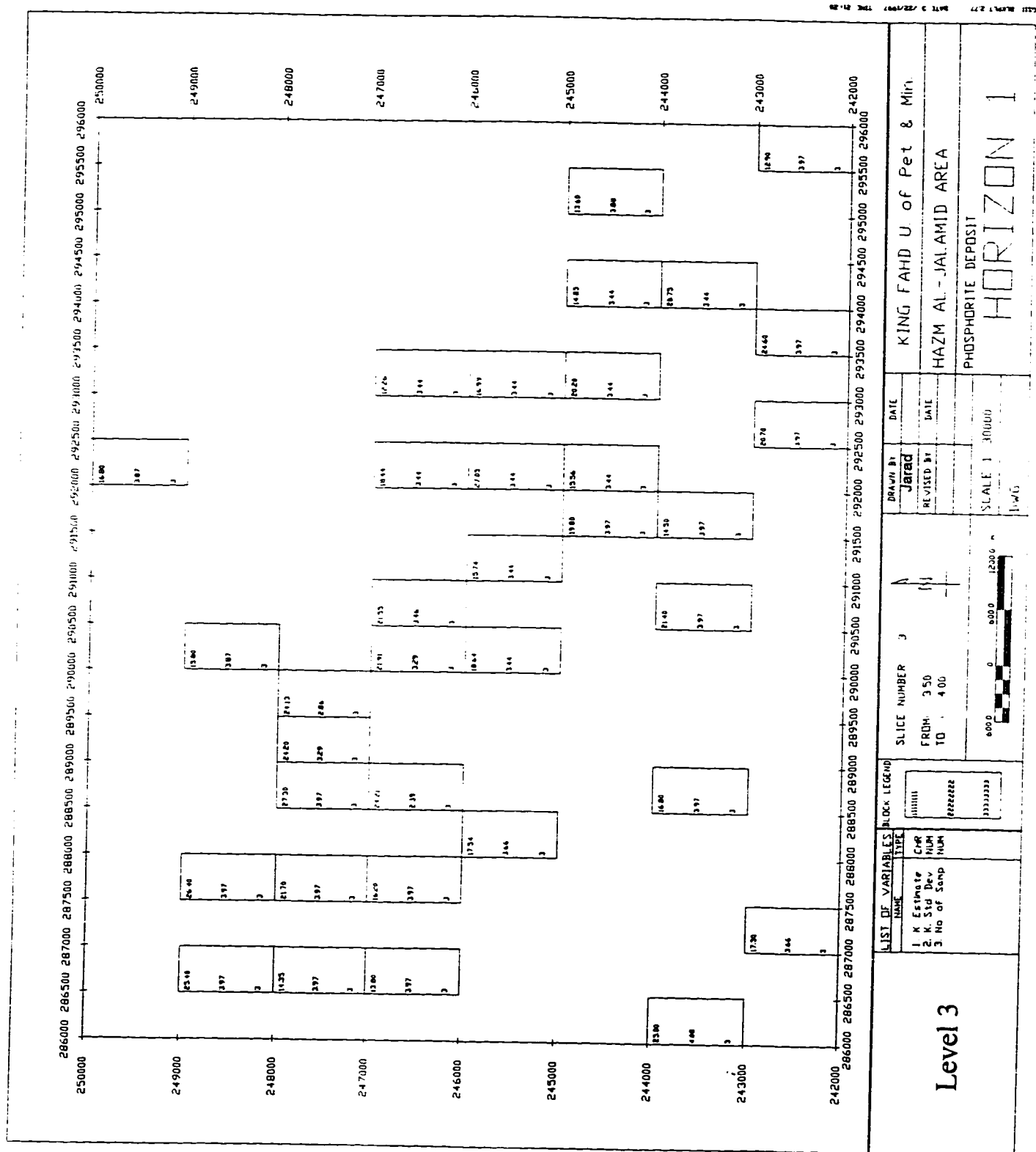


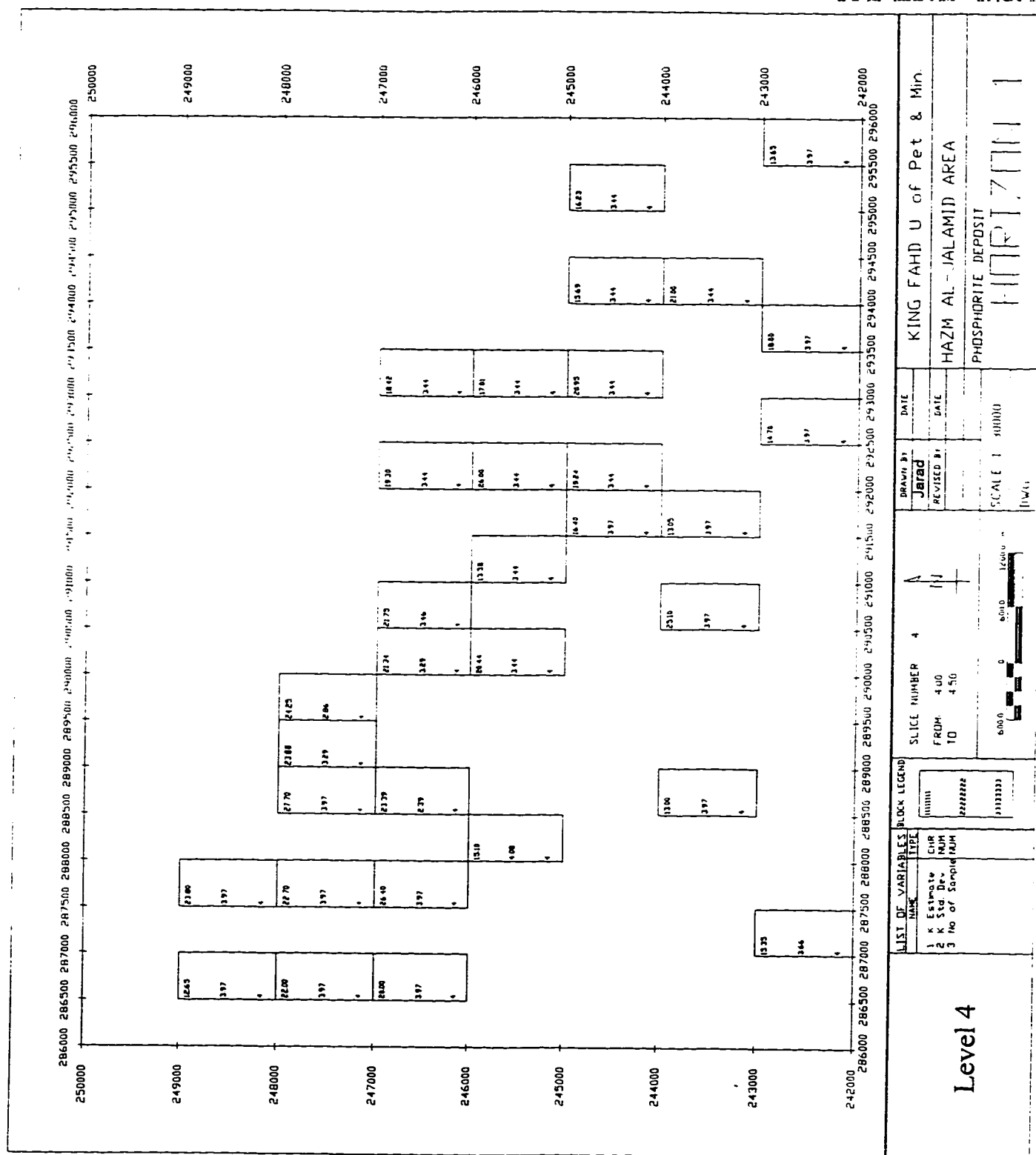
## **APPENDIX H**

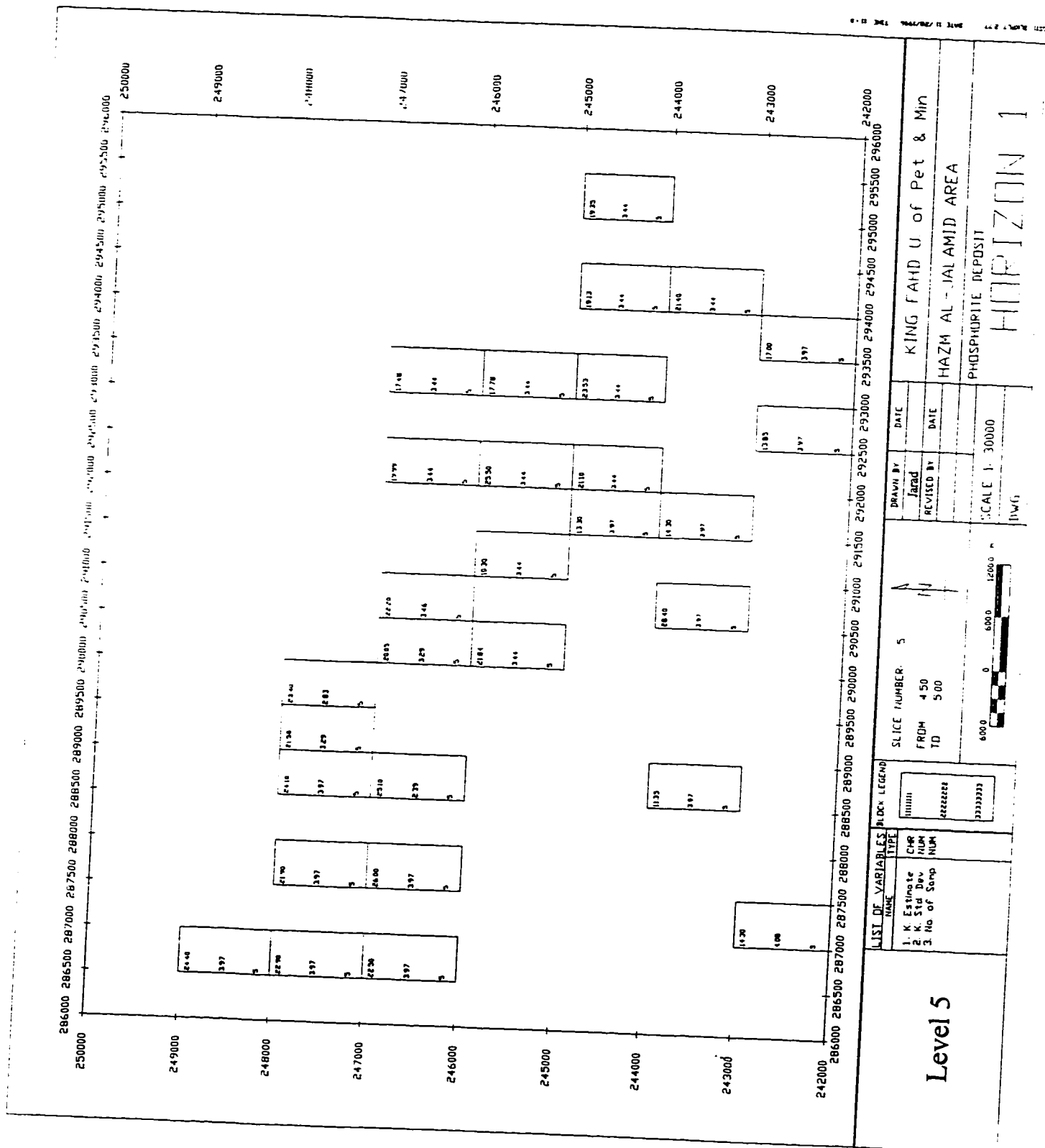
Kriging output maps for Horizon 1



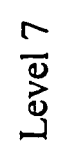




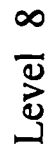


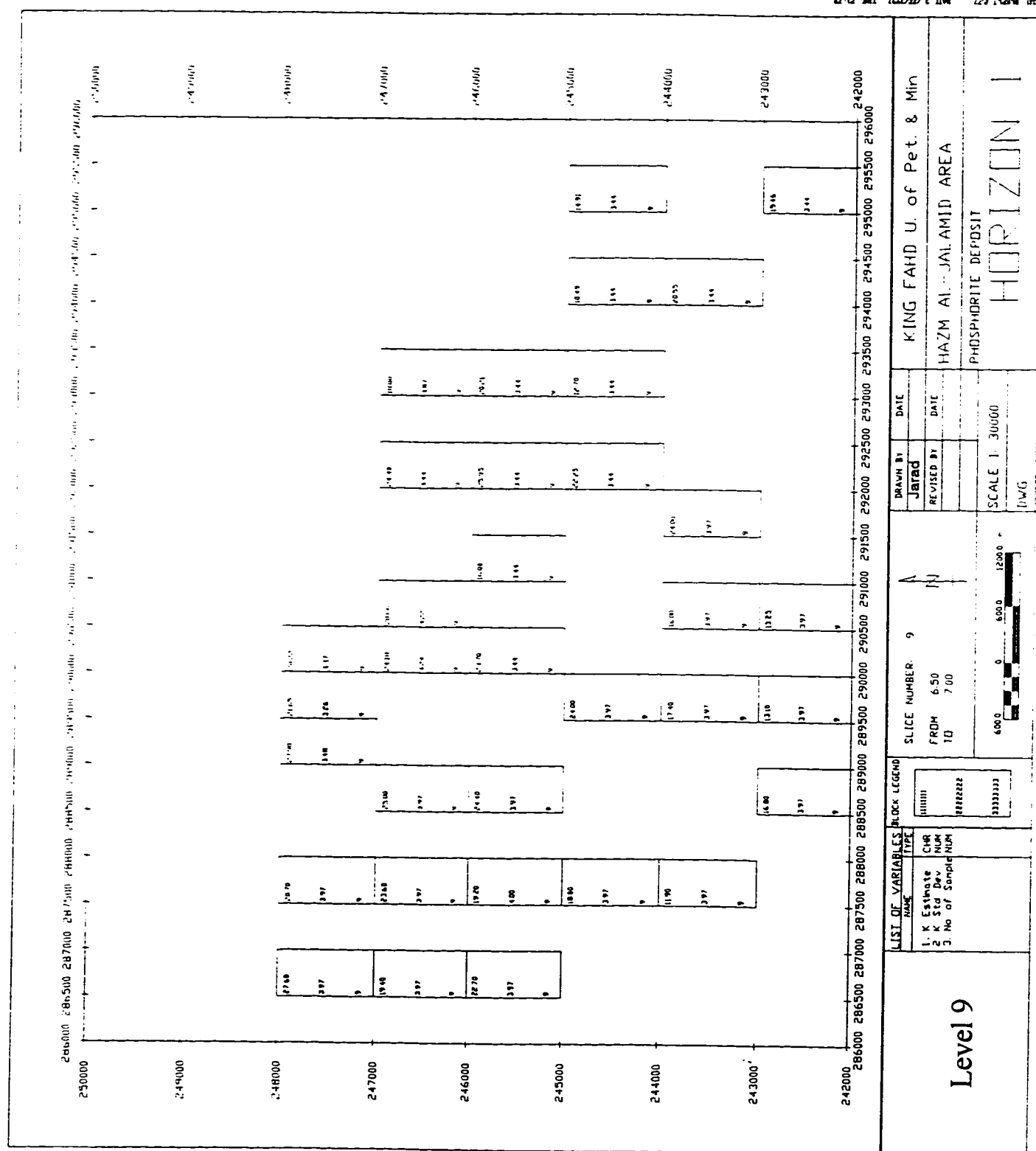


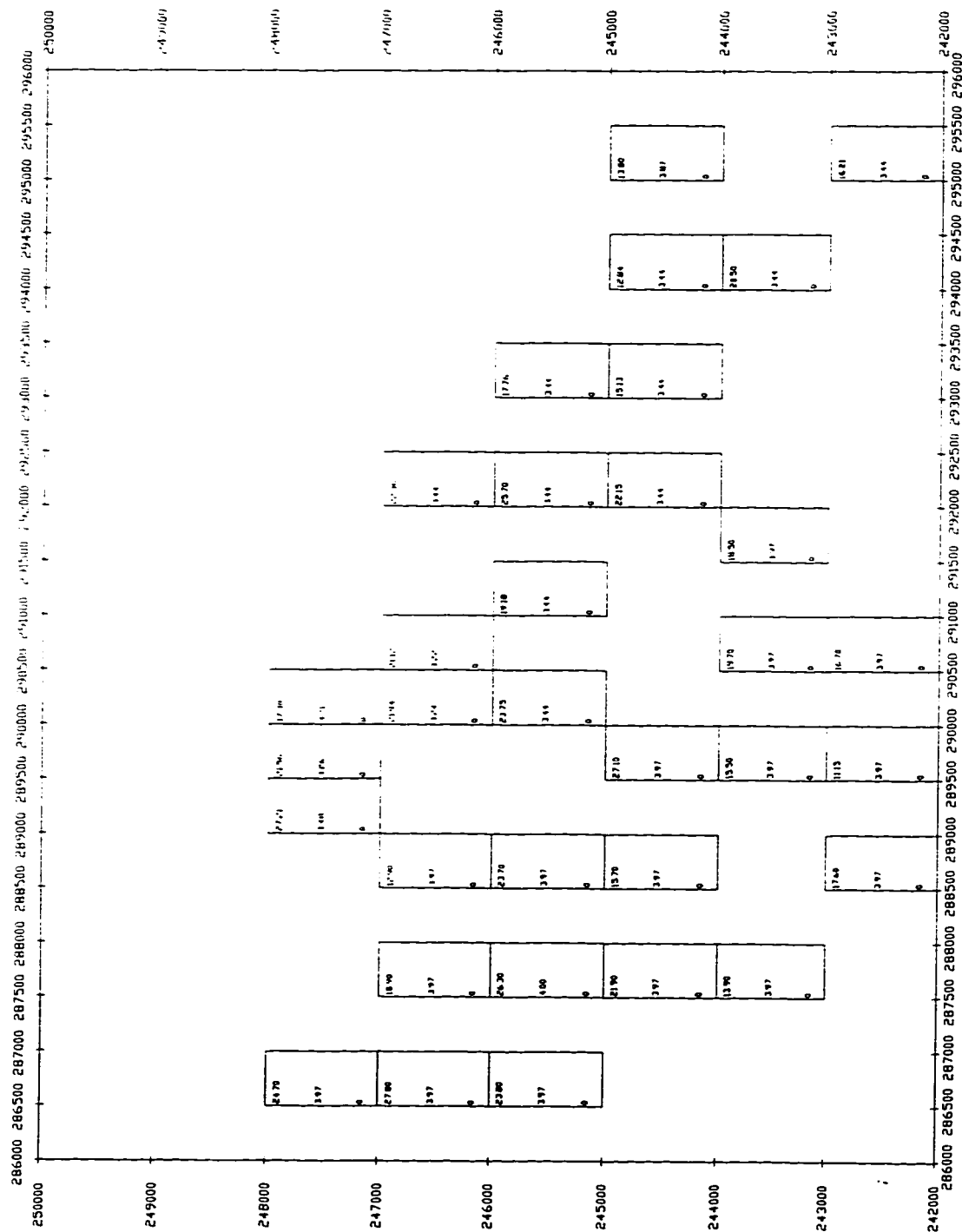












## Level 10

| LIST OF VARIABLES |      | BLOCK LEGEND                                                                                                                                                                                                                                                          |
|-------------------|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| NAME              | TYPE |                                                                                                                                                                                                                                                                       |
| 1 K Estimate      | CHR  | <div style="border: 1px solid black; padding: 5px; margin-bottom: 5px;">           000000<br/>           22222222         </div> <div style="display: flex; align-items: center;"> <div style="margin-left: 5px;">             0 600 0 1200 G           </div> </div> |
| 2 K Slope         | NUM  |                                                                                                                                                                                                                                                                       |
| 3 No of Sops      |      |                                                                                                                                                                                                                                                                       |

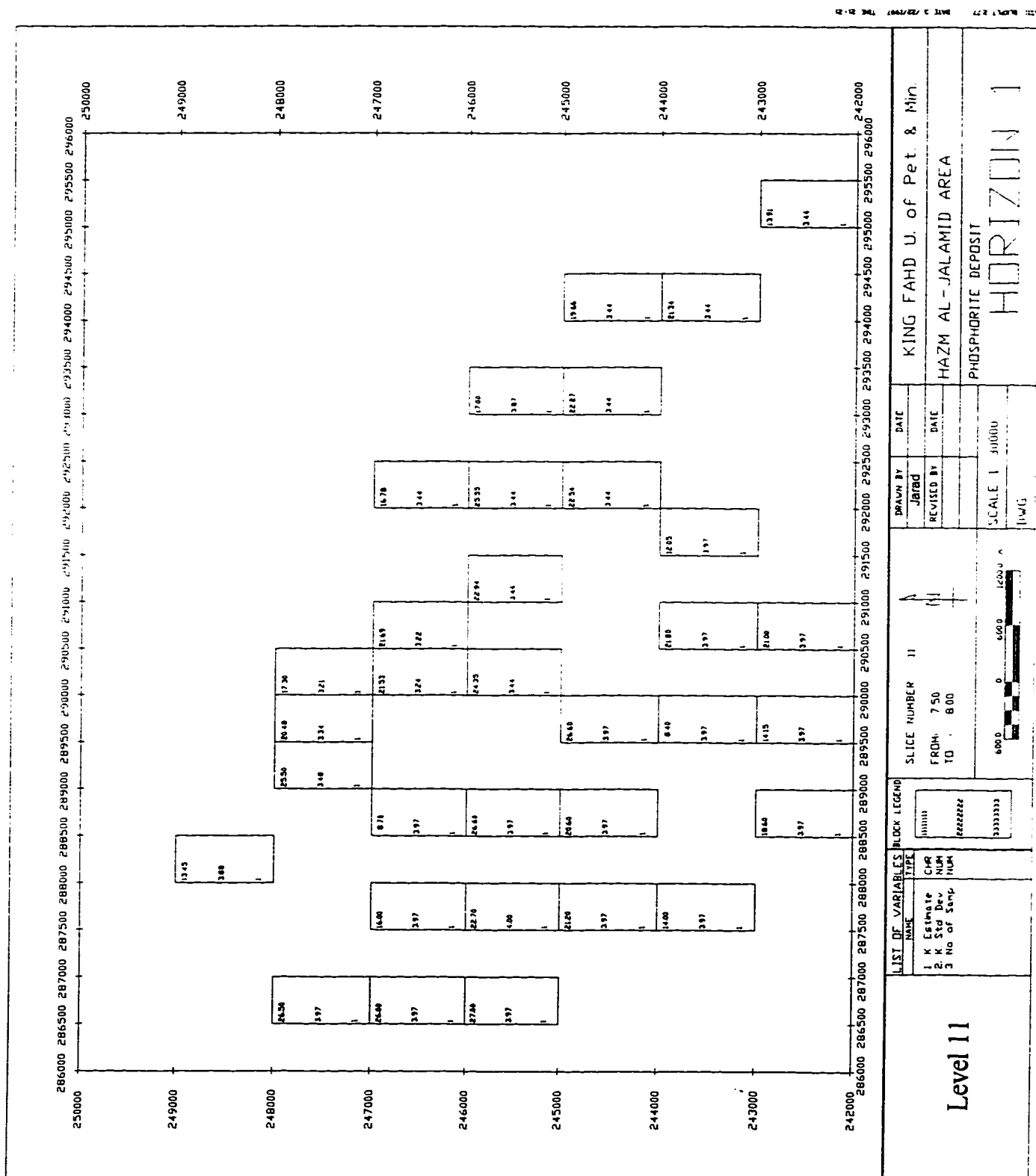
|                  |  |
|------------------|--|
| SLICE NUMBER: 10 |  |
| FROM 700         |  |
| TO 750           |  |

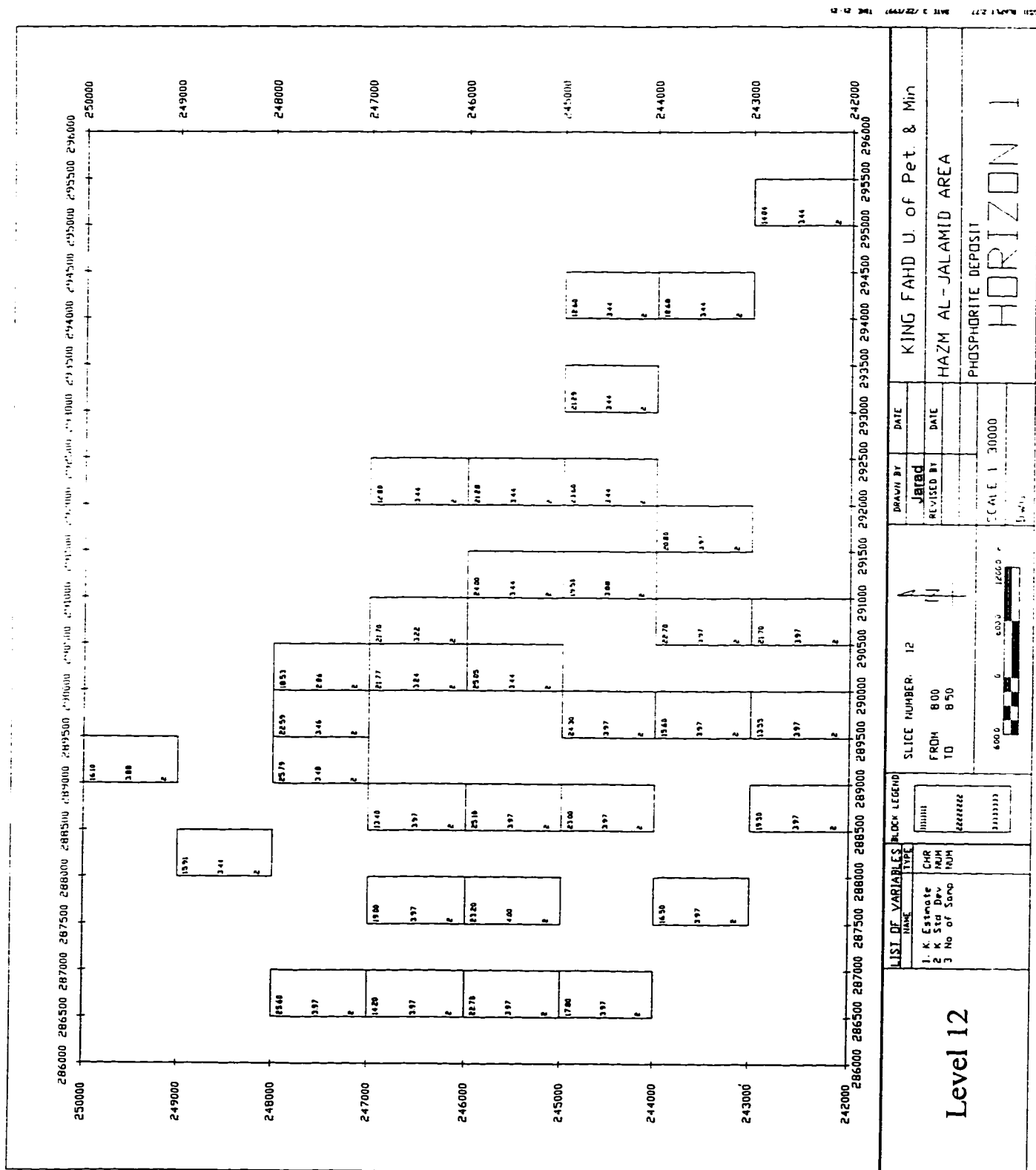
|                      |              |
|----------------------|--------------|
| SCALE 1 10000<br>DWG | DATE<br>DATE |
|----------------------|--------------|

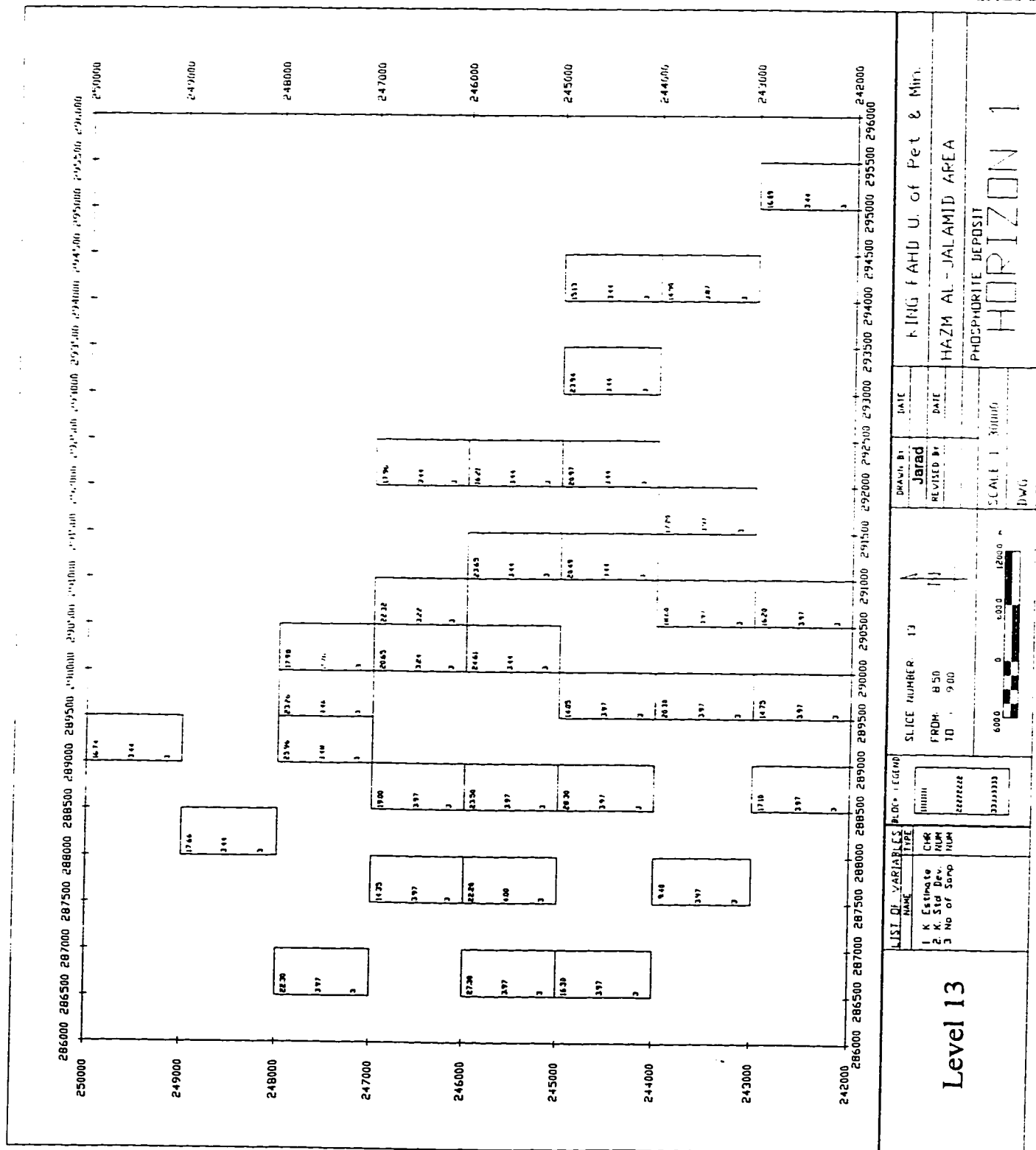
|                          |      |
|--------------------------|------|
| DRAWN BY<br><b>Jasad</b> | DATE |
| REVISED BY               | DATE |

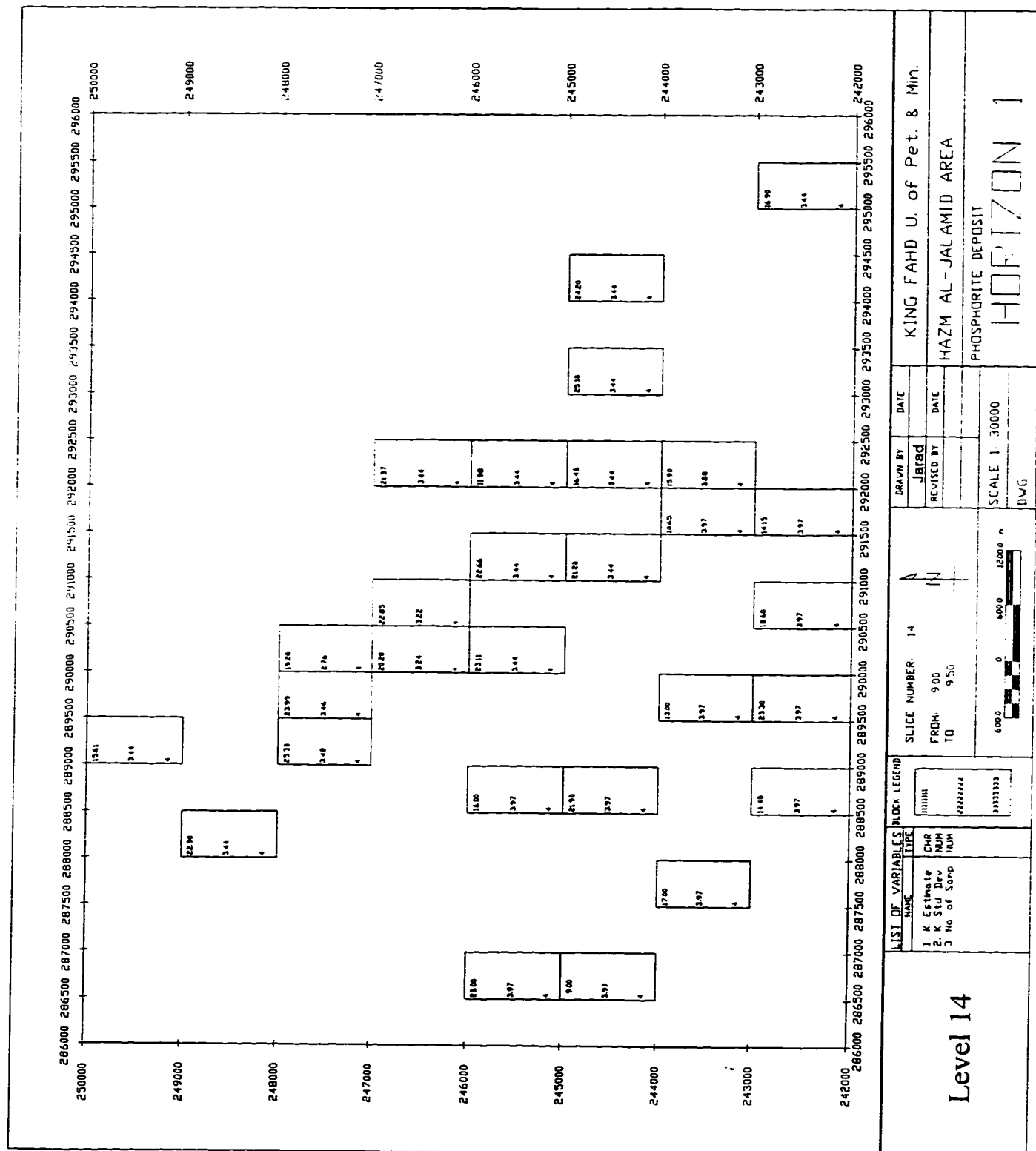
|                           |                        |
|---------------------------|------------------------|
| KING FAHD U. of Pet & Min | HAZM AL - JALAMID AREA |
| PHOSPHORITE DEPOSIT       |                        |

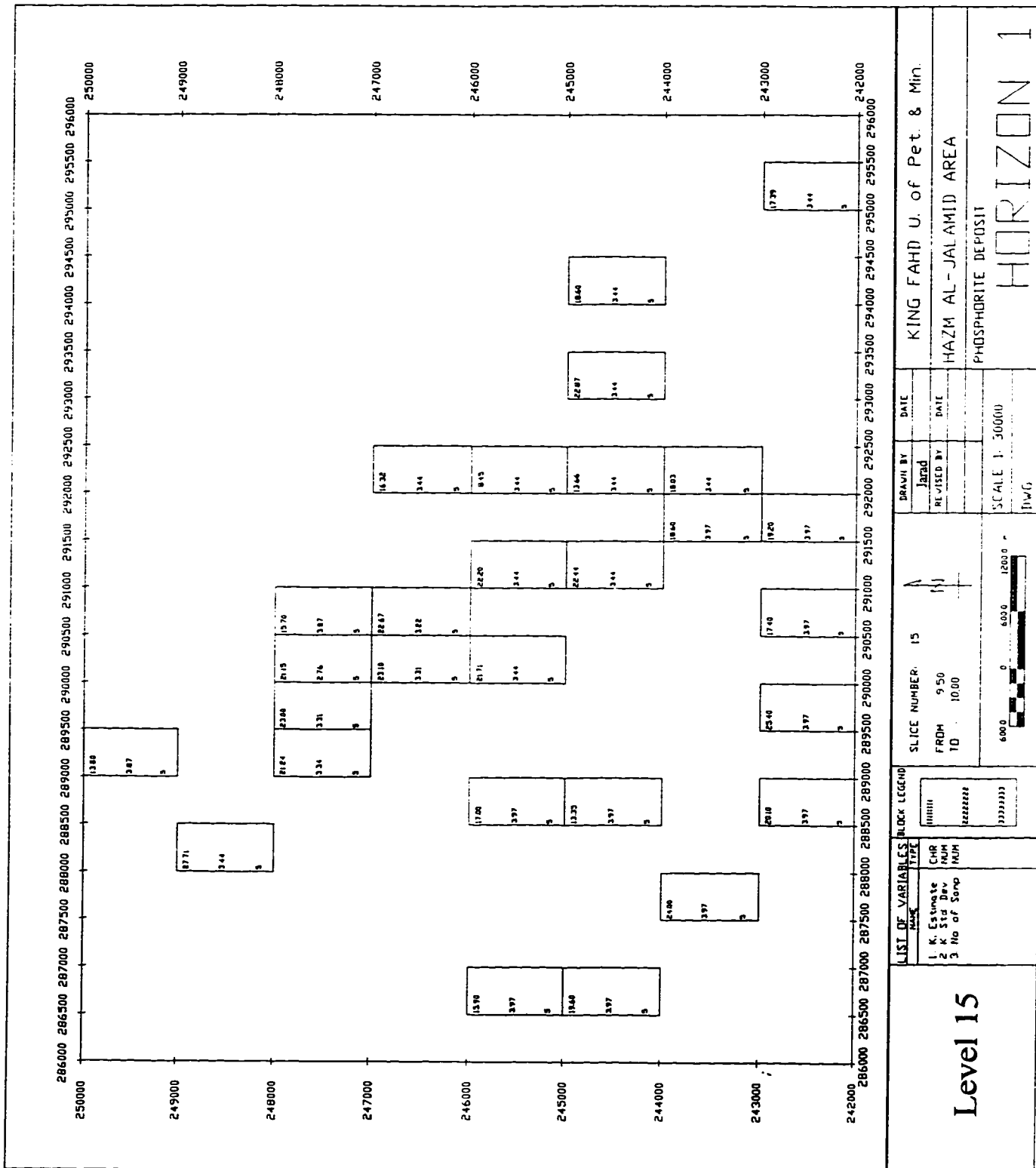
# HORIZON 1



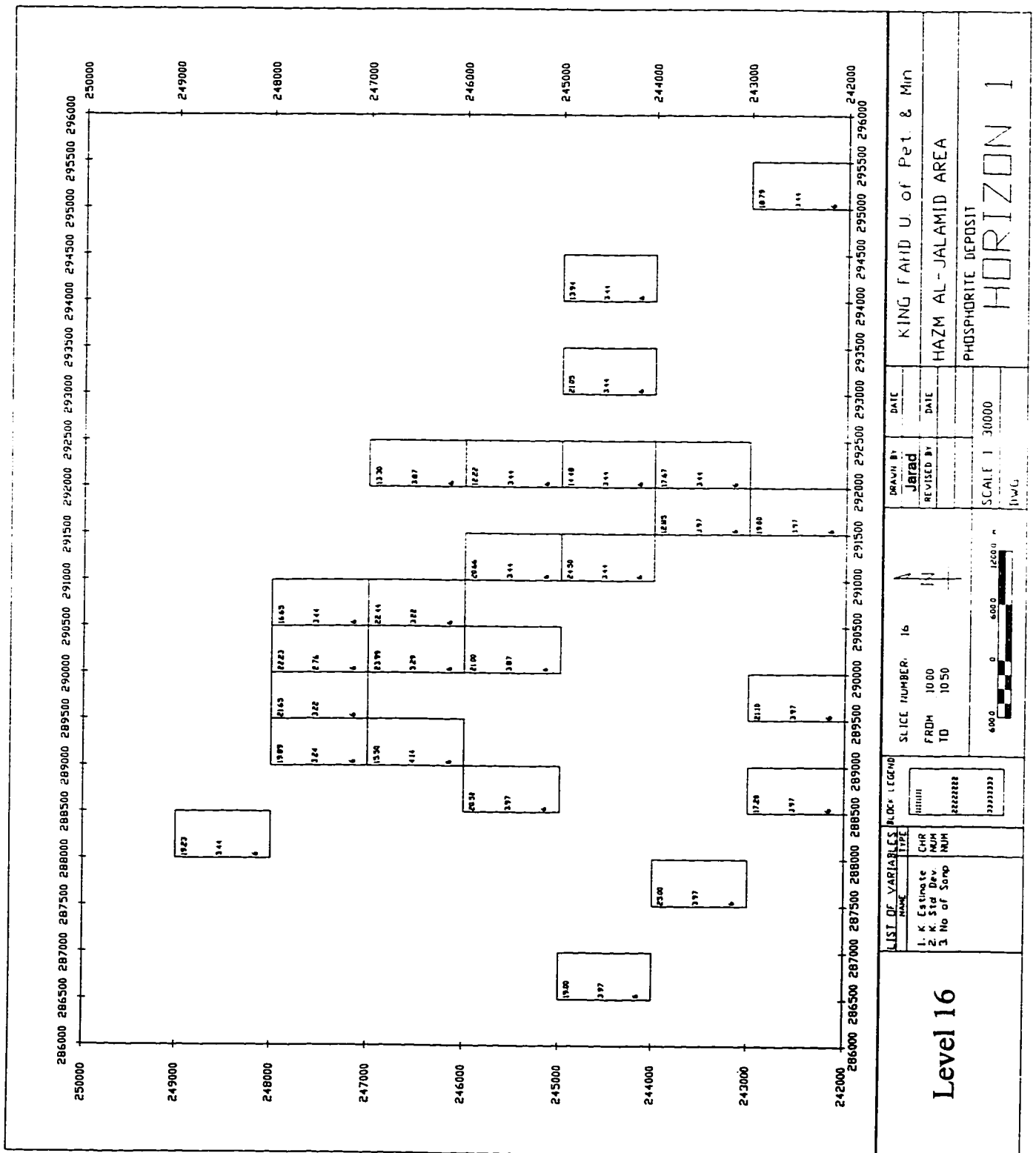


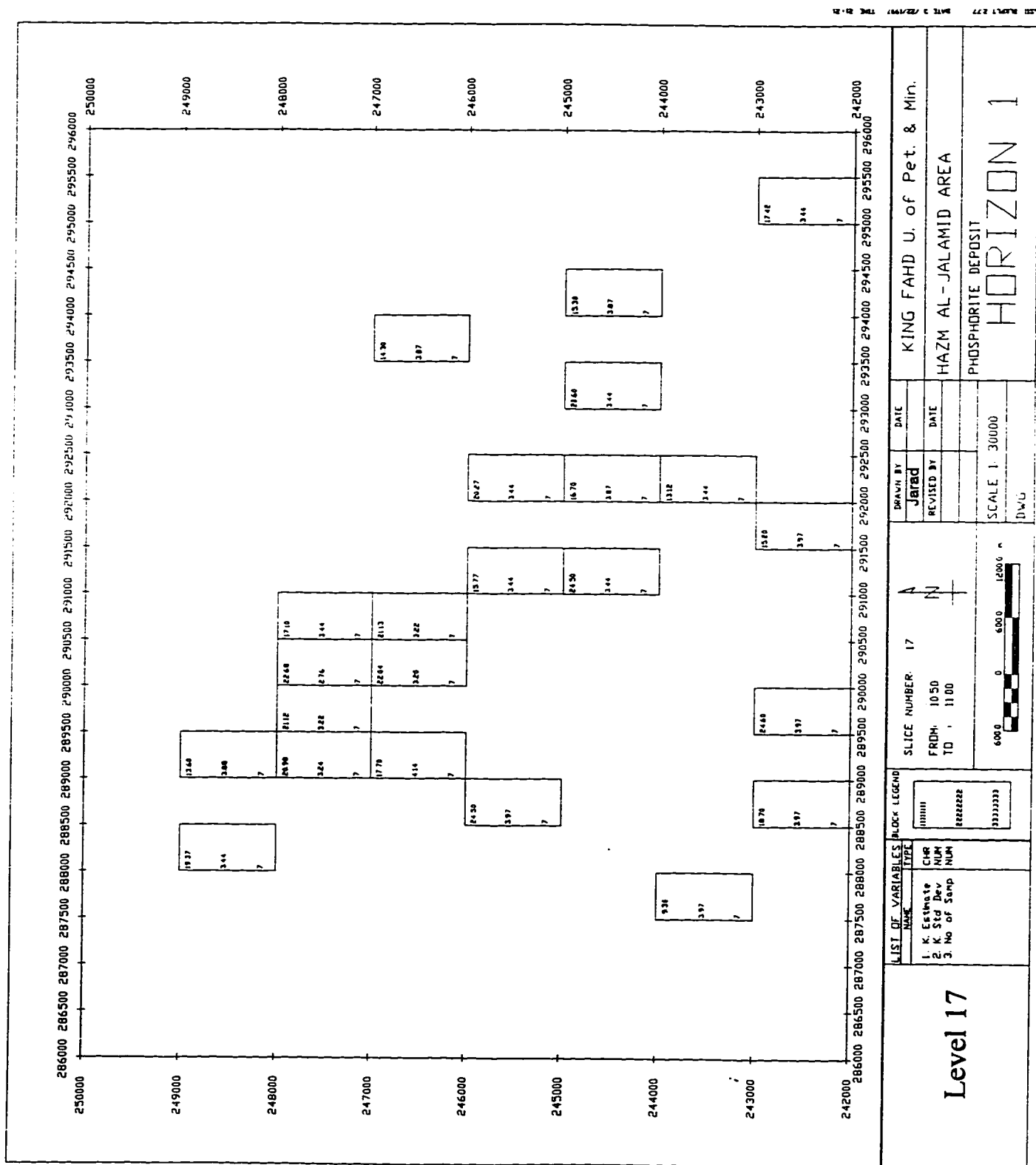


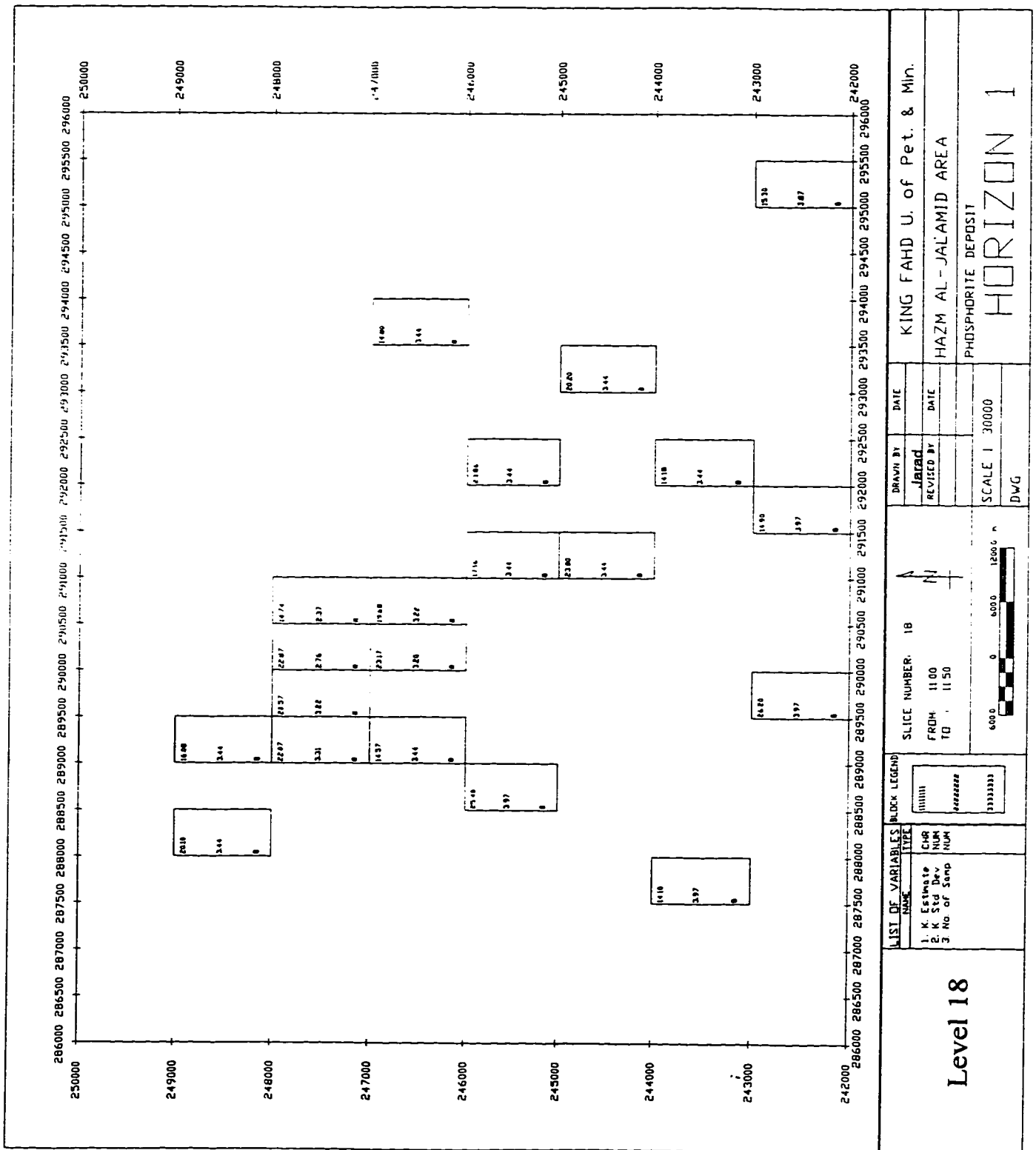


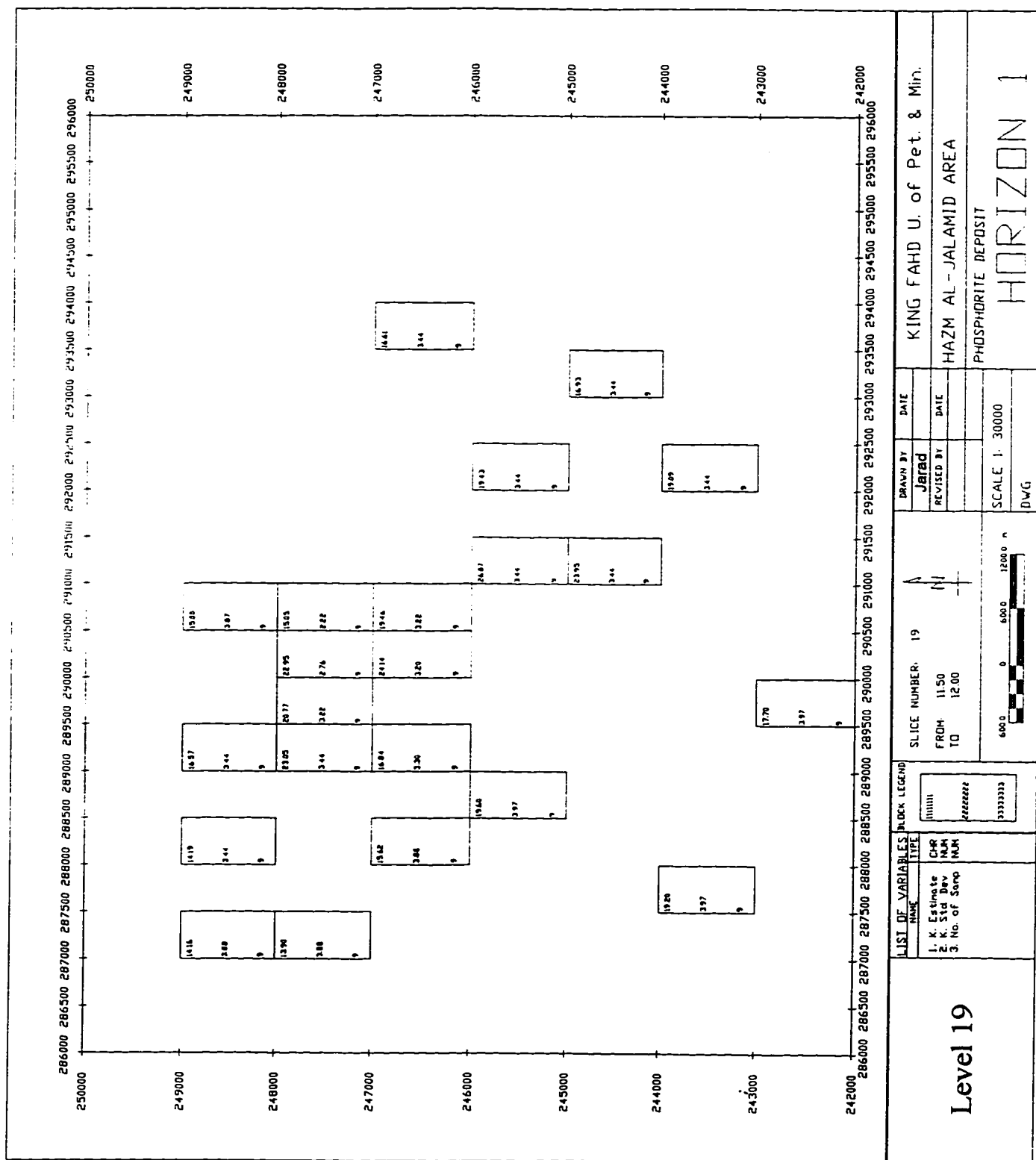


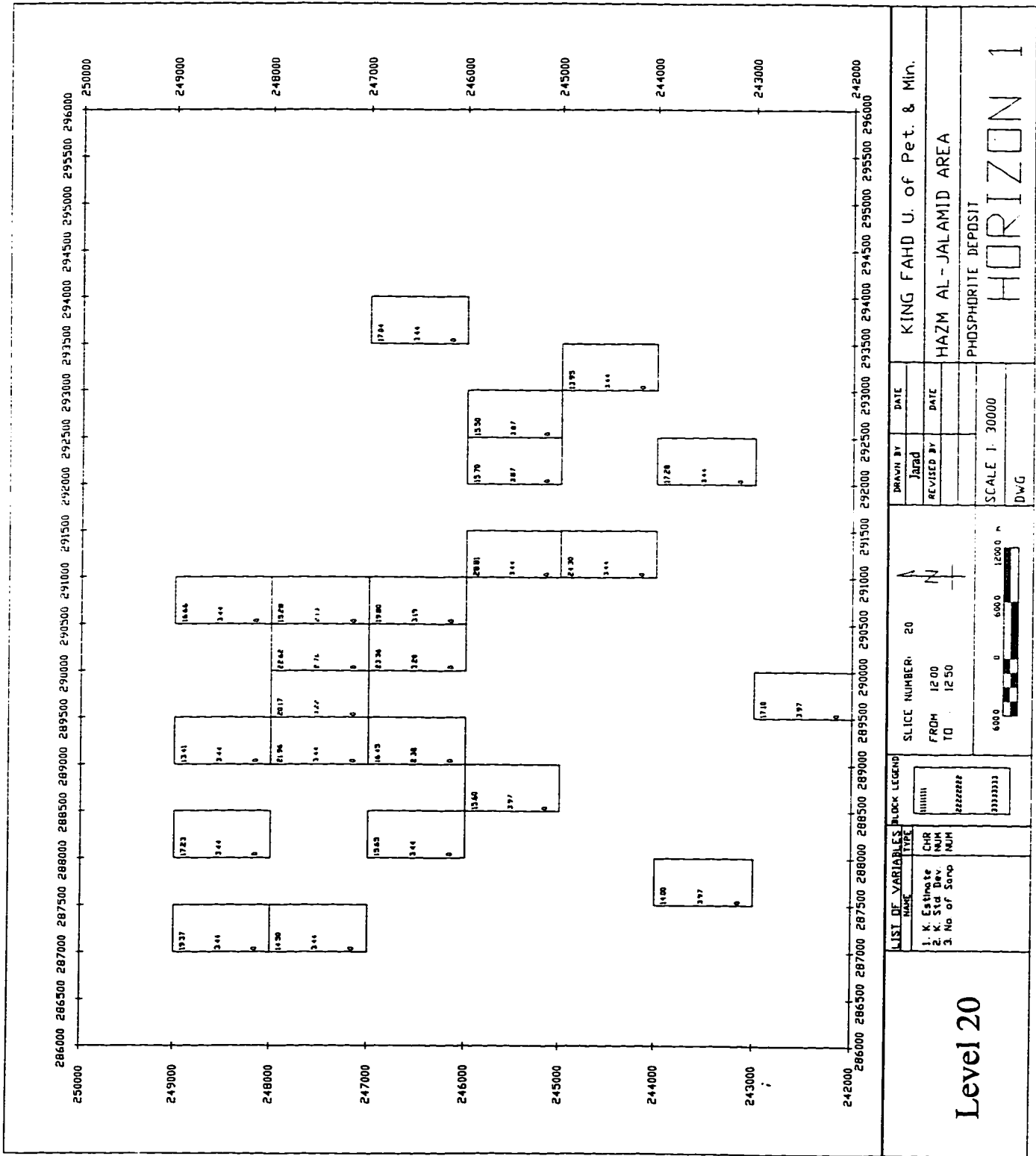


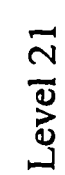


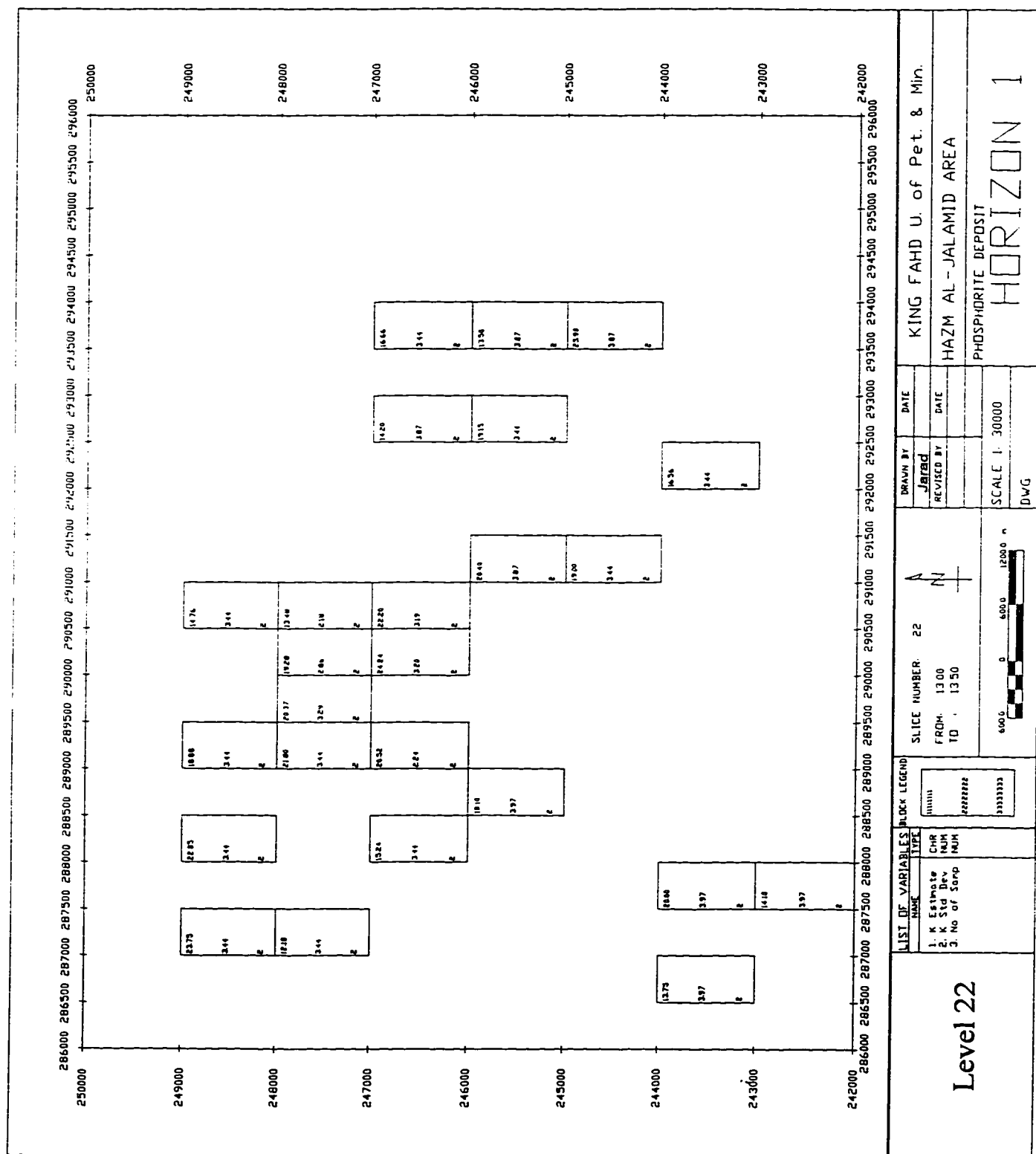


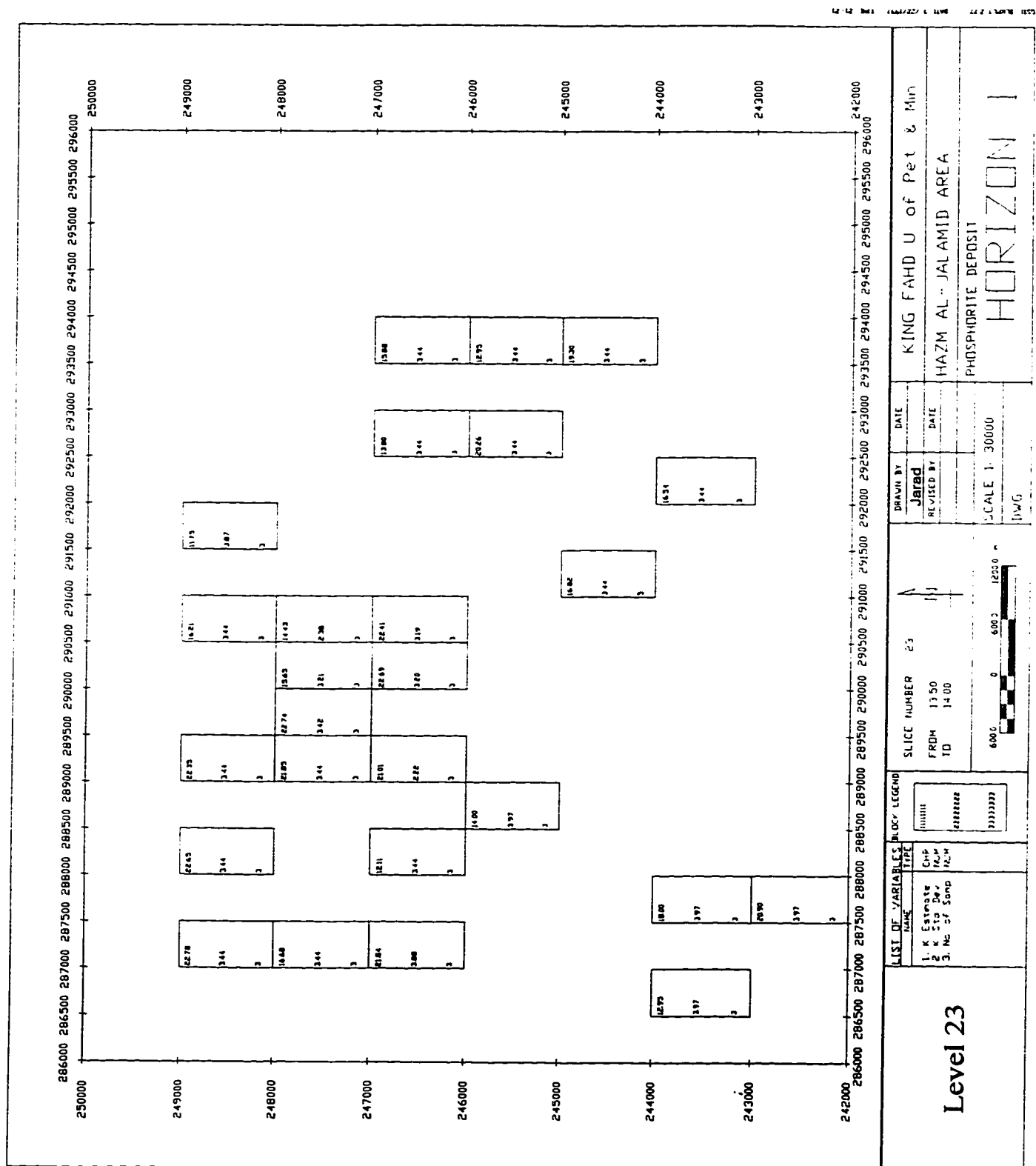




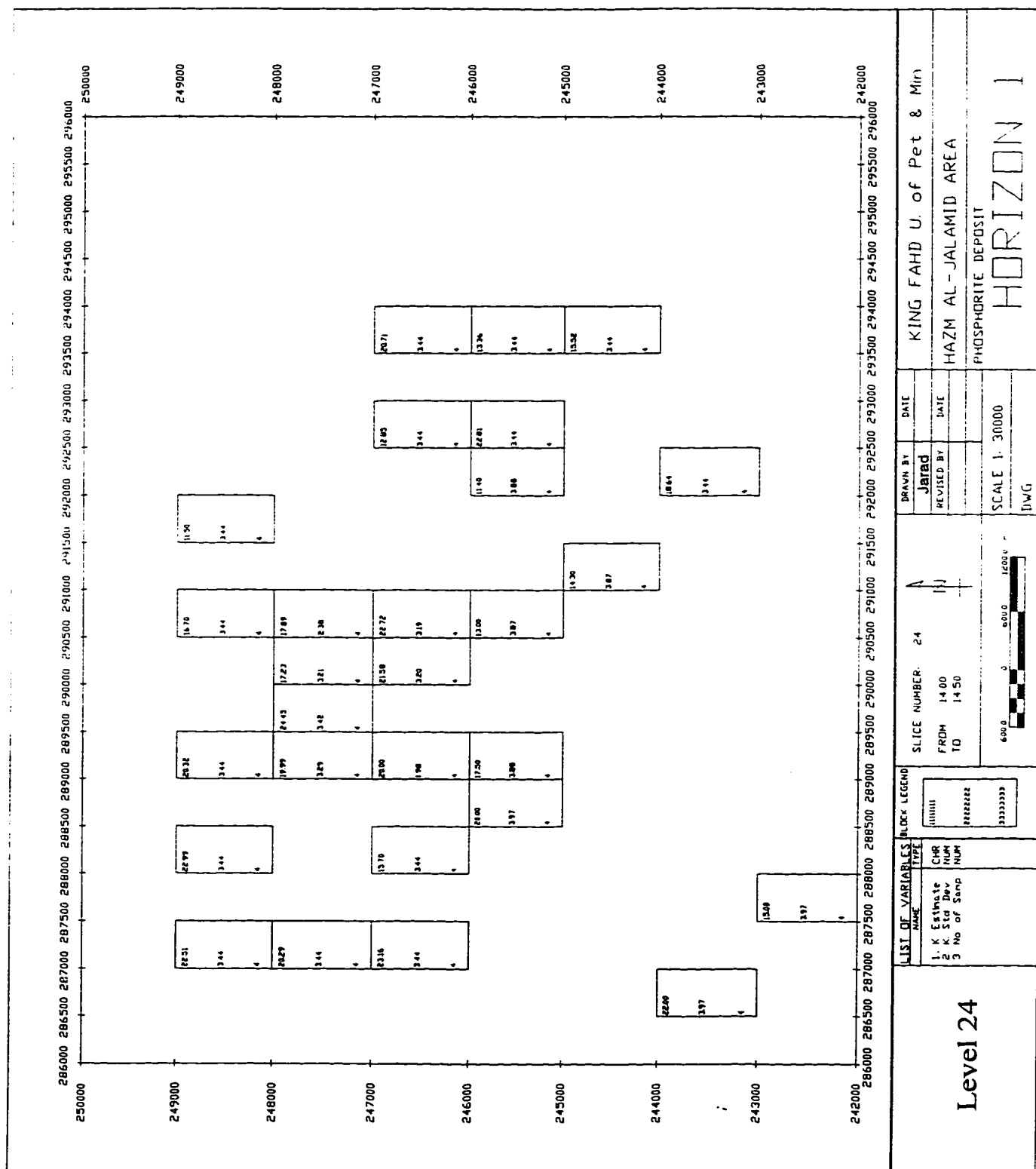


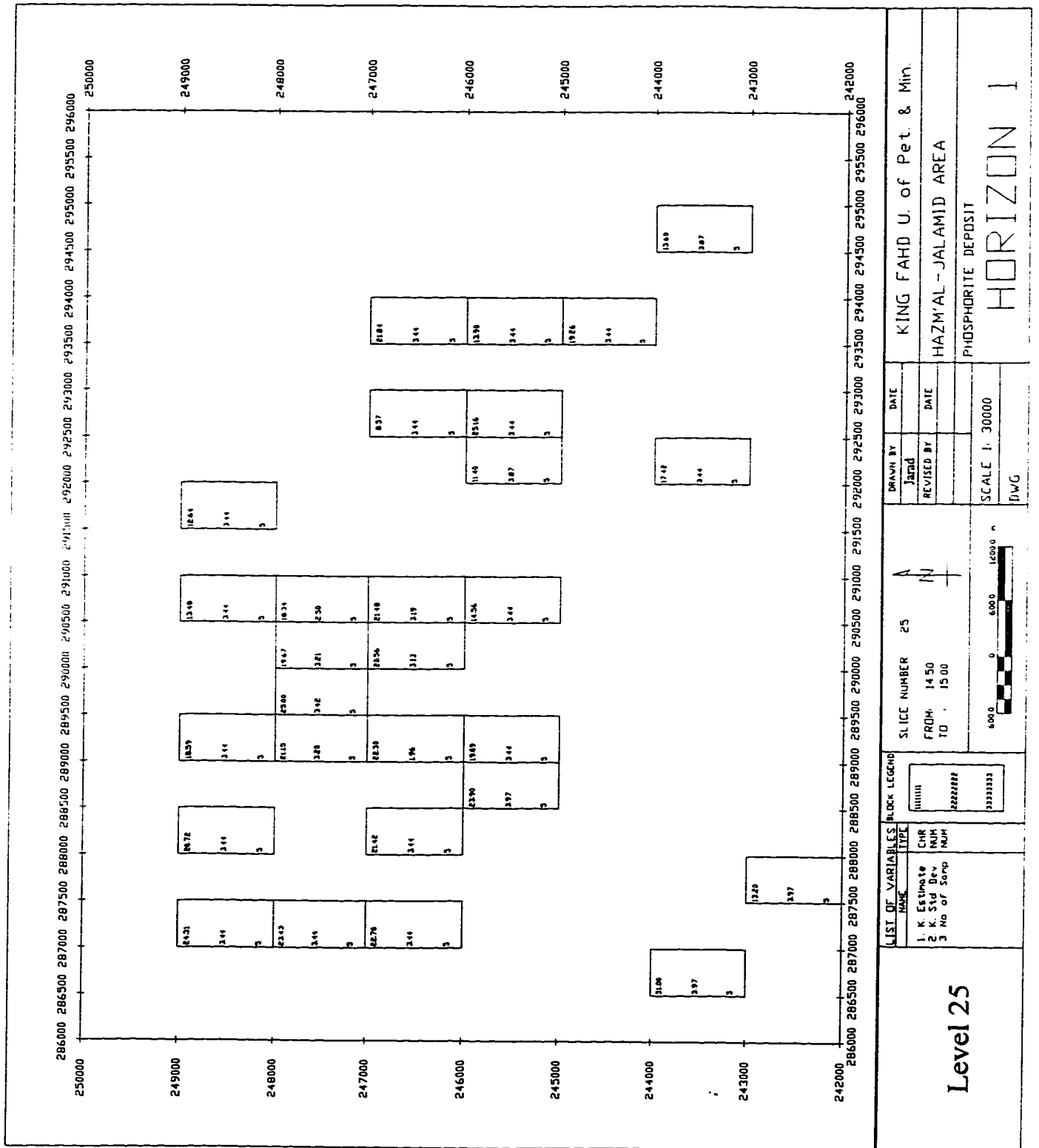


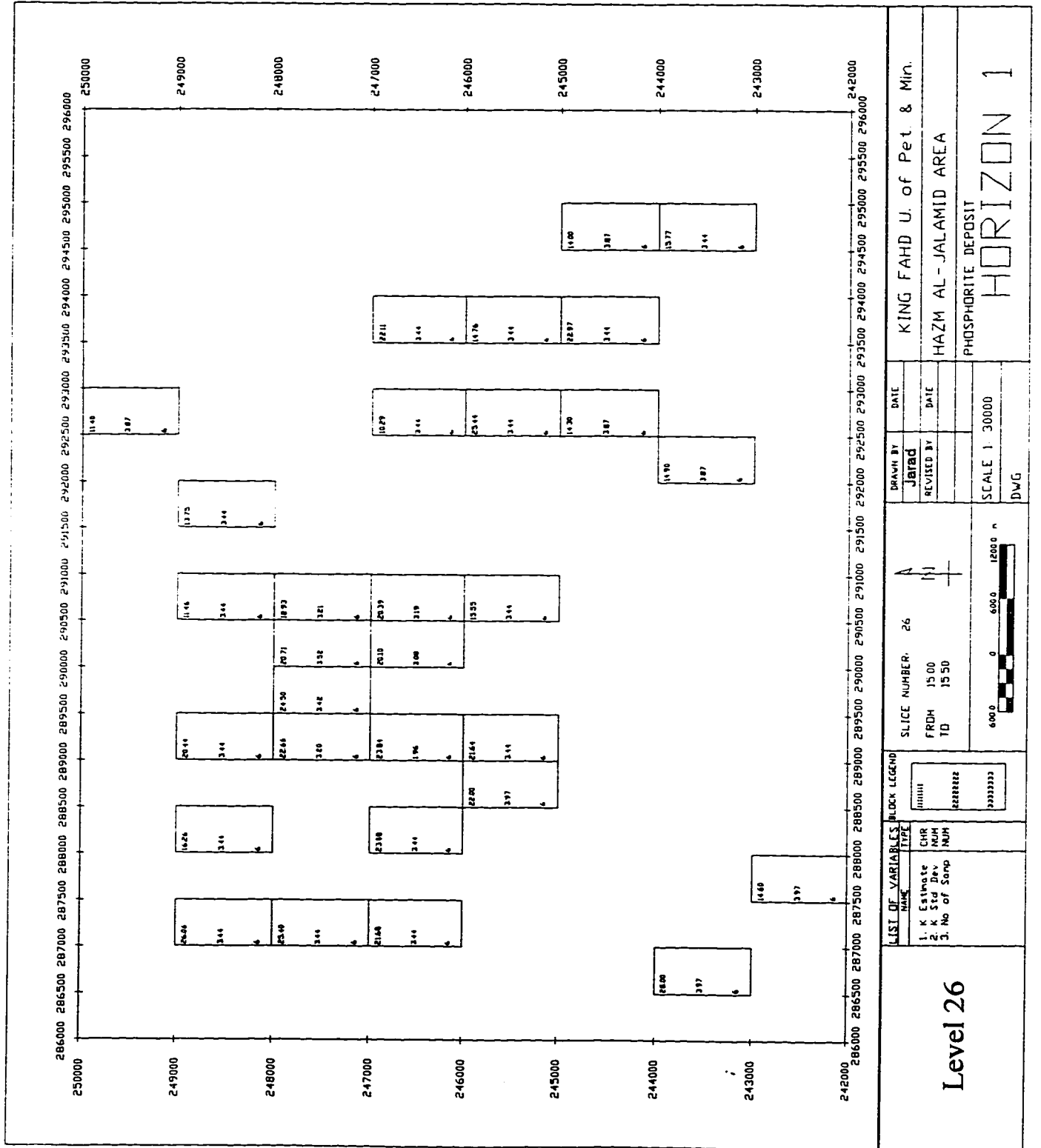




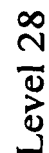


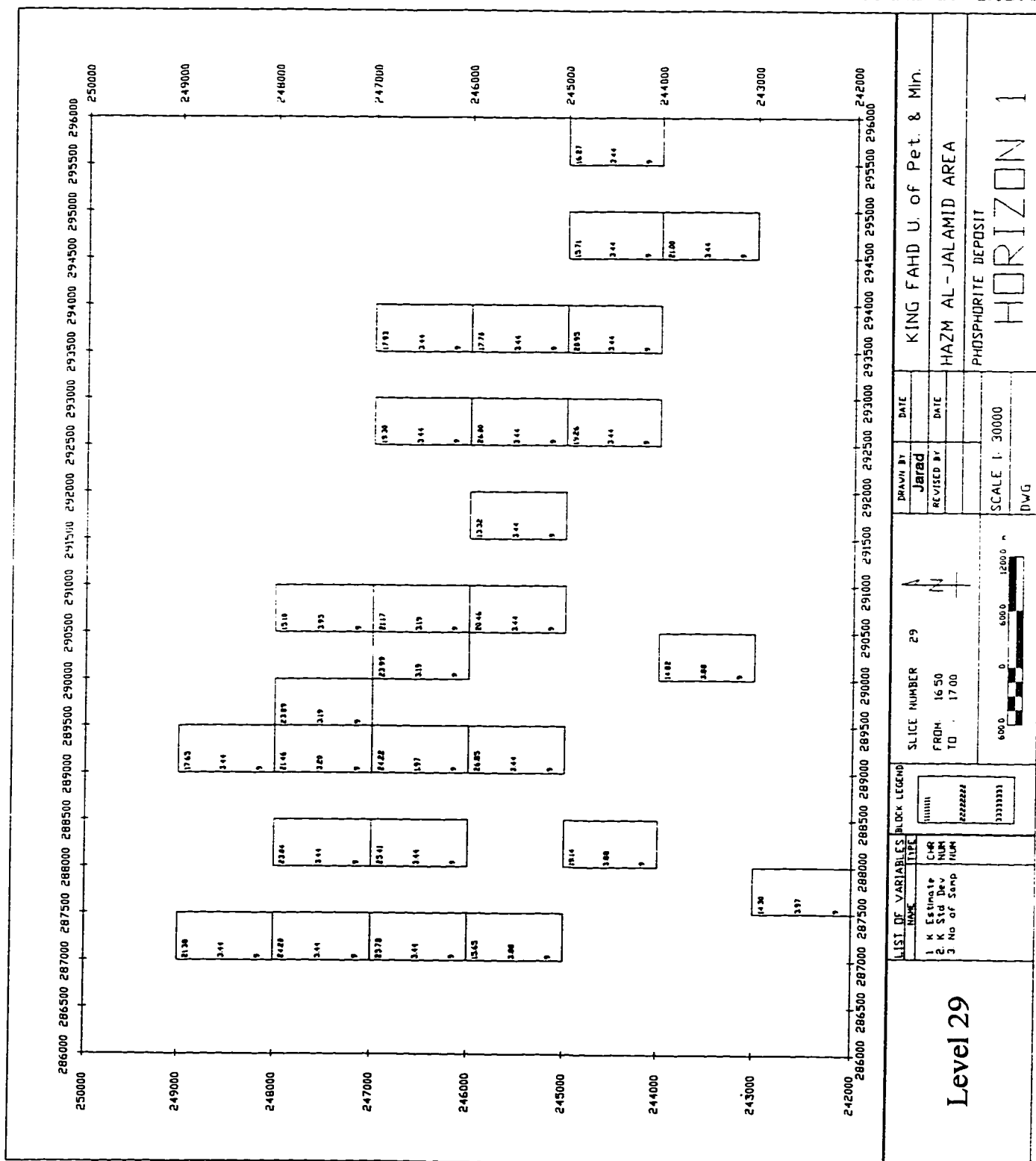


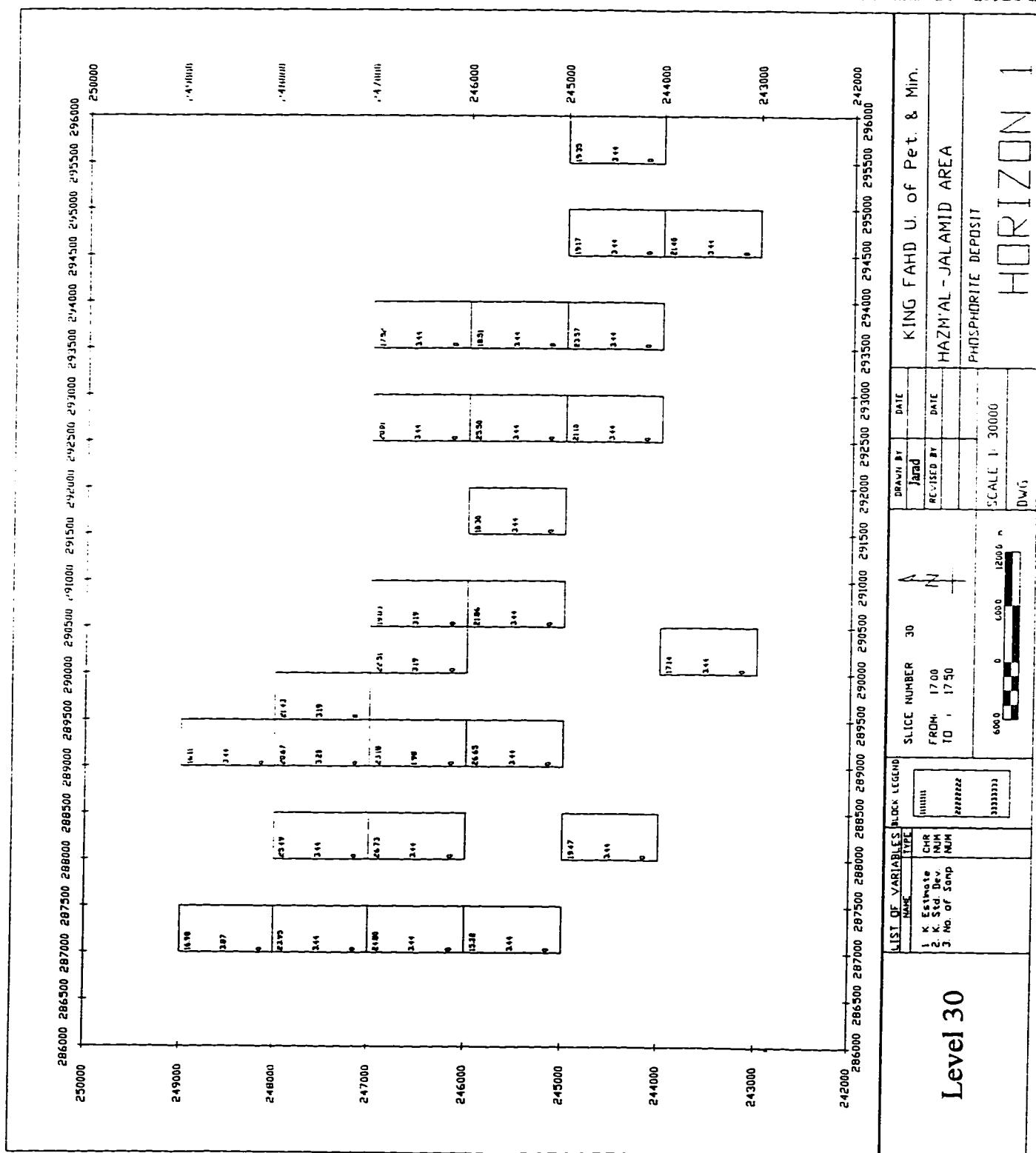


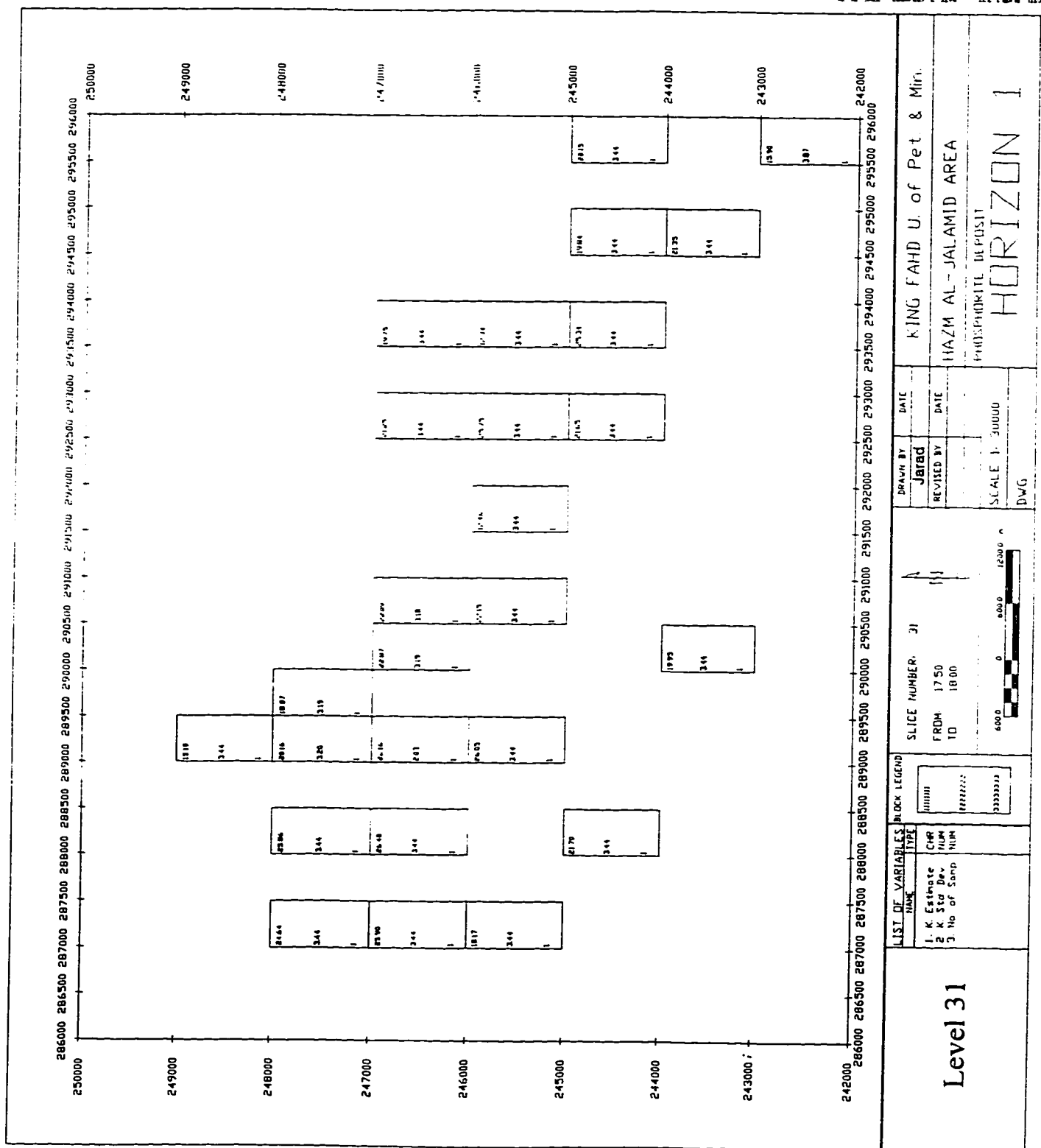




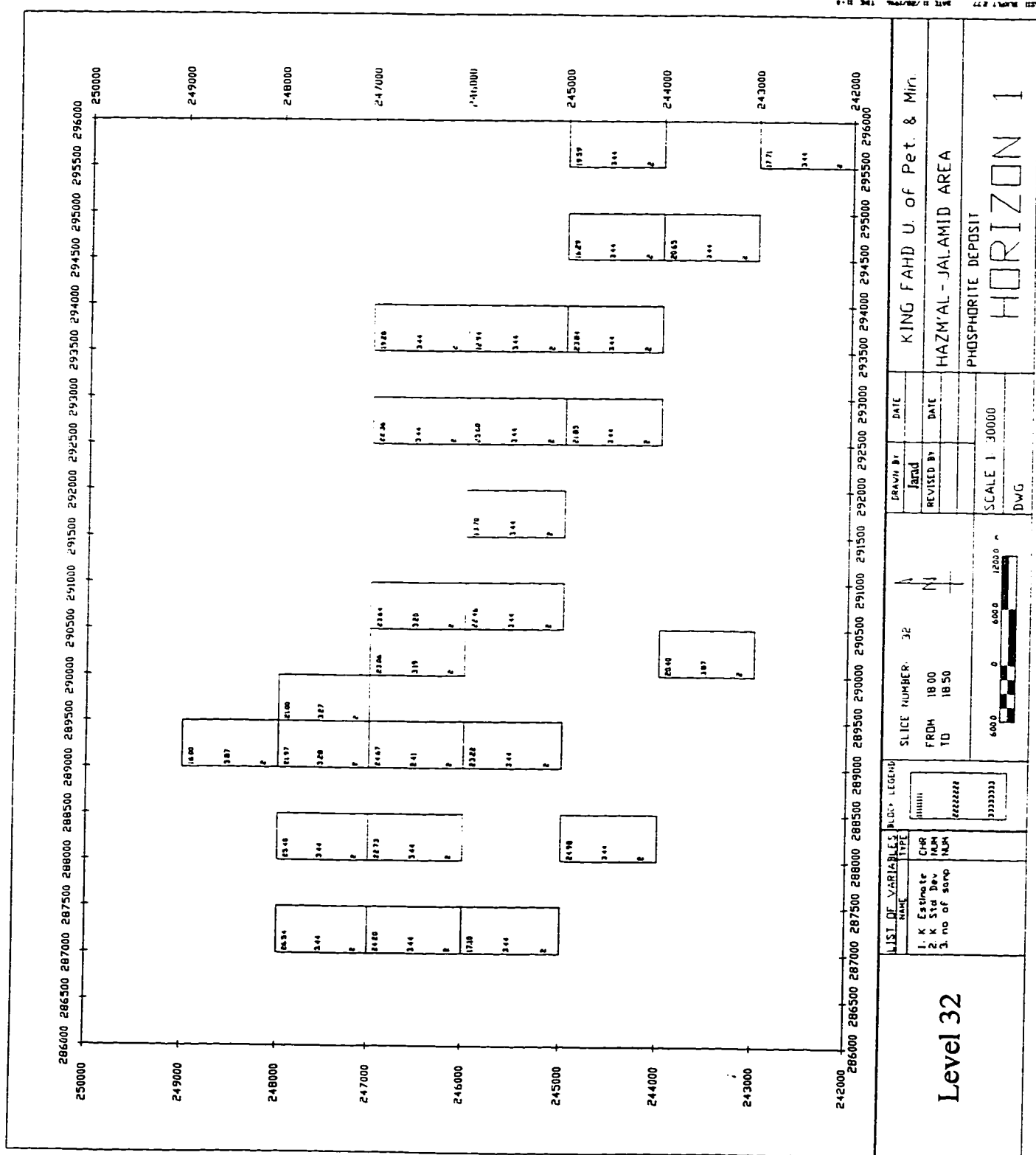


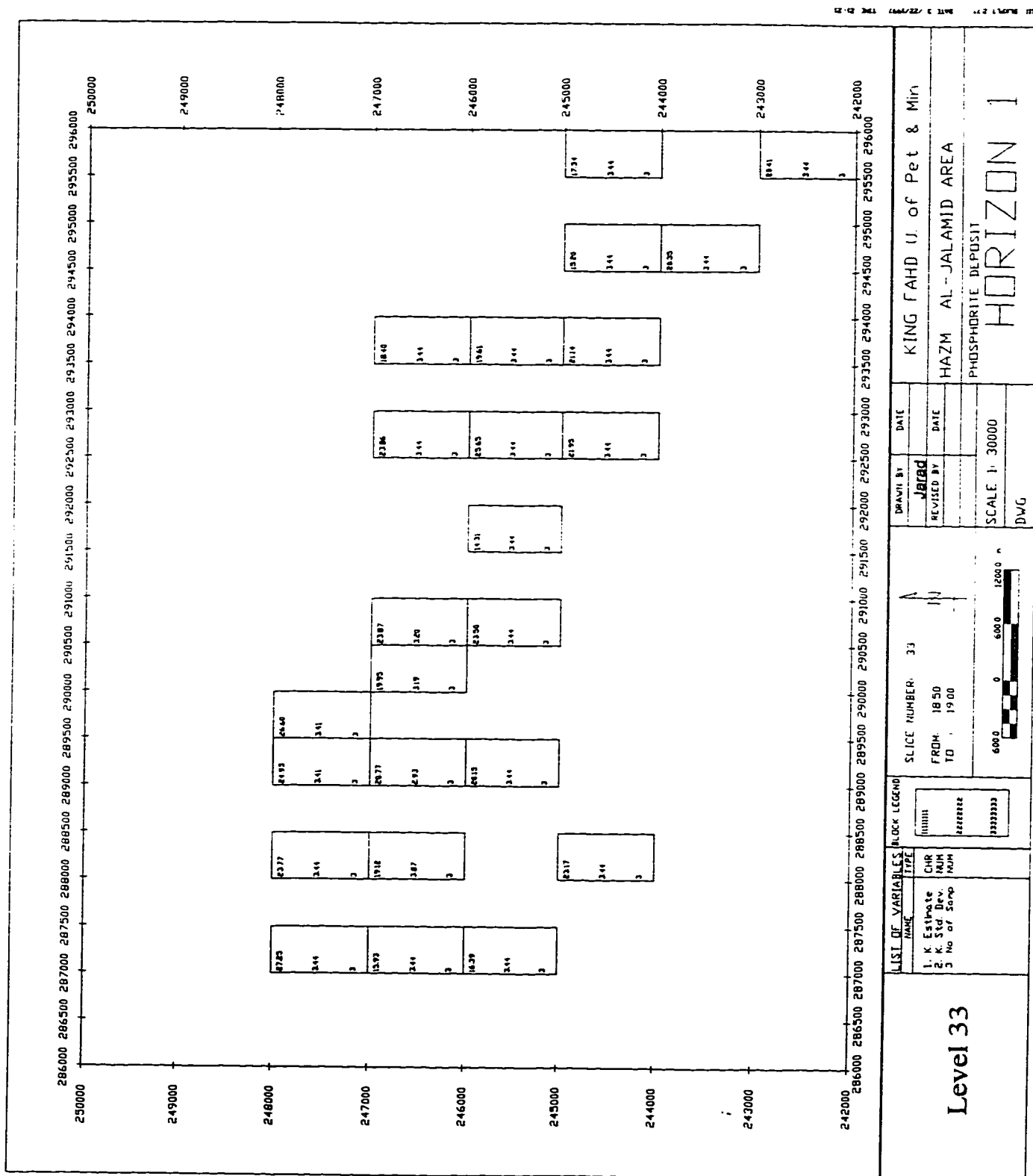


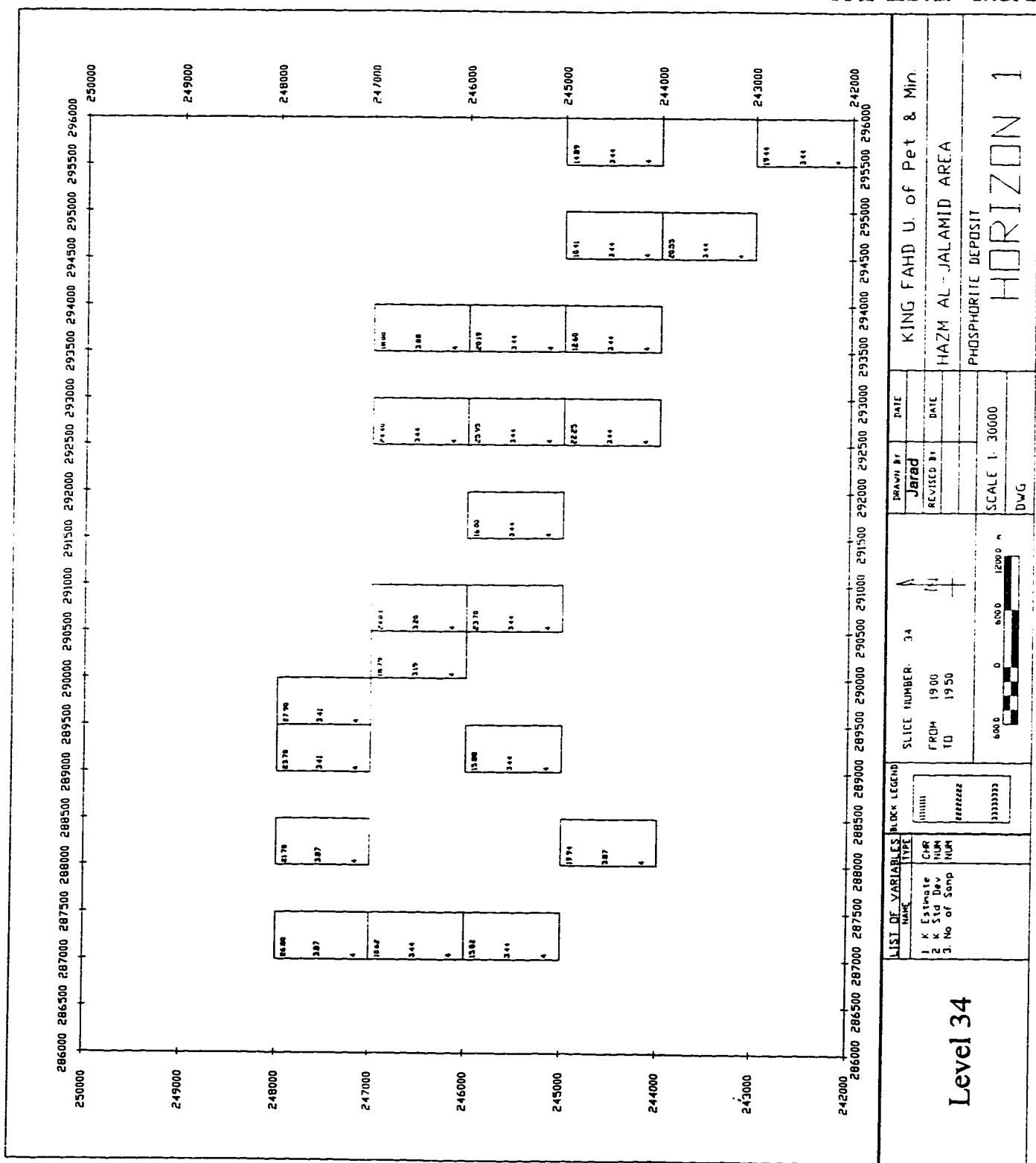




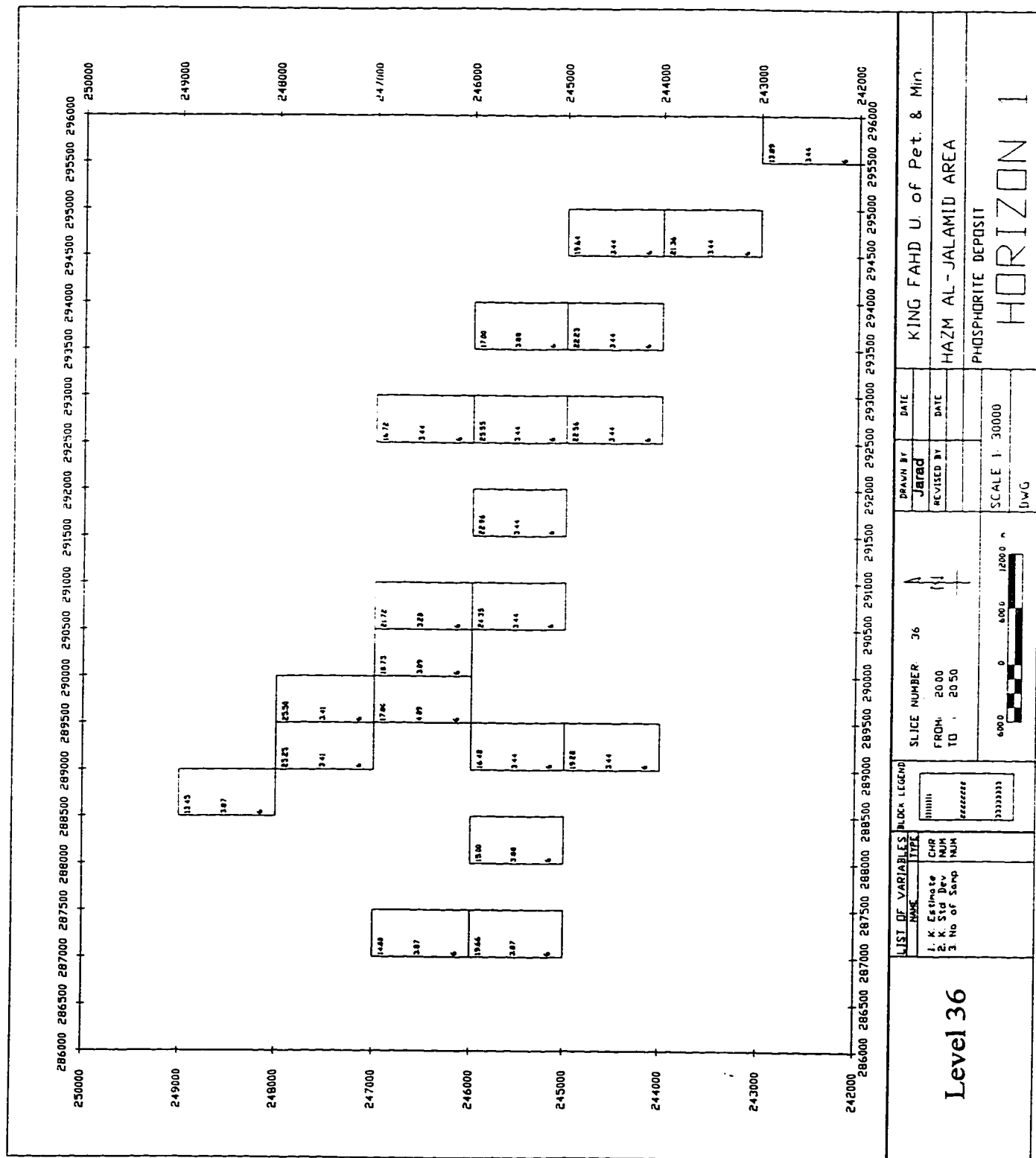


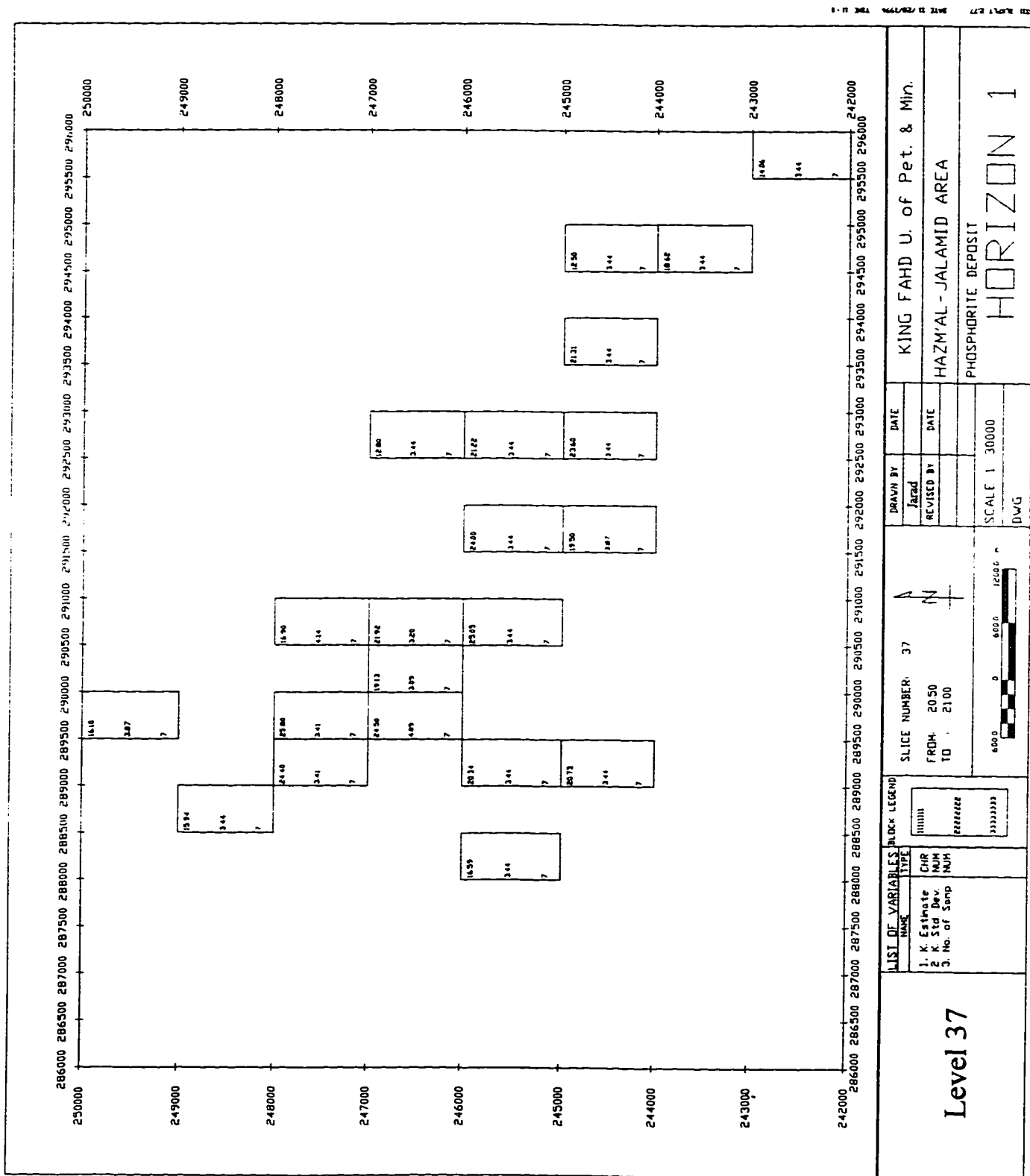


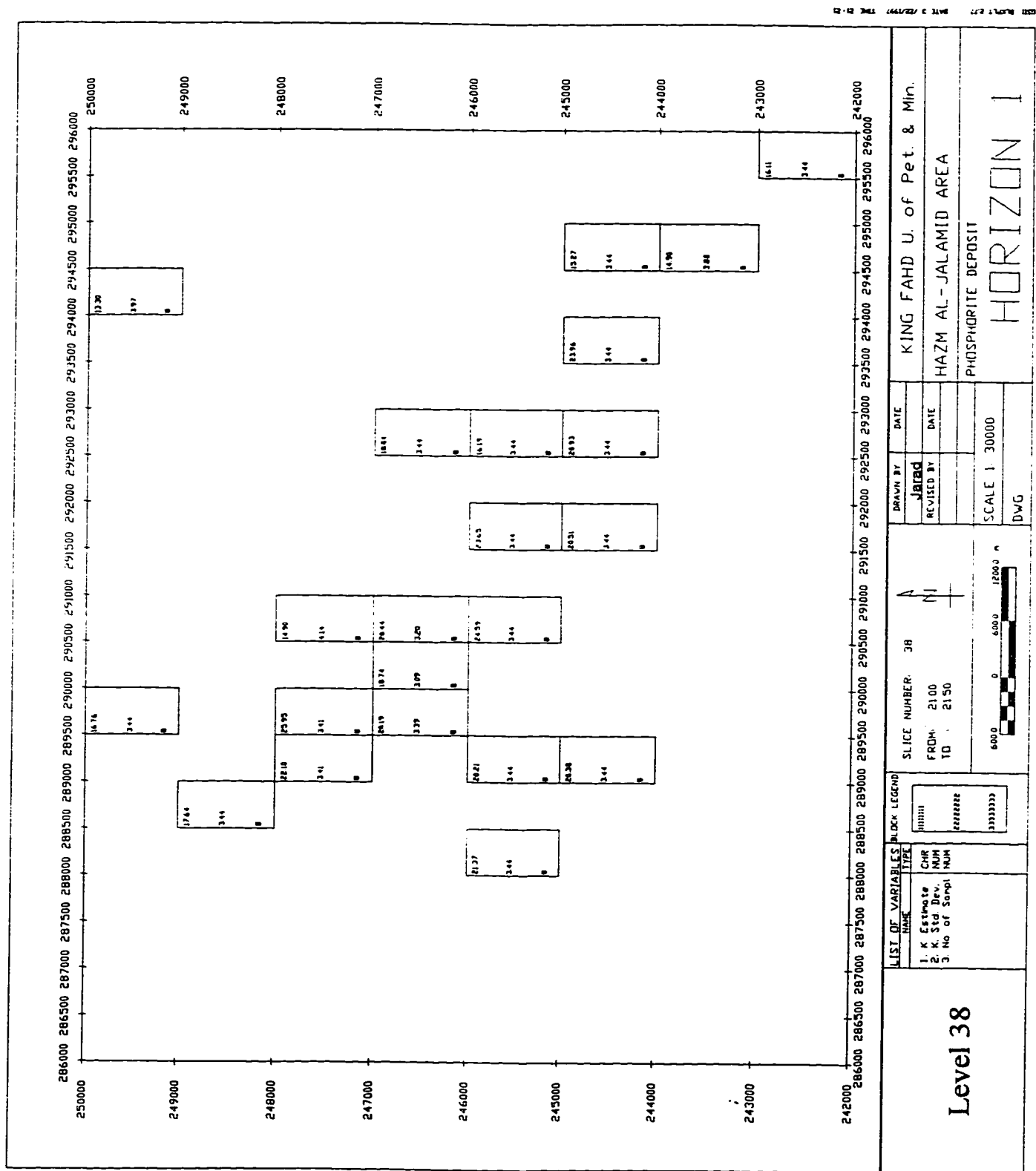


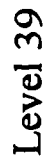




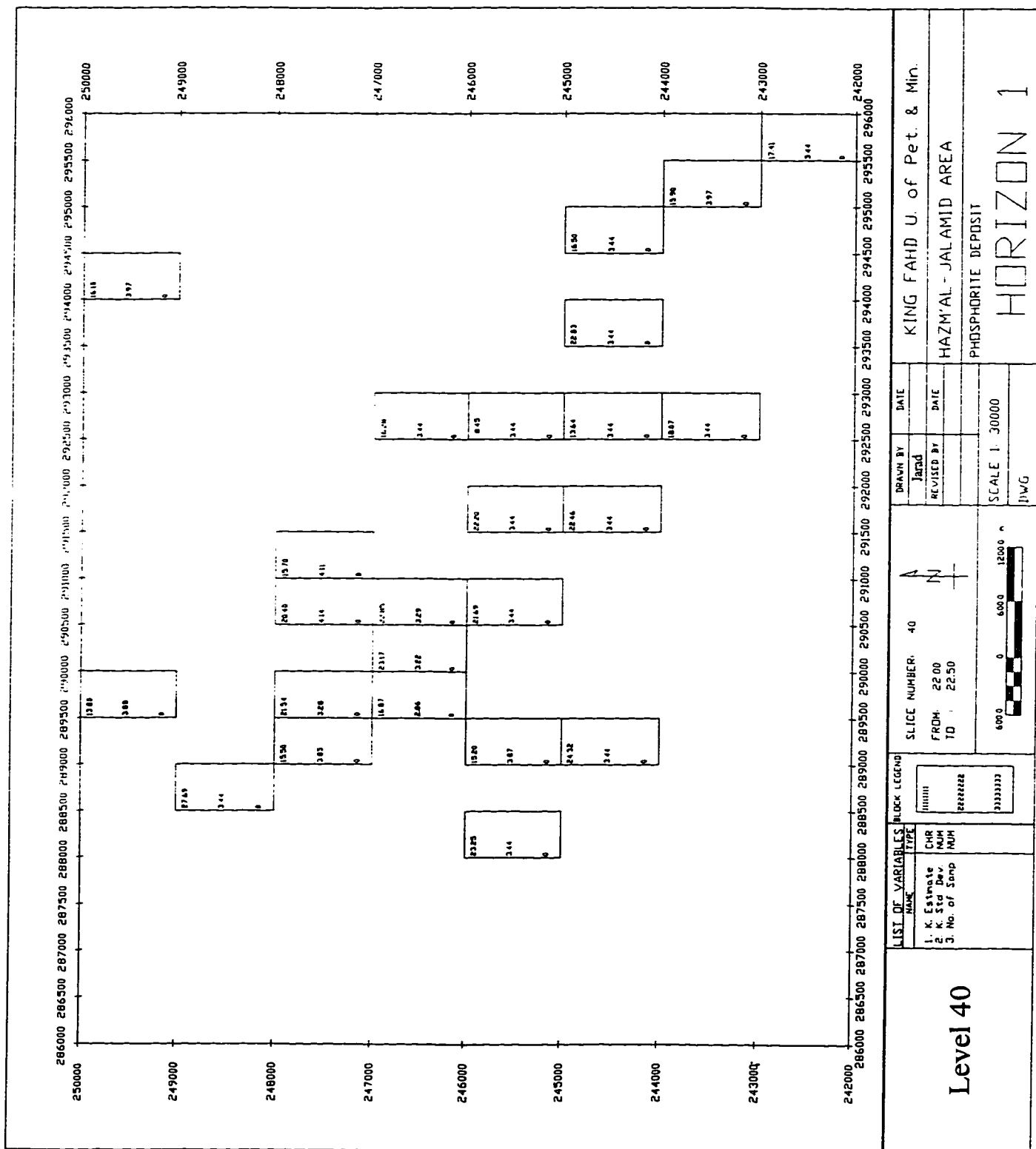




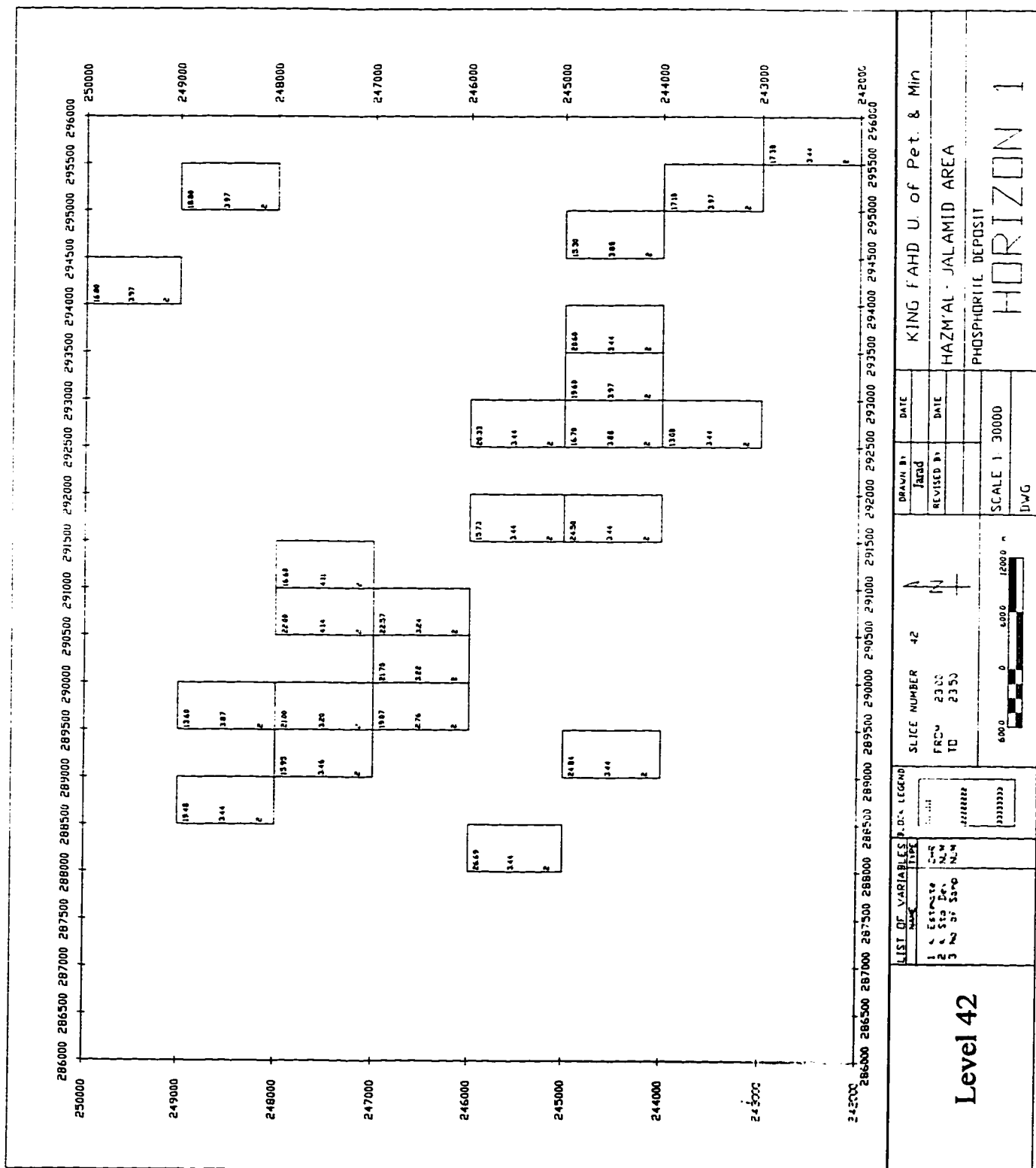


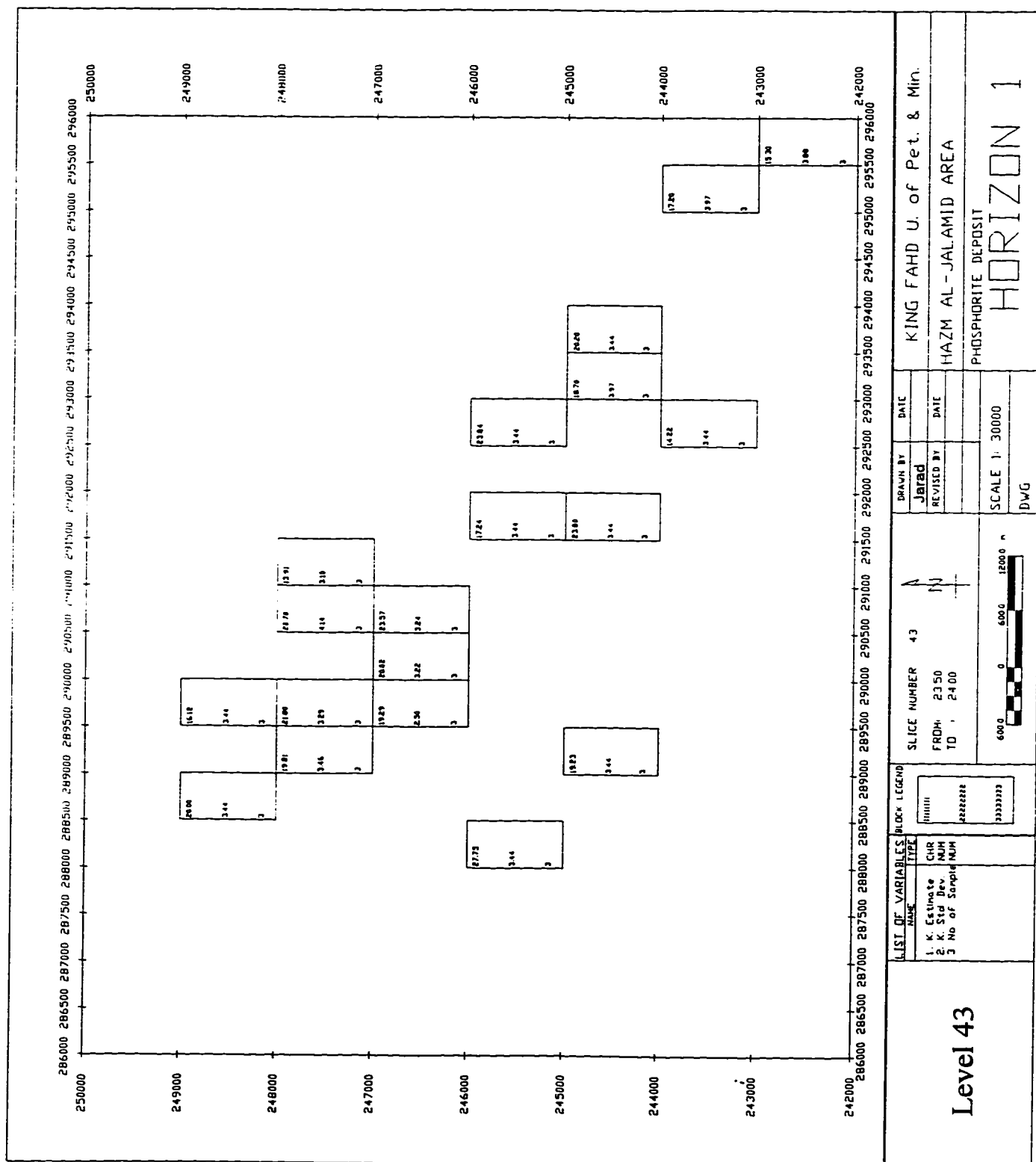


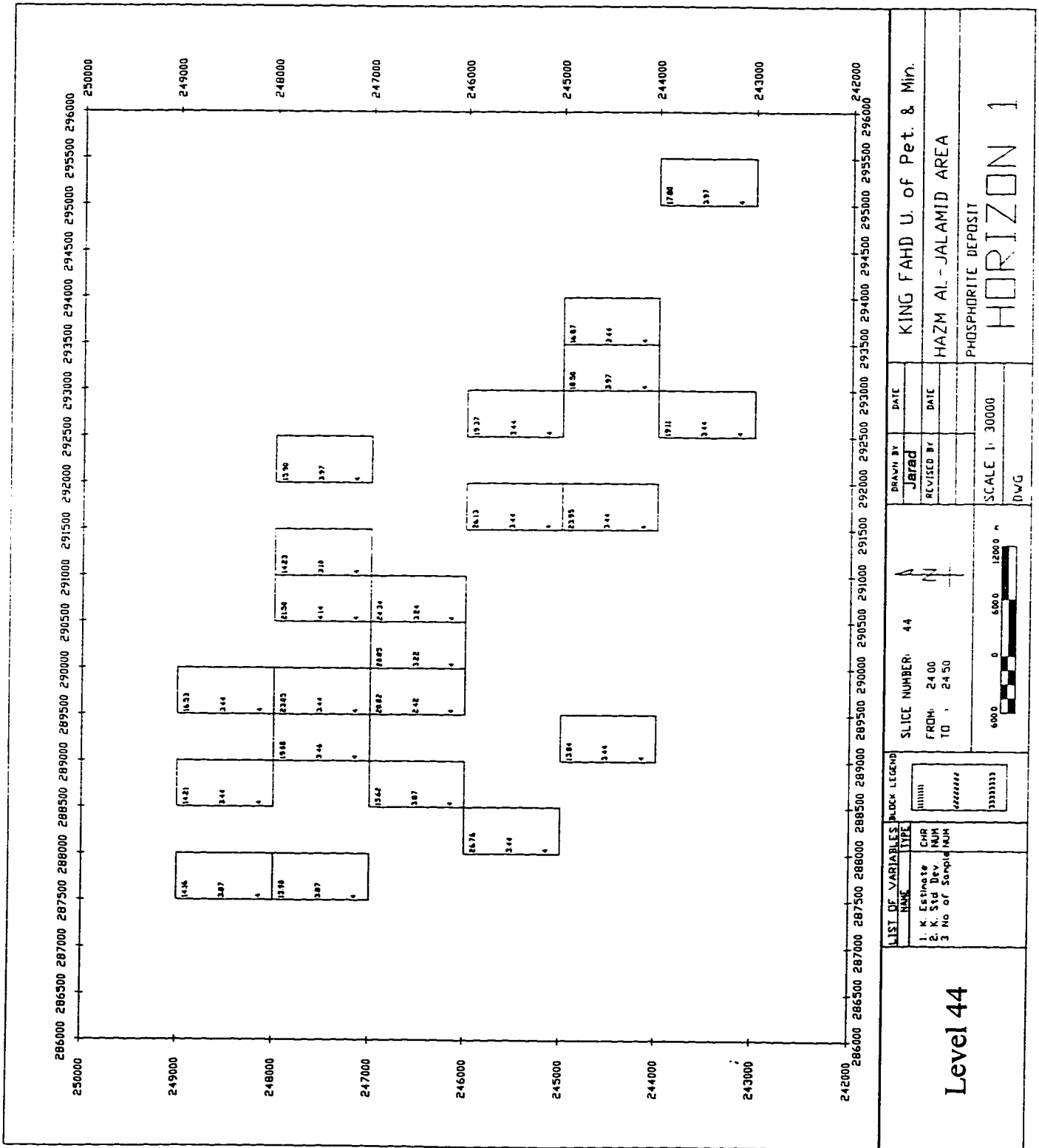


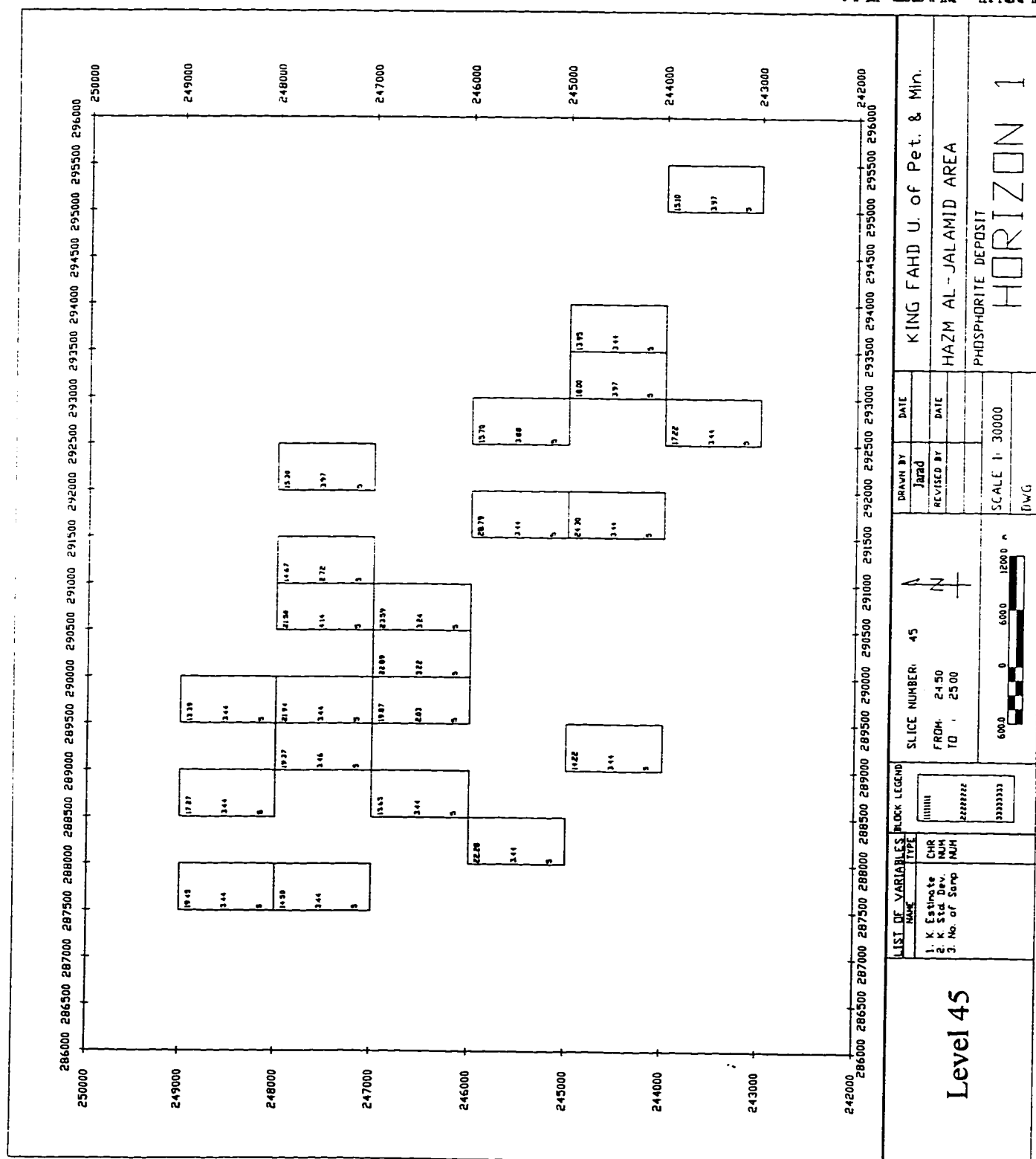


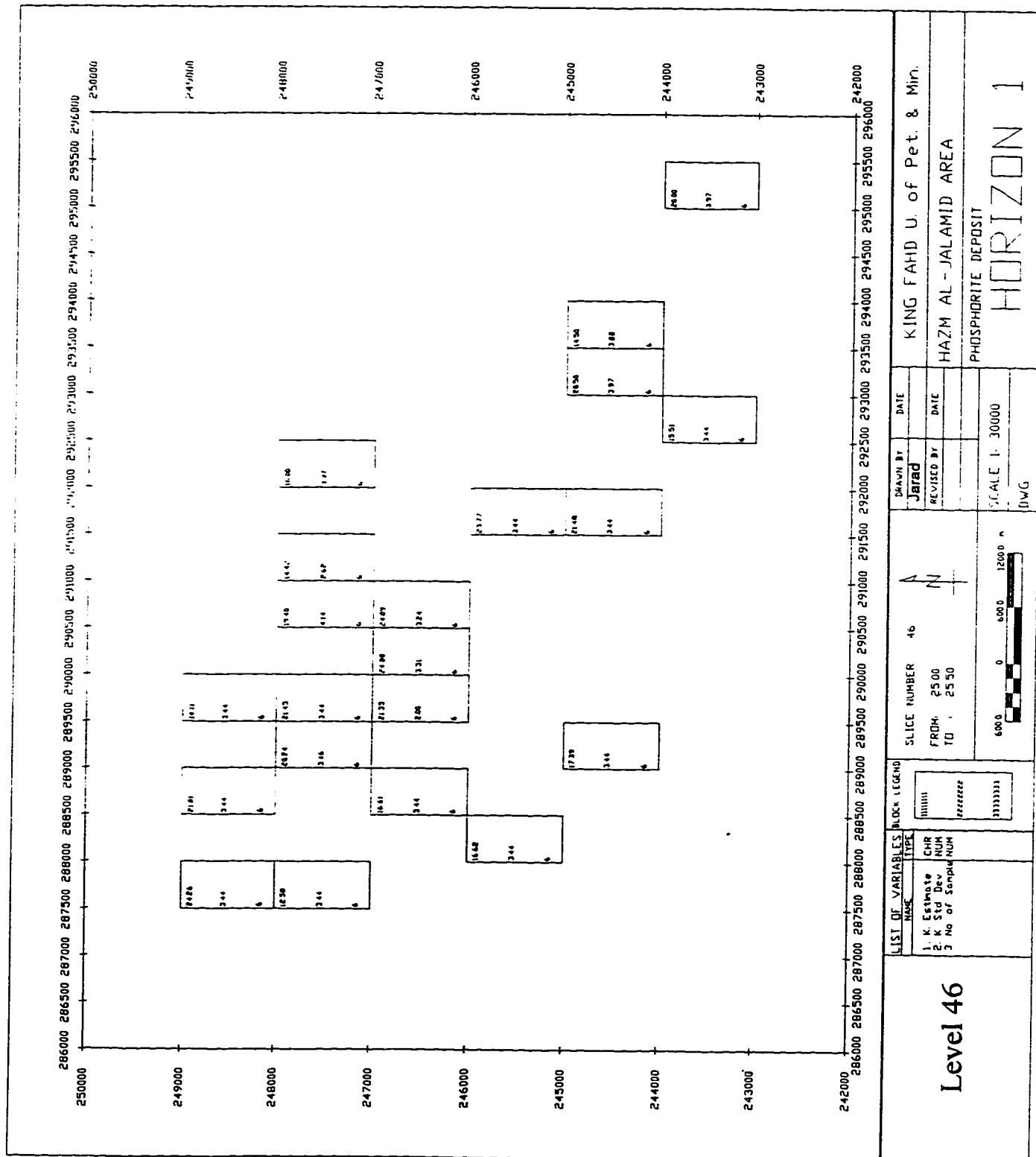


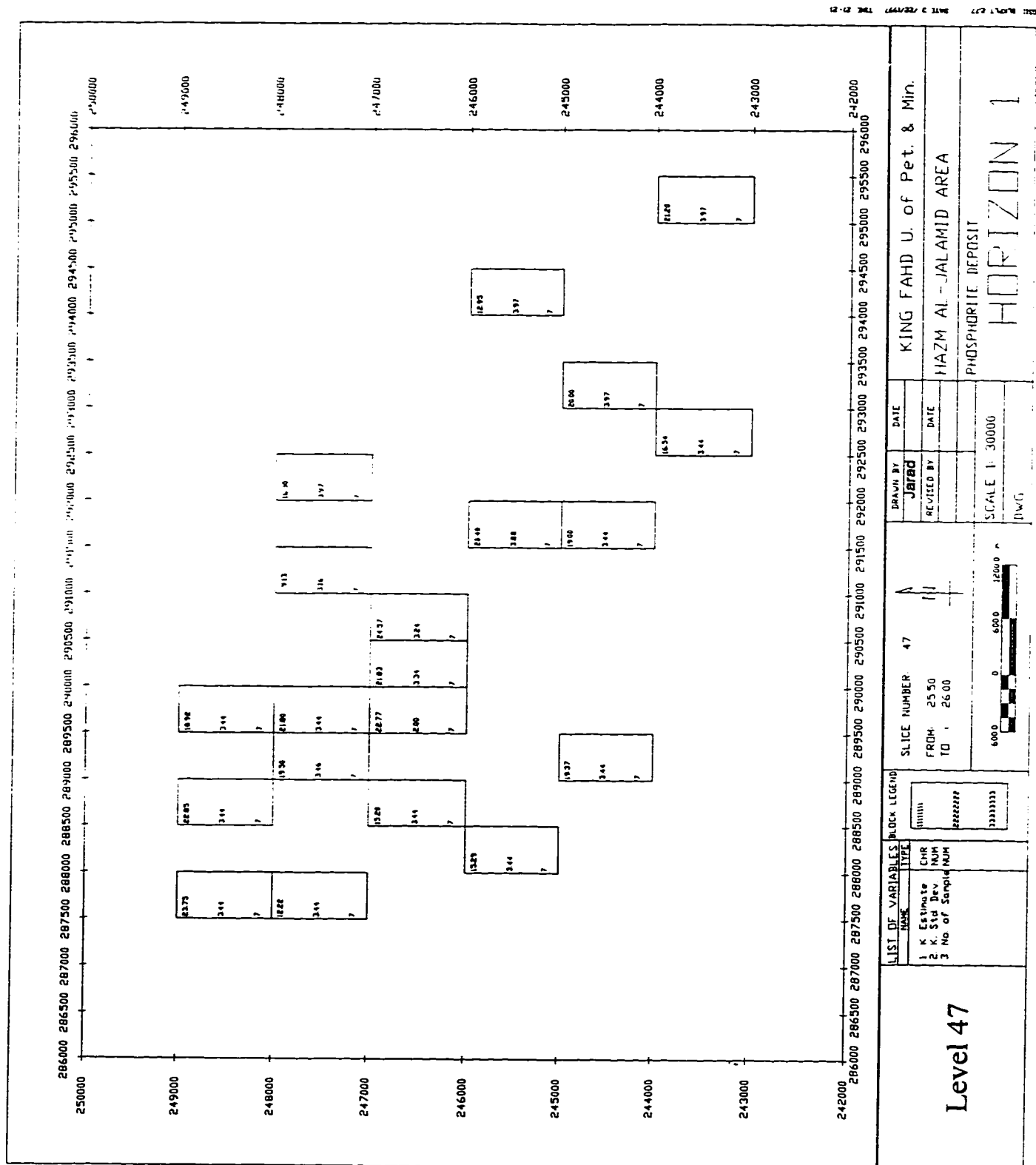






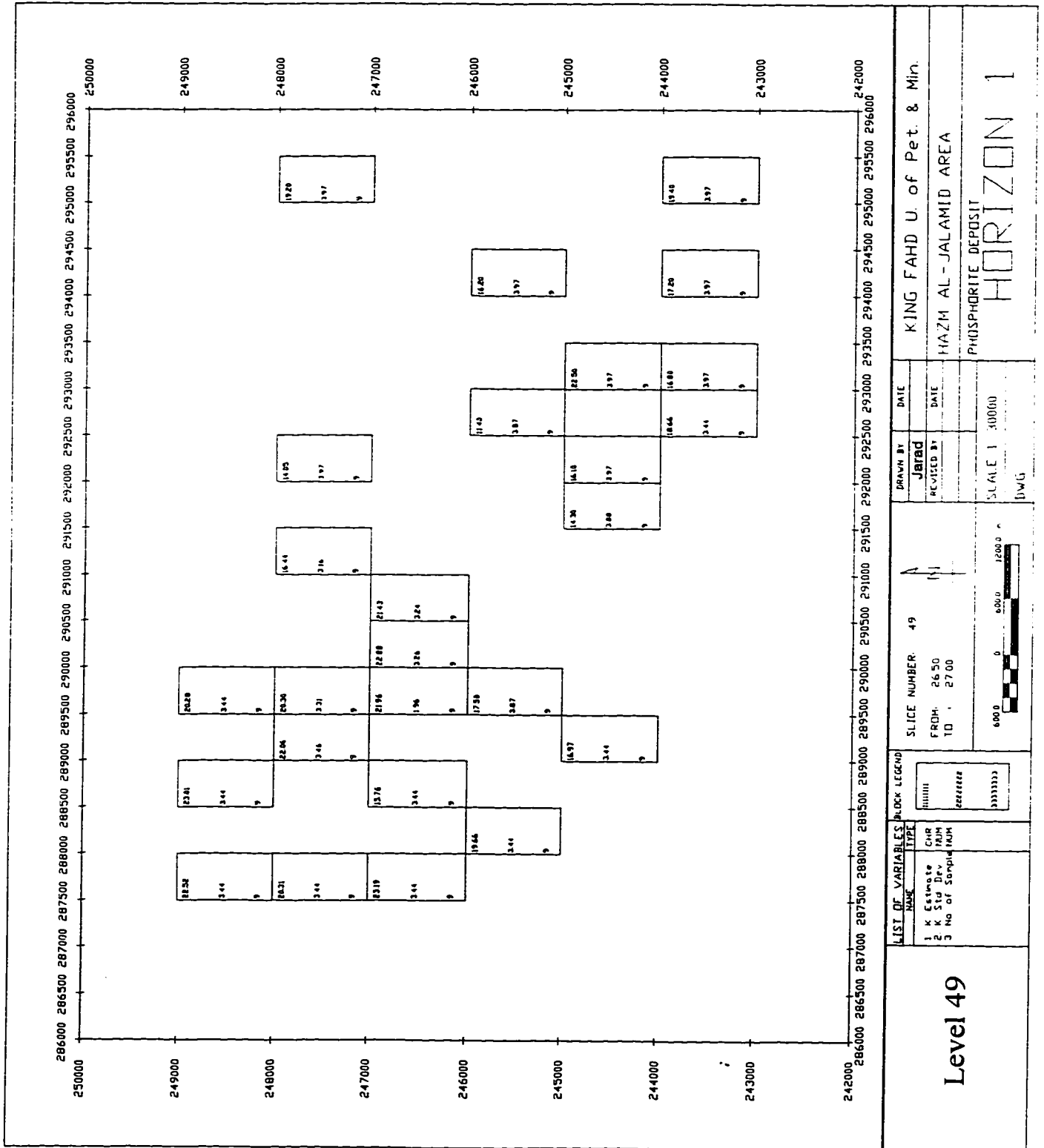


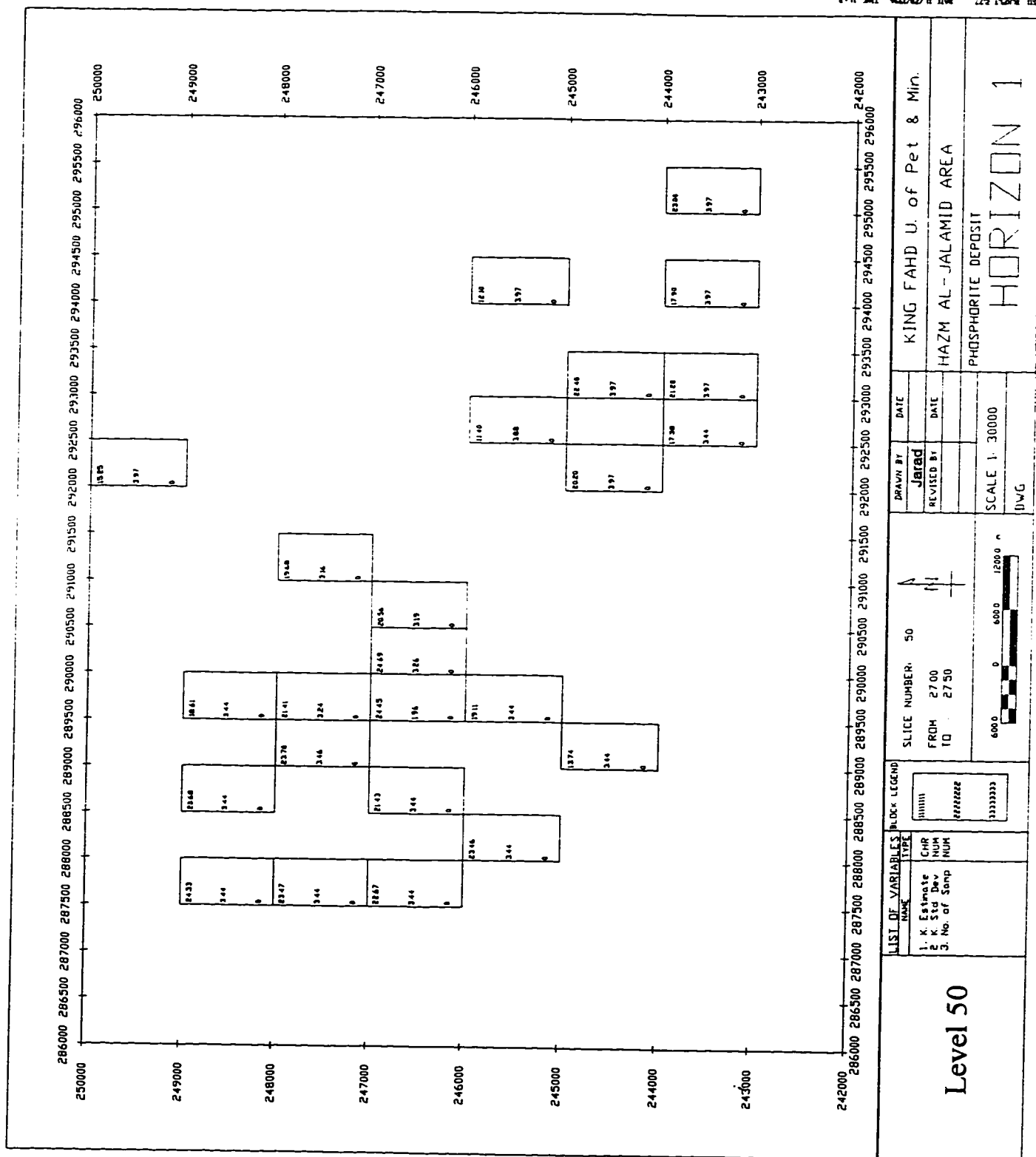


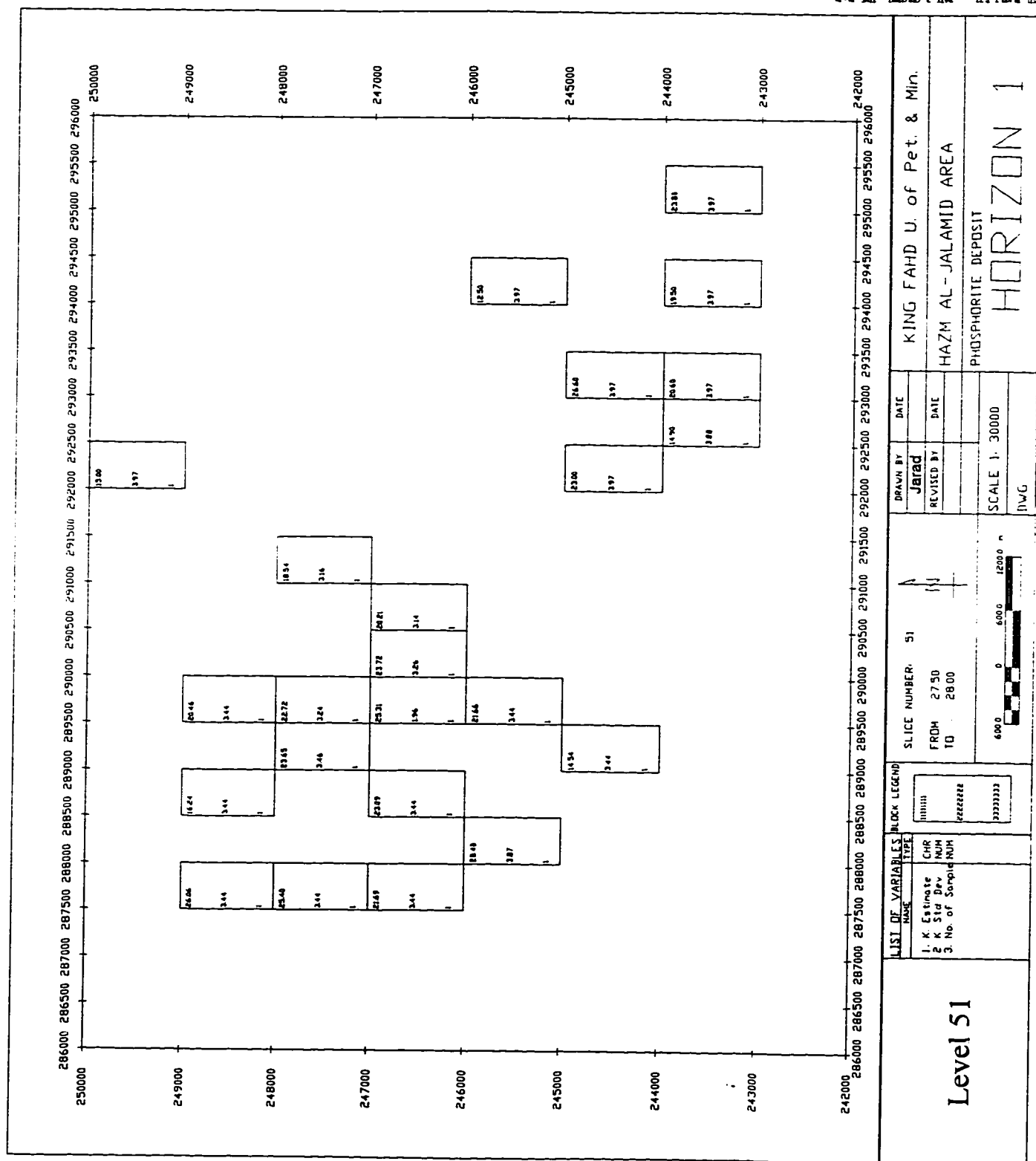


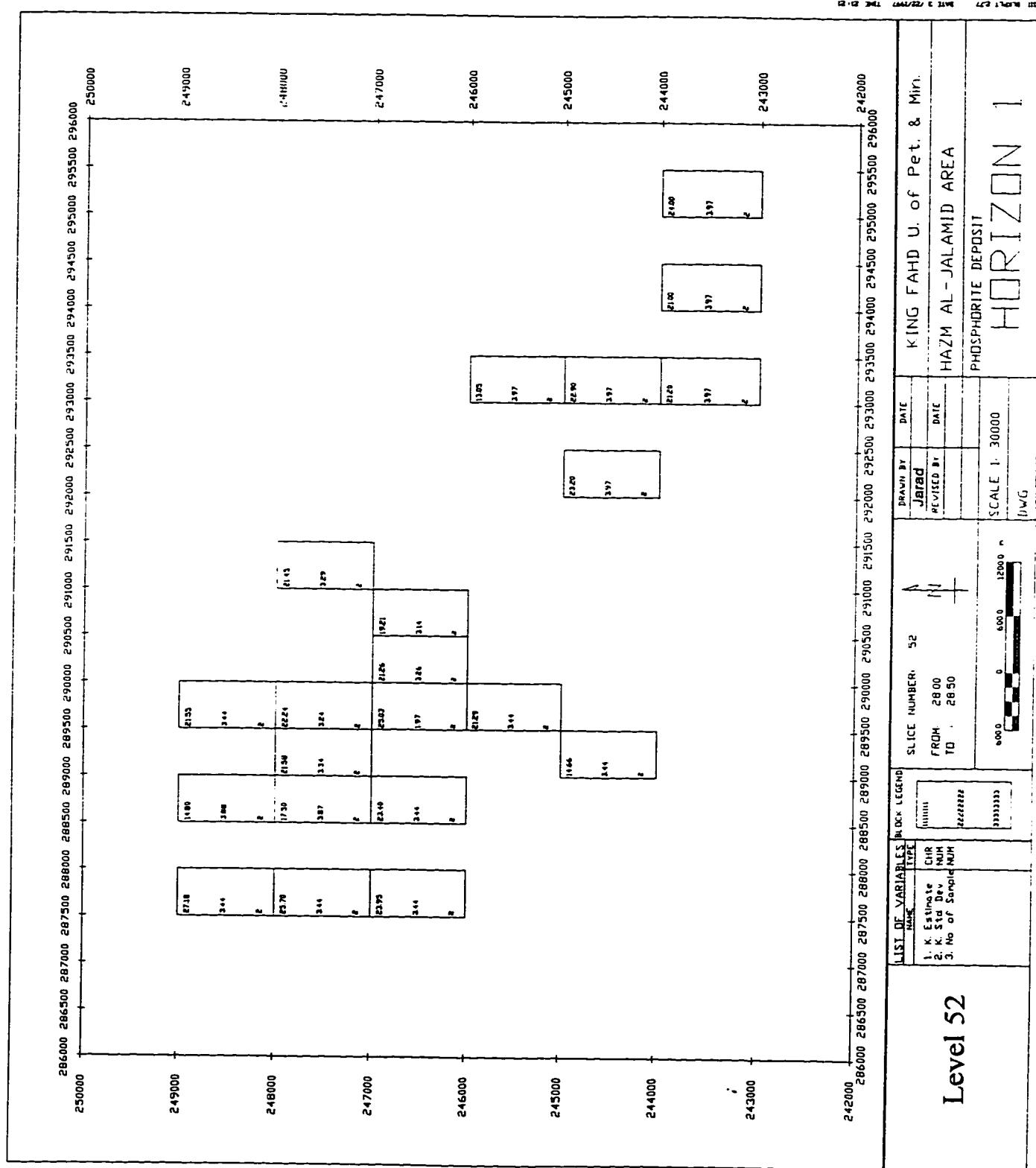


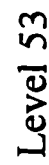


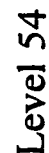


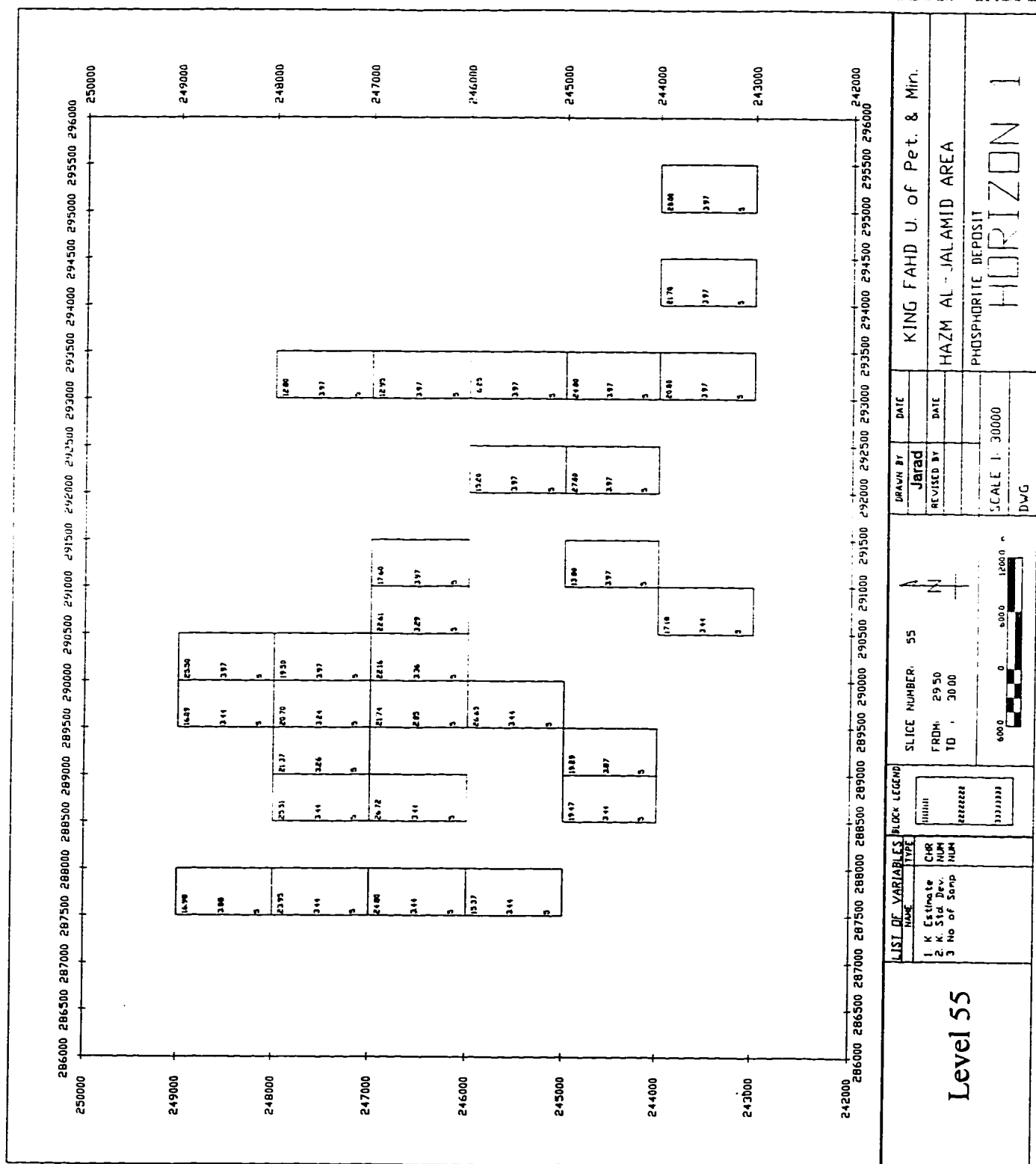




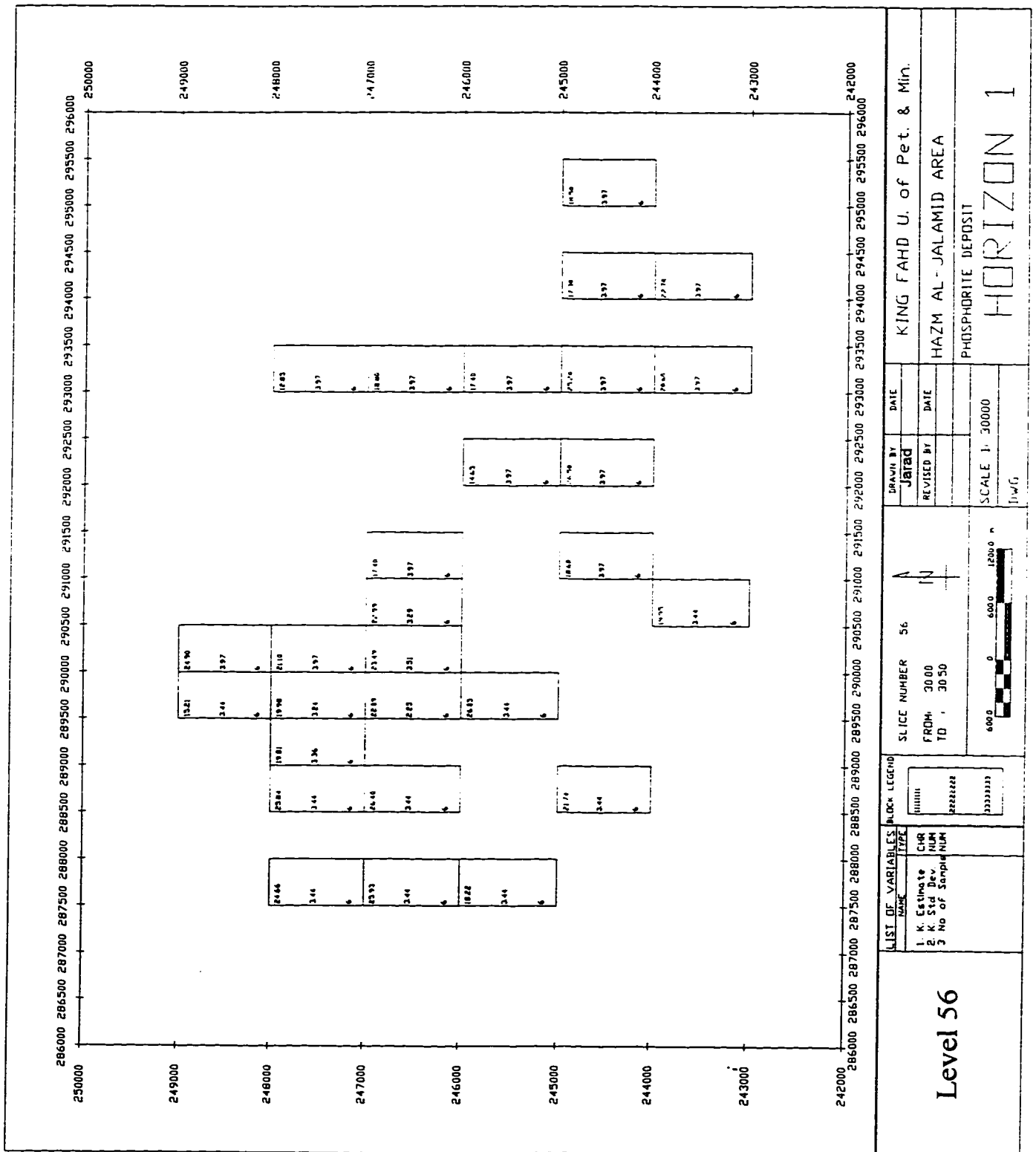




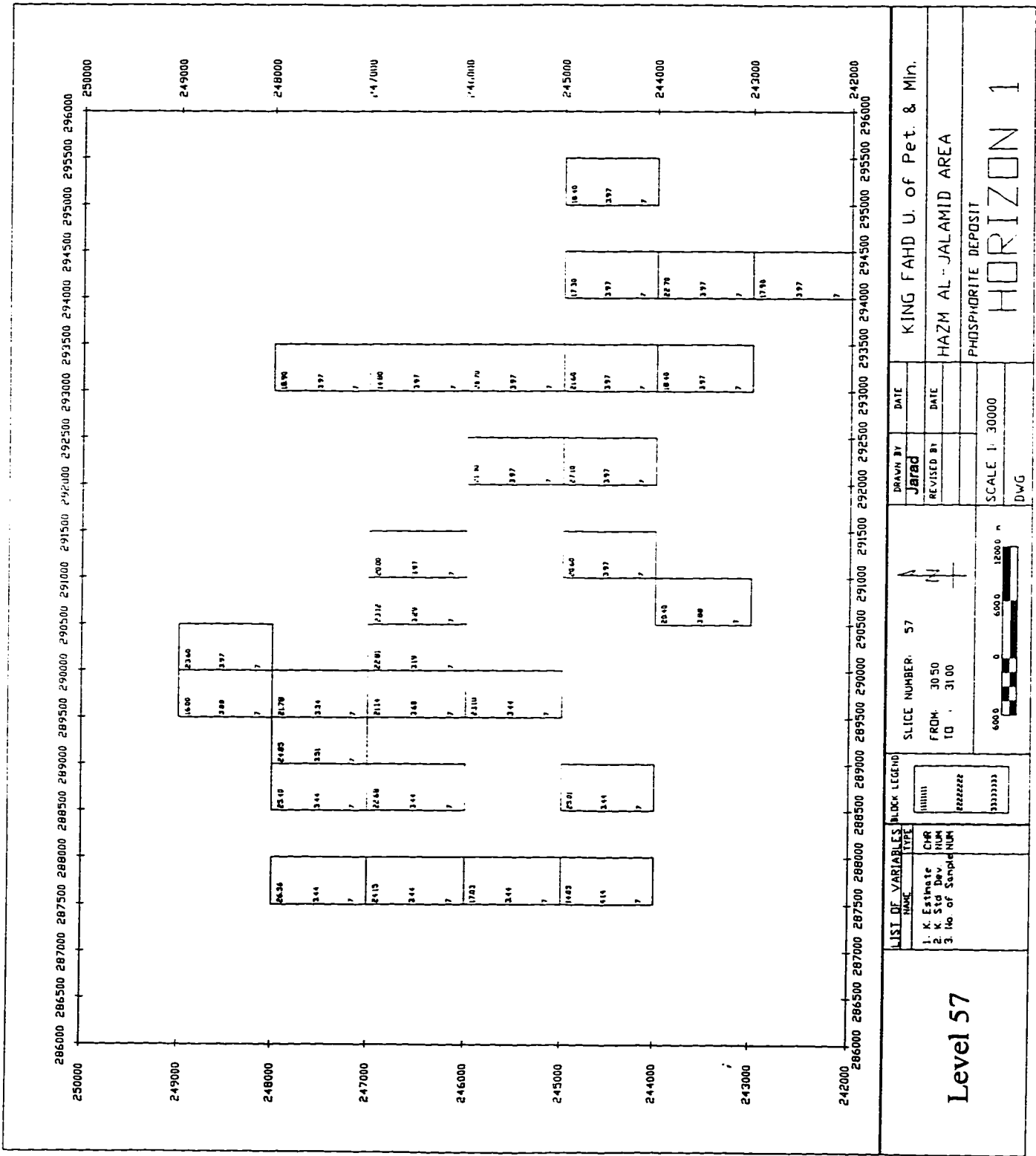


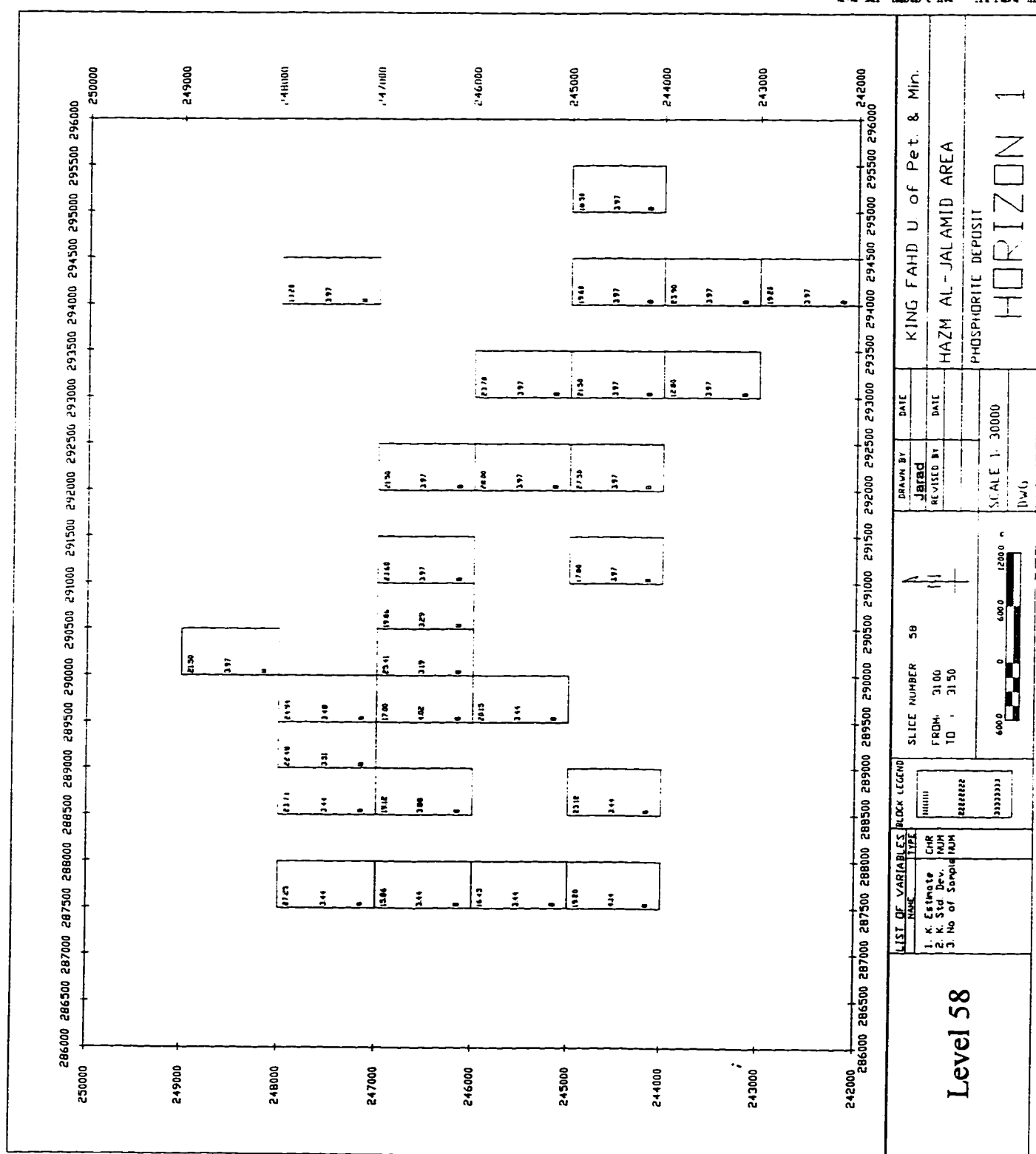


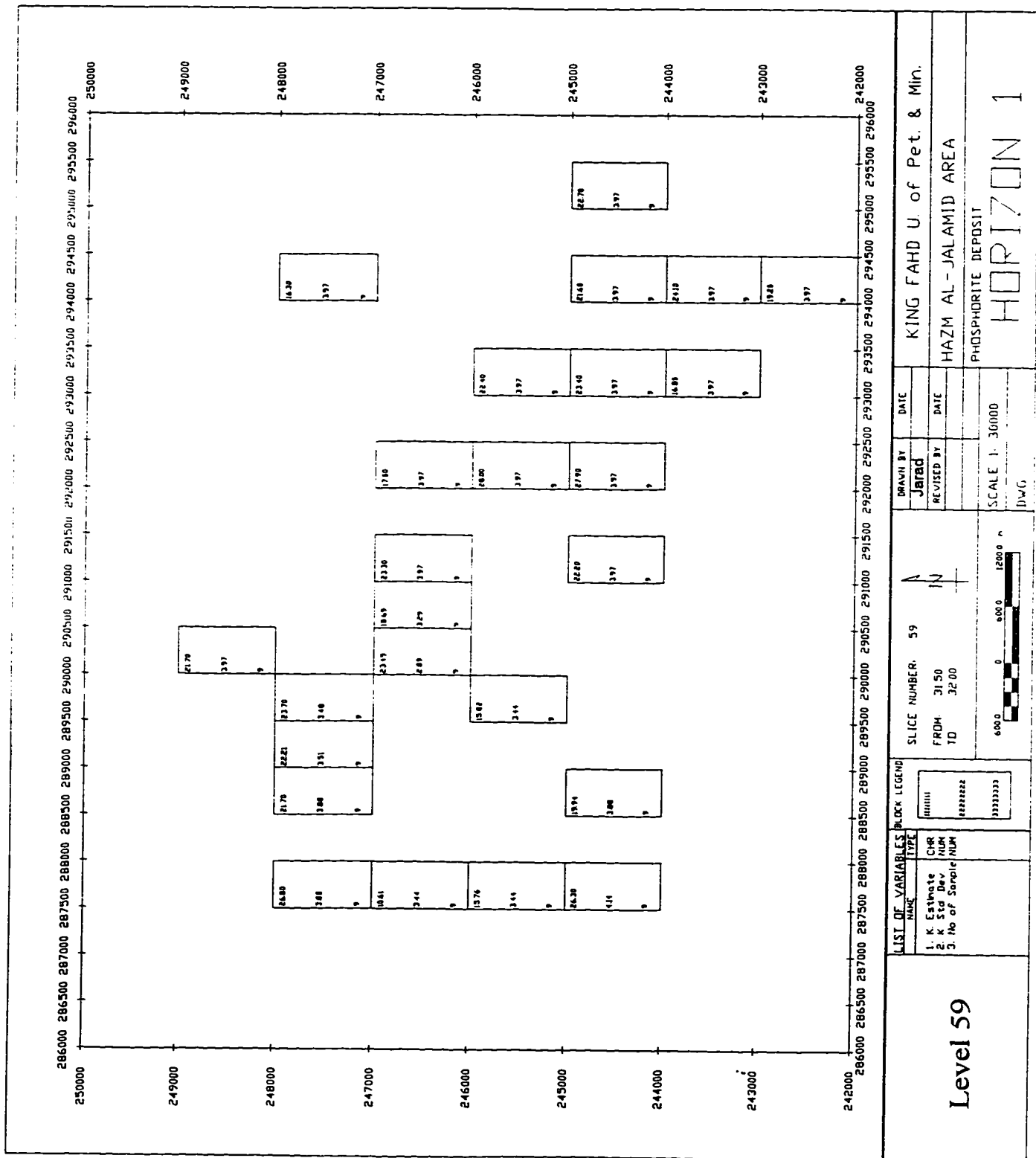




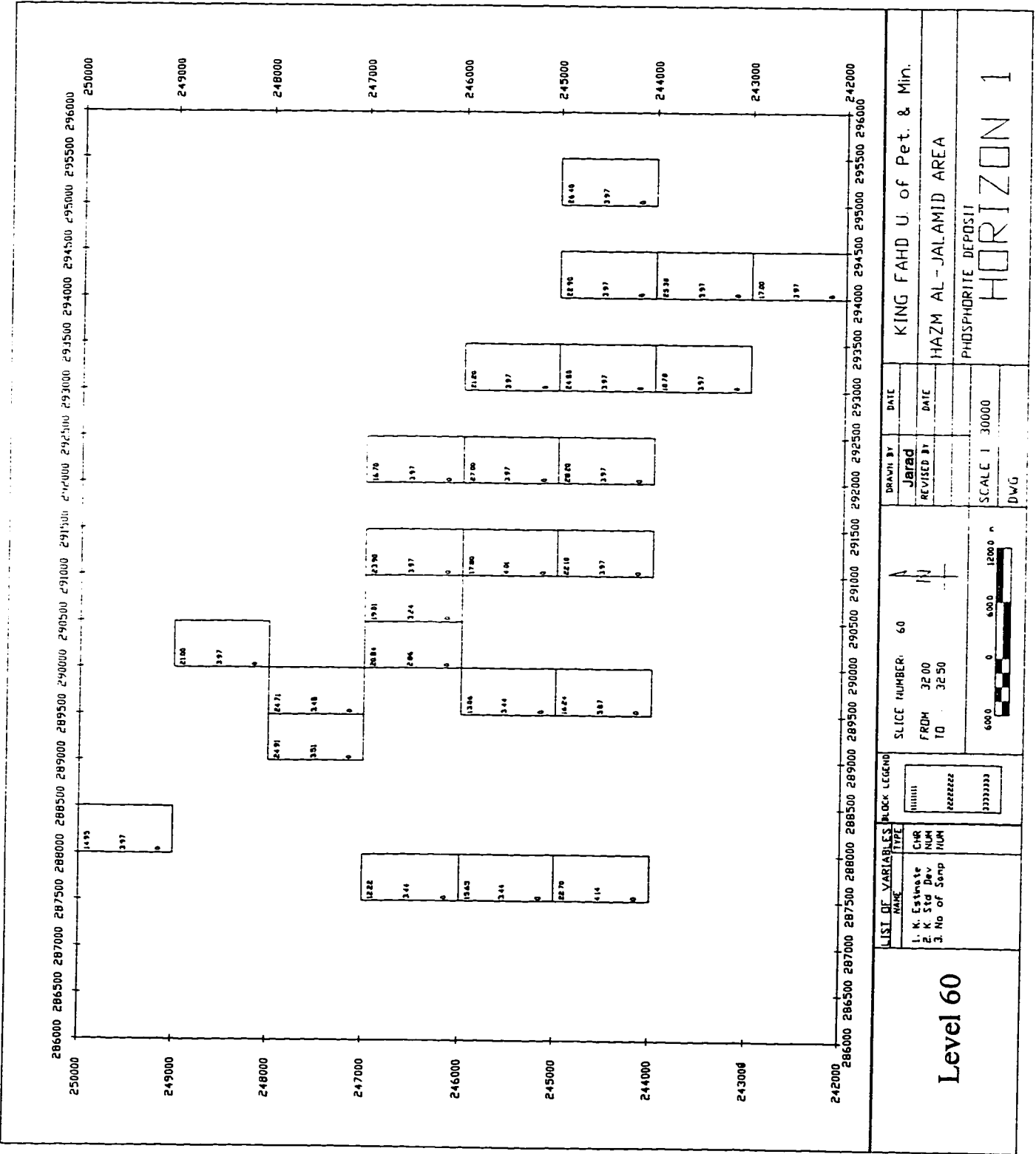
DATE: 3/28/1997 TIME: 21:21

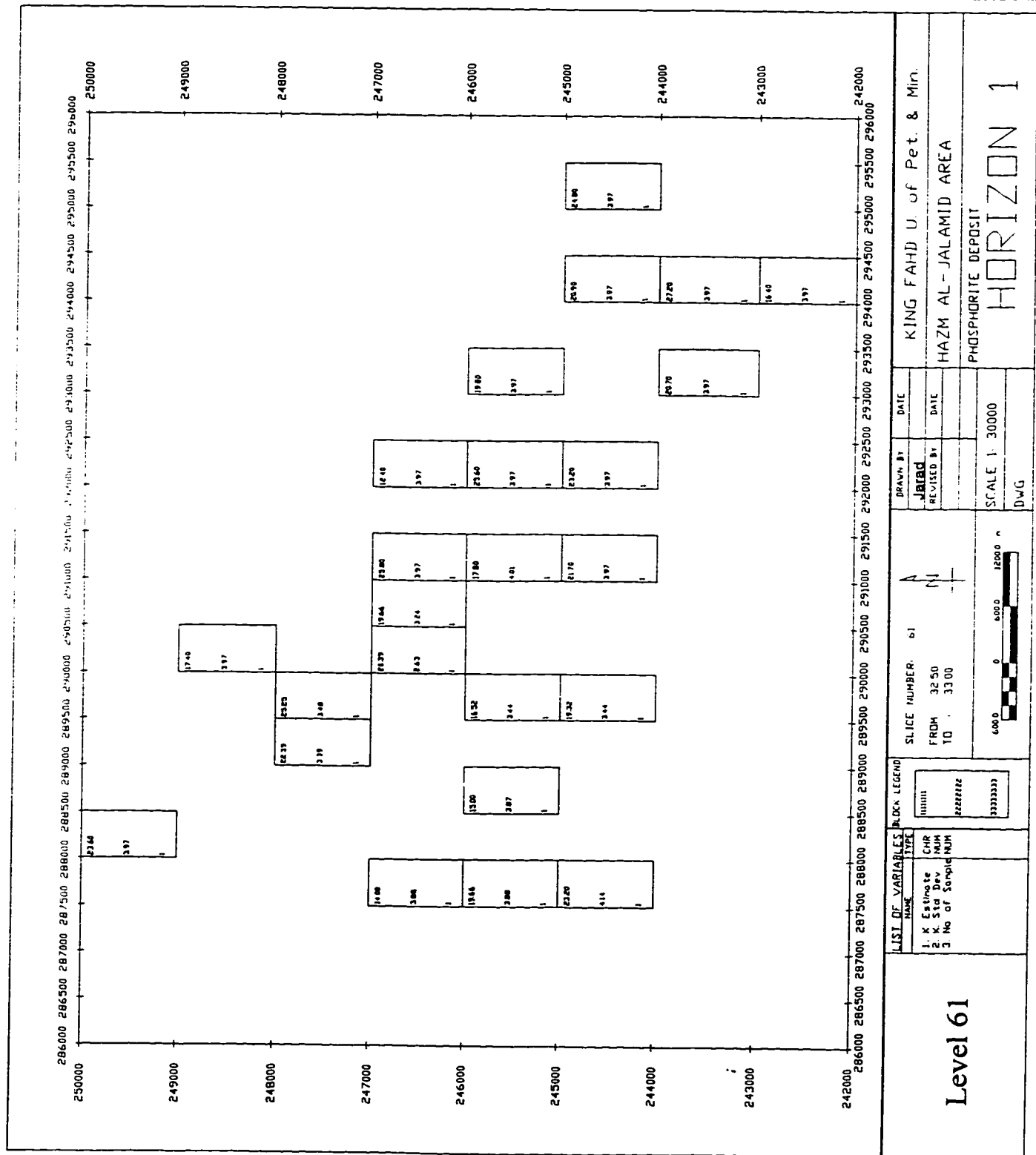


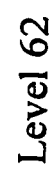


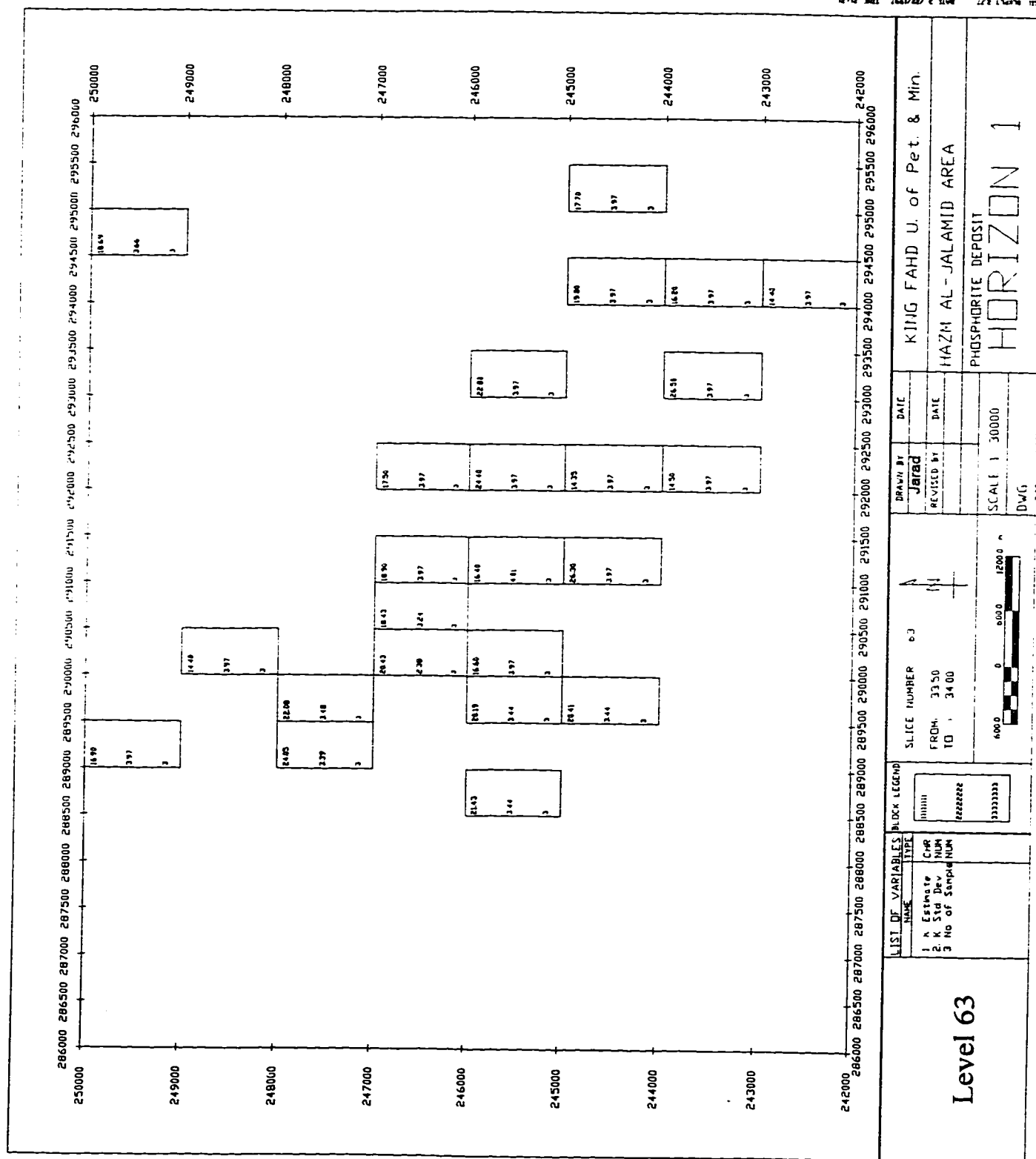


DATE 11/28/2006 TIME 11:00

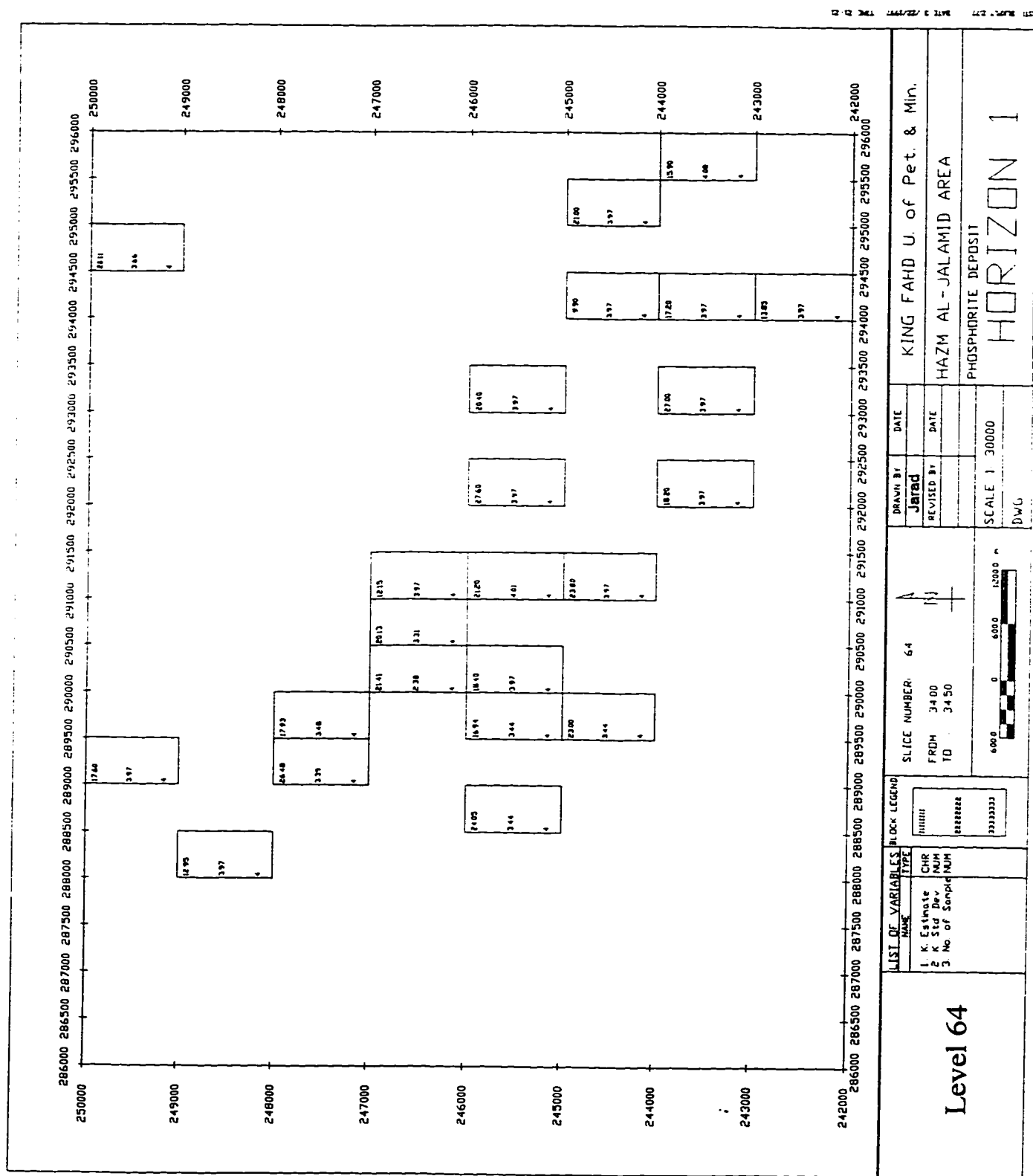


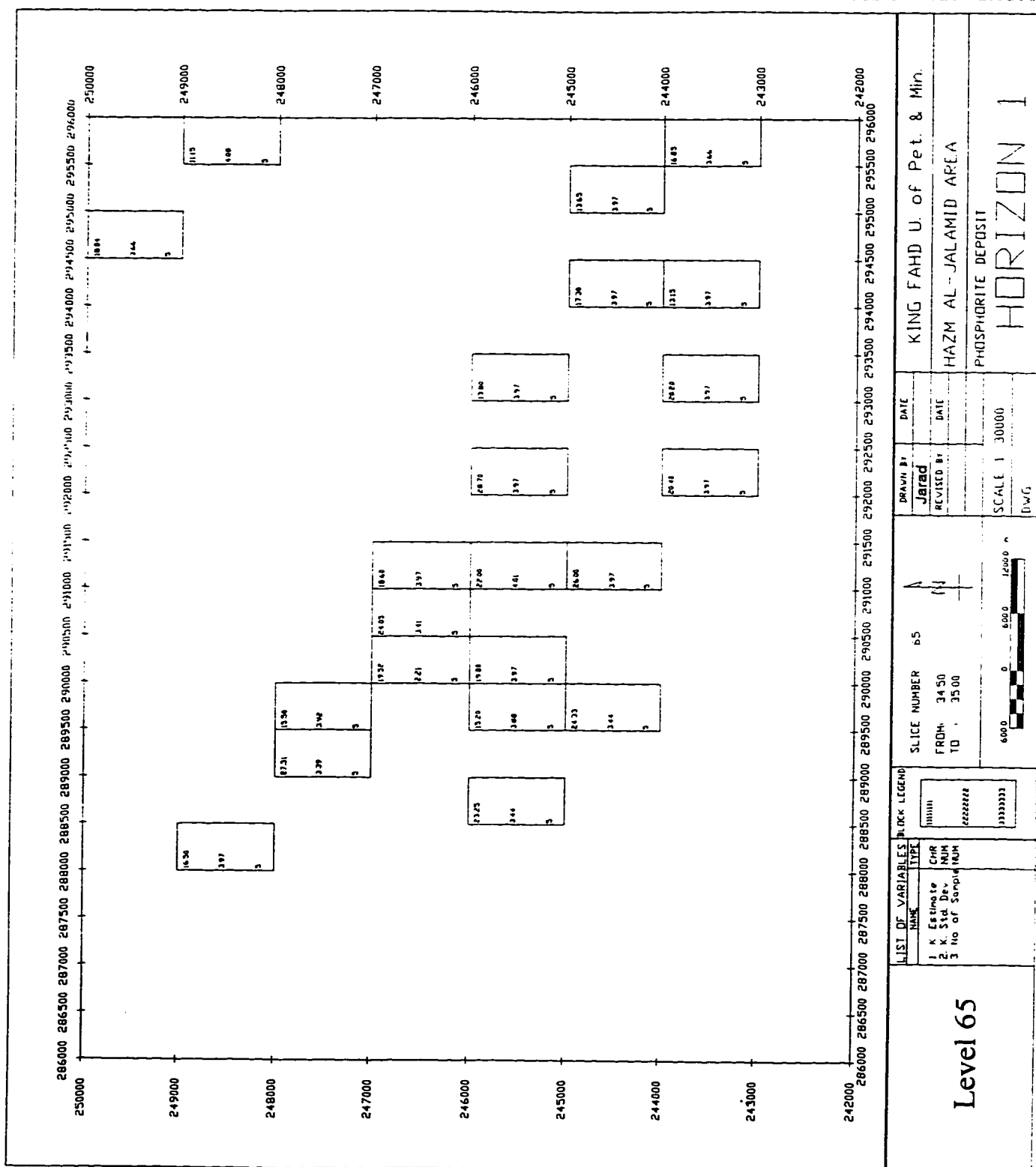


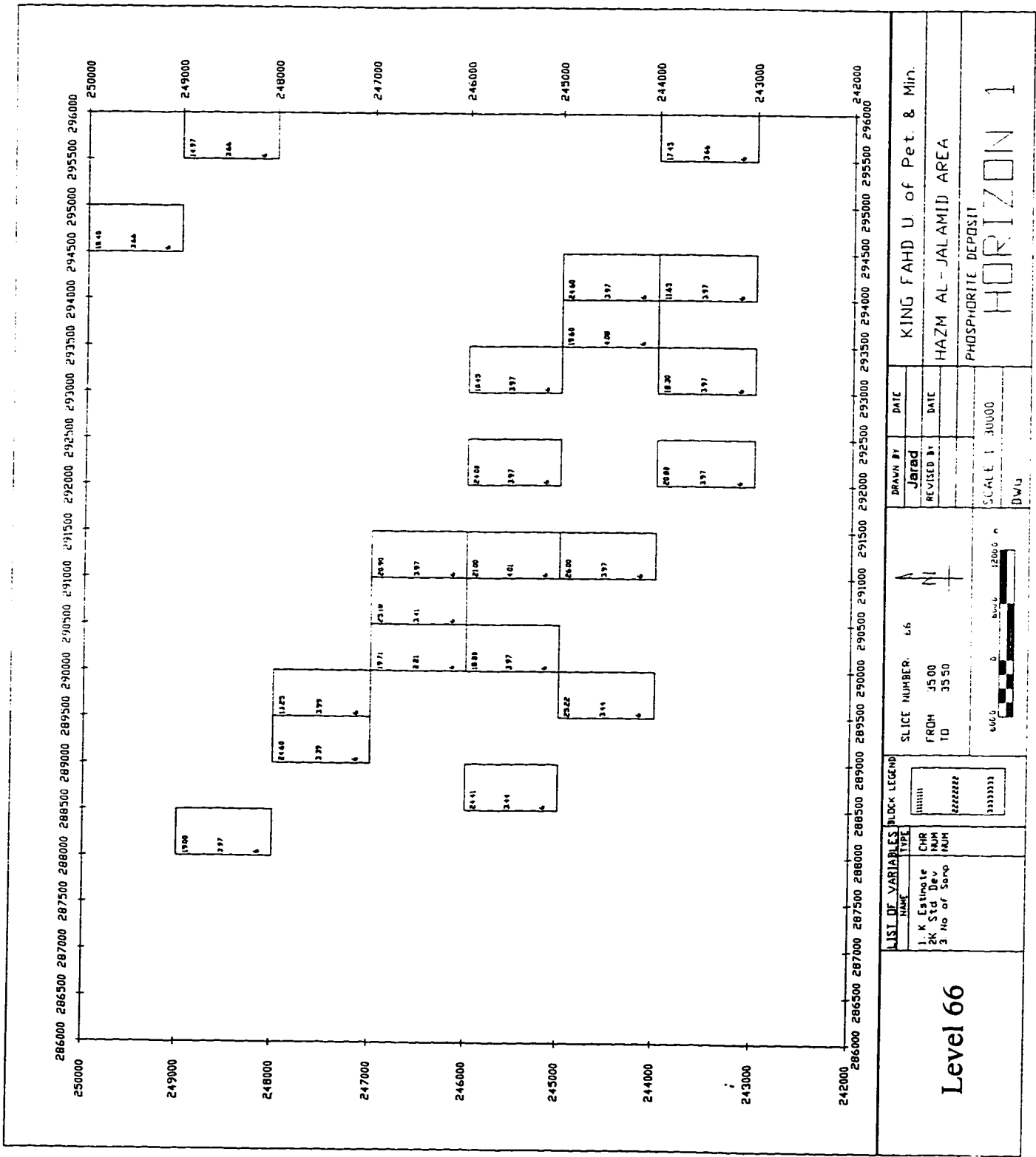








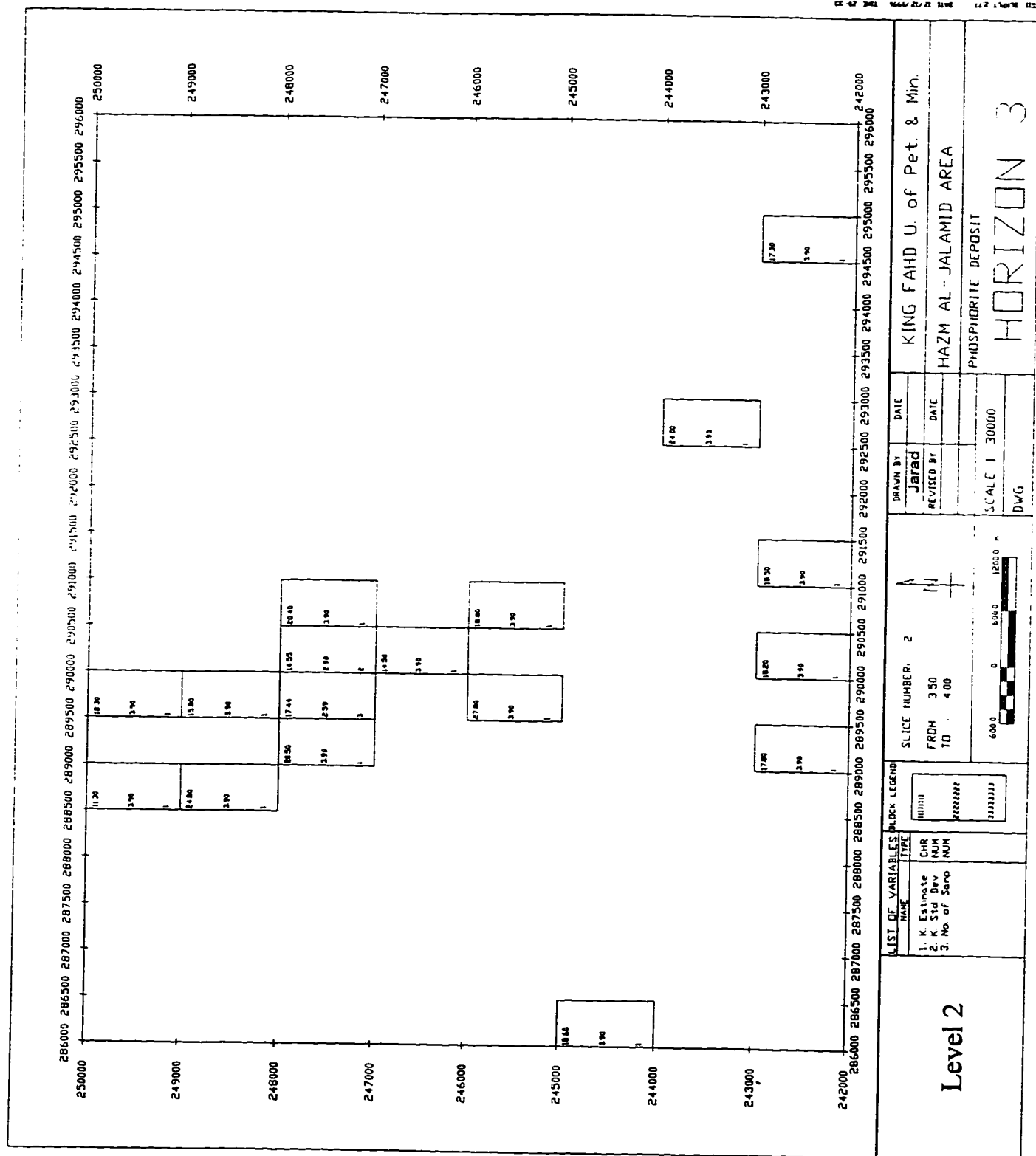


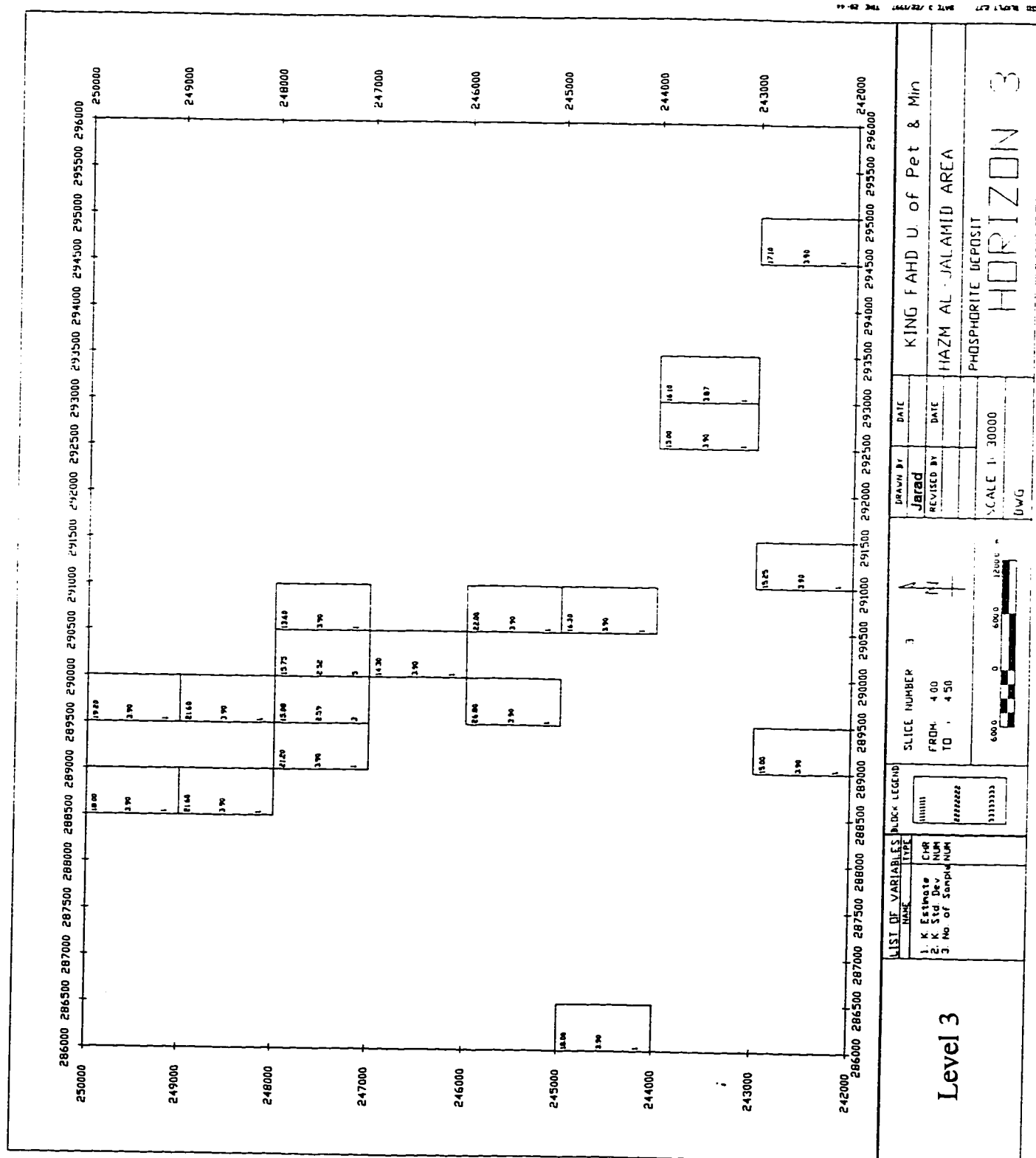


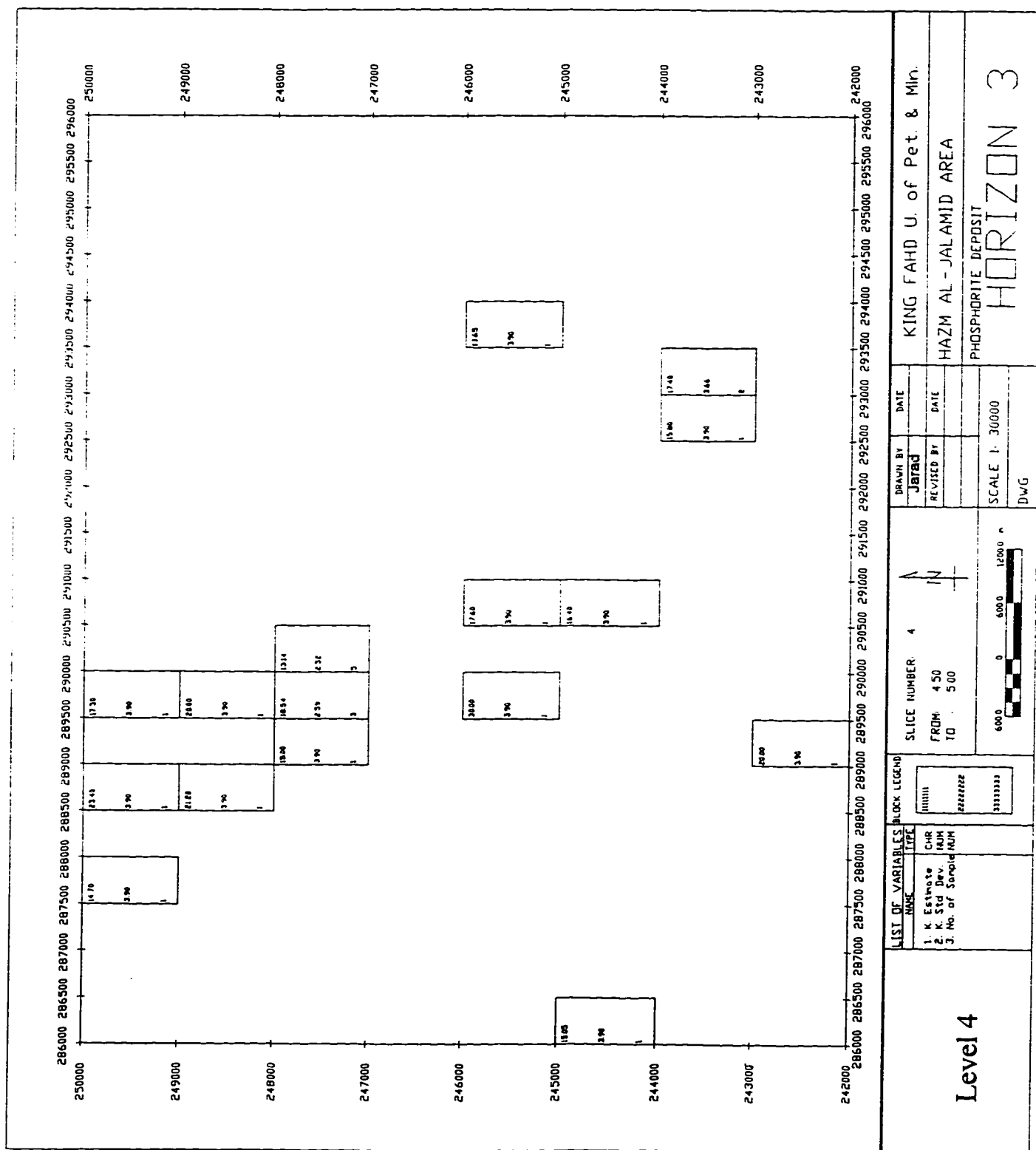
## **APPENDIX I**

Kriging output maps for Horizon 3

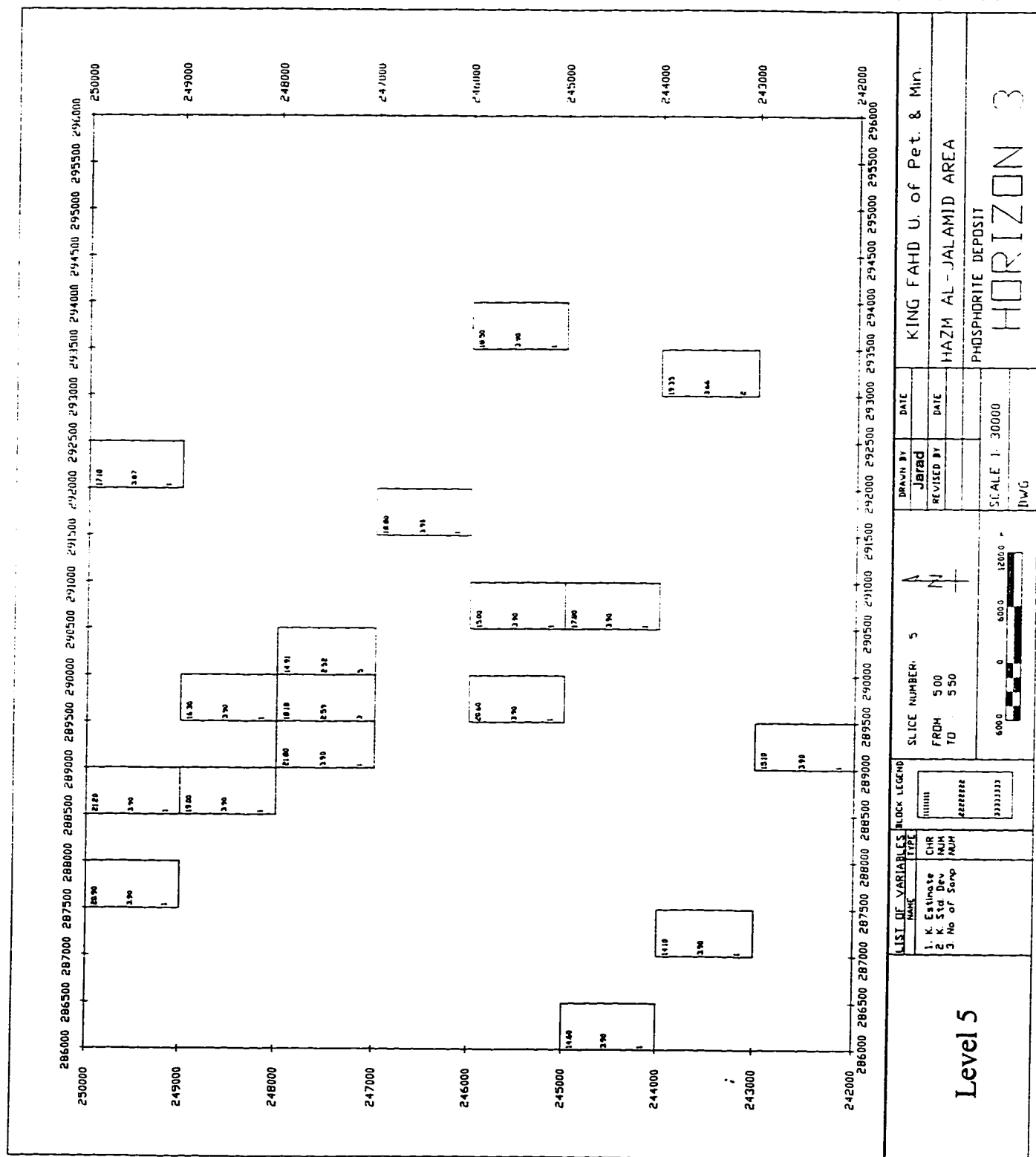




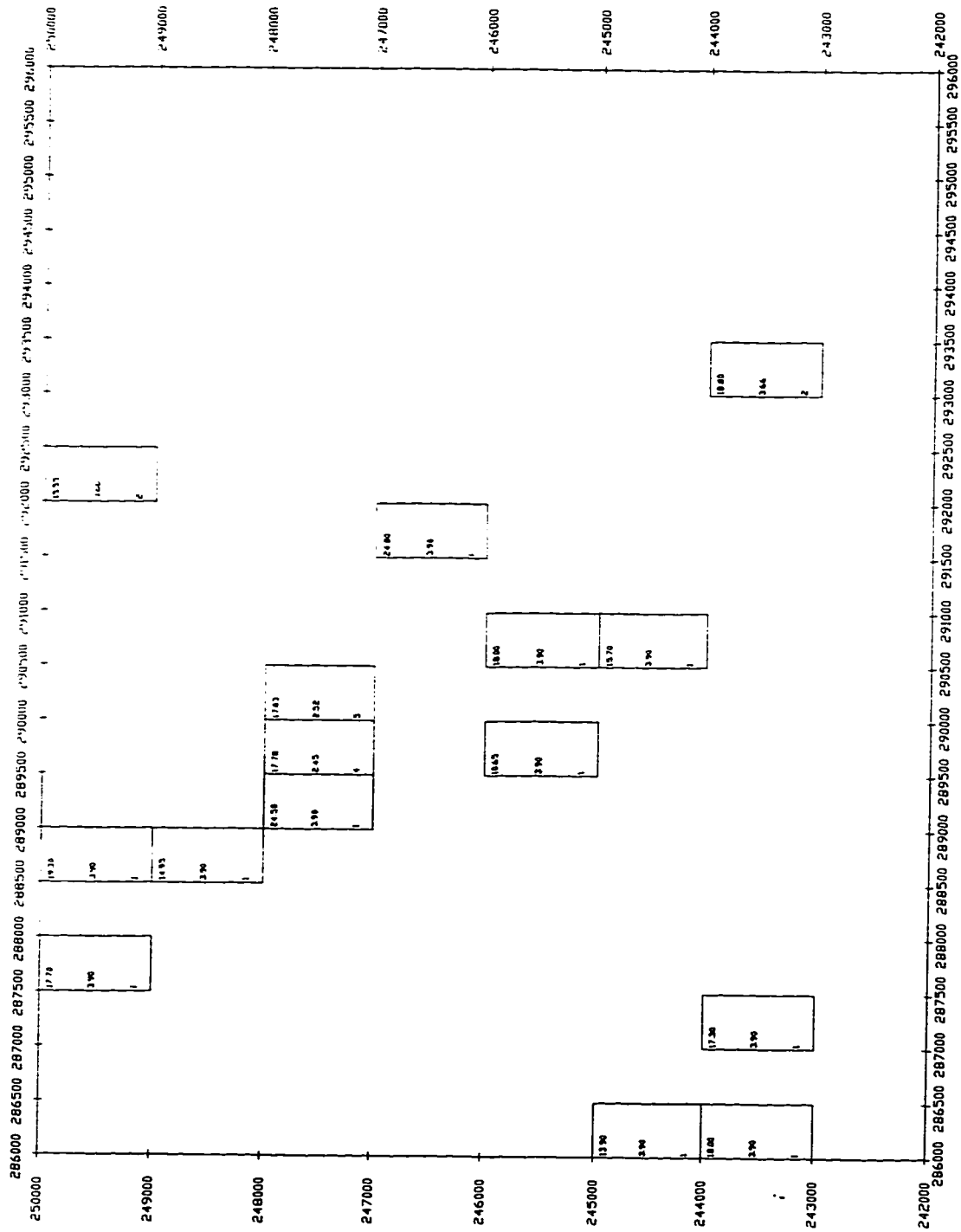




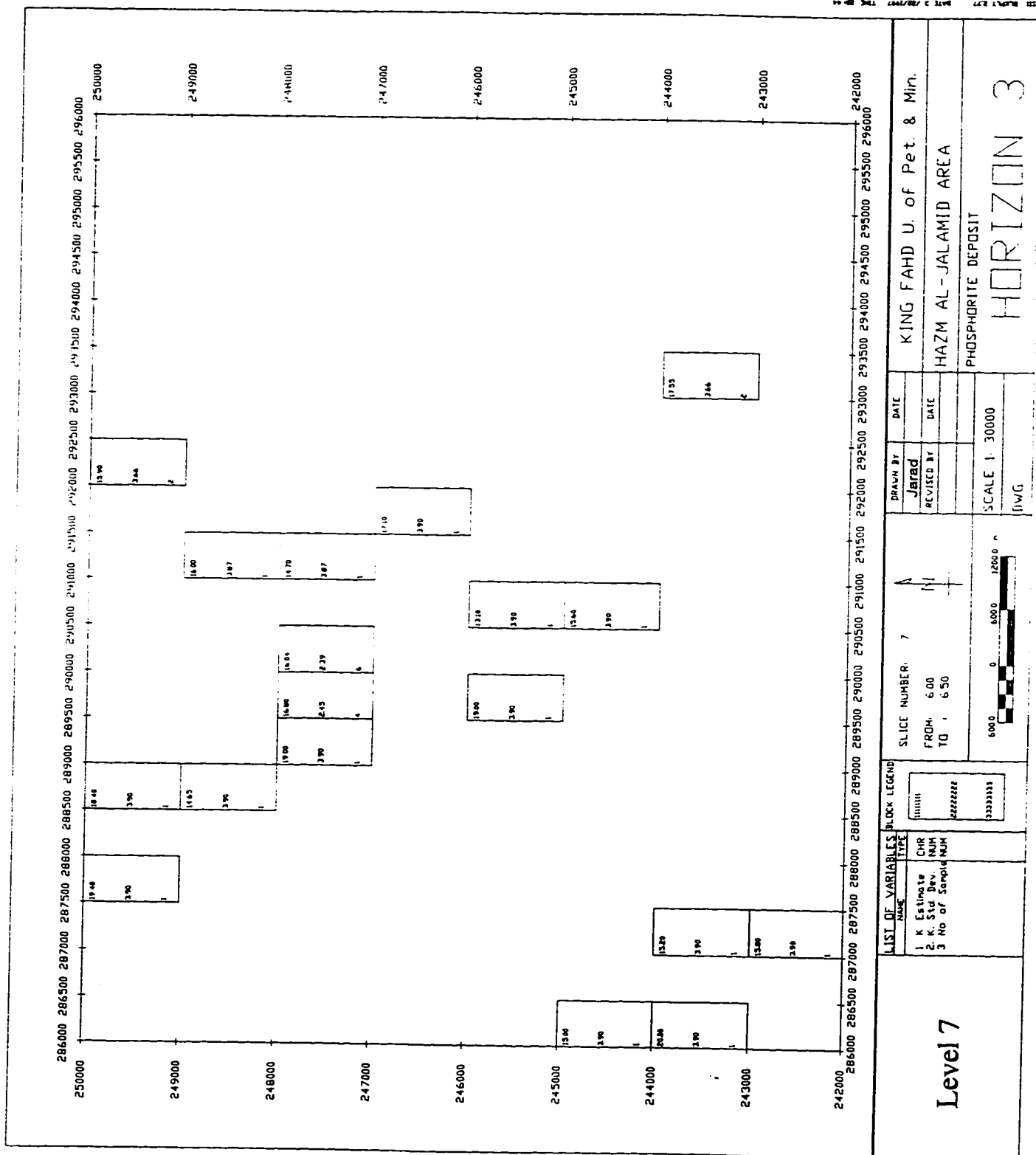




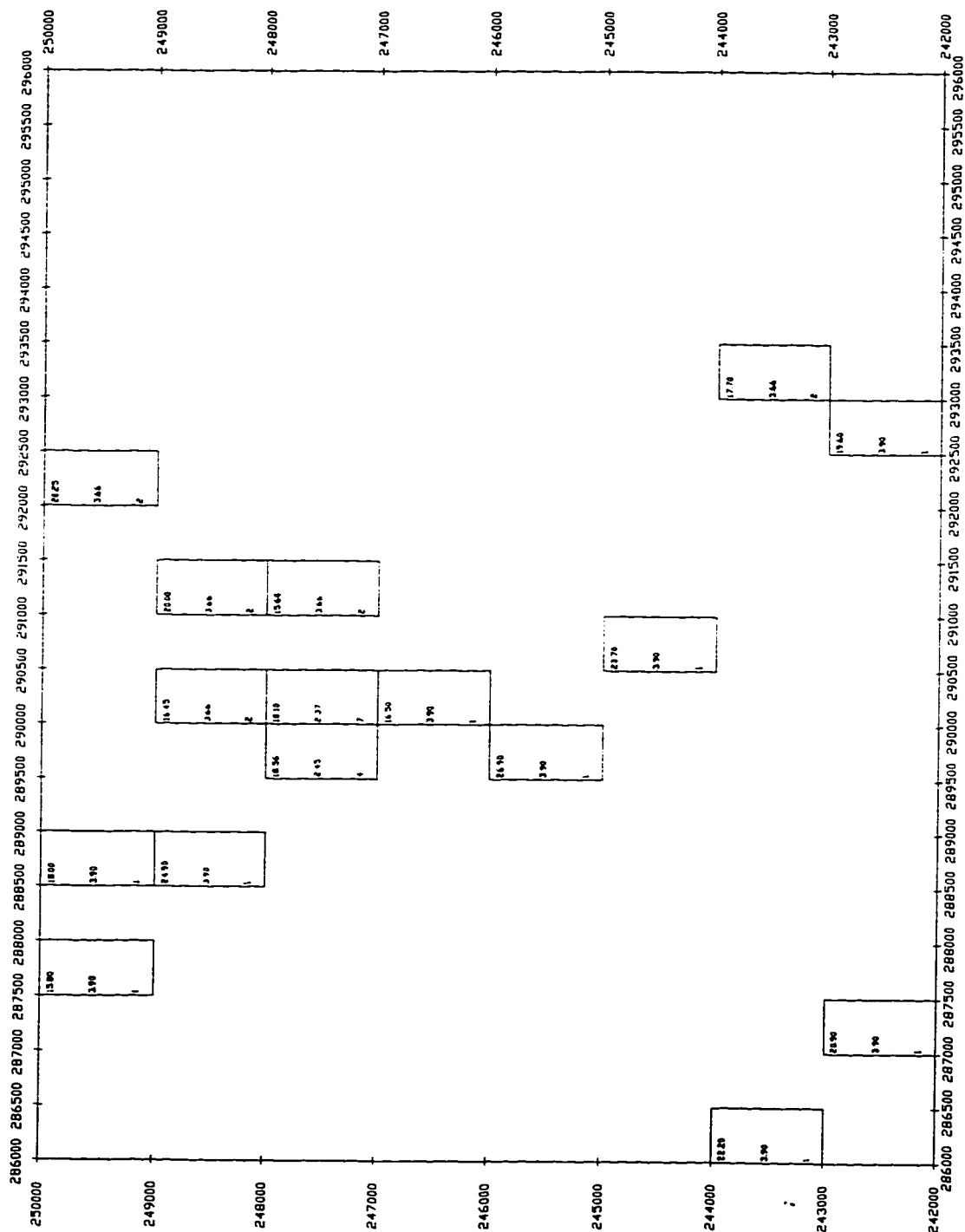
CSO Map 1.27 DATE 2/22/99 TIME 09:44



|         |                   |      |              |  |              |      |            |  |      |  |                             |  |
|---------|-------------------|------|--------------|--|--------------|------|------------|--|------|--|-----------------------------|--|
| Level 6 | LIST OF VARIABLES |      | BLOCK LEGEND |  | SLICE NUMBER |      | DRAWN BY   |  | DATE |  | KING FAHD U. of Pet. & Min. |  |
|         | NAME              | TYPE |              |  | FROM         | TO   | Jafar      |  |      |  | HAZM AL-JALAMID AREA        |  |
|         | 1. Estimate       | CHR  |              |  | 5.50         | 6.00 | REVISED BY |  | DATE |  | PHOSPHORITE DEPOSIT         |  |
|         | 2. Std Dev        | NUM  |              |  |              |      |            |  |      |  | HORIZON 3                   |  |
|         | 3. No of Sample   | NUM  |              |  |              |      |            |  |      |  | SCALE 1: 30000              |  |
|         |                   |      |              |  |              |      |            |  |      |  | DWG                         |  |







## Level 9

KING FAHD U. of Pet. &amp; Min.

HAZM AL - JALAMID AREA

PHOSPHORITE DEPOSIT

### HORIZON 3

| DATE | DRAWN BY |
|------|----------|
|      |          |

**DRAWN BY**

| REVISED BY | DATE |
|------------|------|
|------------|------|

0351A3

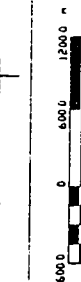
CALE 1. 30000

56

SLICE NUMBER 9

587M. 700

FROM: 700  
TO: 750



| LIST OF VARIABLES |     | BLOCK | LEGEND |
|-------------------|-----|-------|--------|
| 1                 | ... | ...   | ...    |
| 2                 | ... | ...   | ...    |
| 3                 | ... | ...   | ...    |
| 4                 | ... | ...   | ...    |
| 5                 | ... | ...   | ...    |
| 6                 | ... | ...   | ...    |
| 7                 | ... | ...   | ...    |
| 8                 | ... | ...   | ...    |
| 9                 | ... | ...   | ...    |
| 10                | ... | ...   | ...    |
| 11                | ... | ...   | ...    |
| 12                | ... | ...   | ...    |
| 13                | ... | ...   | ...    |
| 14                | ... | ...   | ...    |
| 15                | ... | ...   | ...    |
| 16                | ... | ...   | ...    |
| 17                | ... | ...   | ...    |
| 18                | ... | ...   | ...    |
| 19                | ... | ...   | ...    |
| 20                | ... | ...   | ...    |
| 21                | ... | ...   | ...    |
| 22                | ... | ...   | ...    |
| 23                | ... | ...   | ...    |
| 24                | ... | ...   | ...    |
| 25                | ... | ...   | ...    |
| 26                | ... | ...   | ...    |
| 27                | ... | ...   | ...    |
| 28                | ... | ...   | ...    |
| 29                | ... | ...   | ...    |
| 30                | ... | ...   | ...    |
| 31                | ... | ...   | ...    |
| 32                | ... | ...   | ...    |
| 33                | ... | ...   | ...    |
| 34                | ... | ...   | ...    |
| 35                | ... | ...   | ...    |
| 36                | ... | ...   | ...    |
| 37                | ... | ...   | ...    |
| 38                | ... | ...   | ...    |
| 39                | ... | ...   | ...    |
| 40                | ... | ...   | ...    |
| 41                | ... | ...   | ...    |
| 42                | ... | ...   | ...    |
| 43                | ... | ...   | ...    |
| 44                | ... | ...   | ...    |
| 45                | ... | ...   | ...    |
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| 47                | ... | ...   | ...    |
| 48                | ... | ...   | ...    |
| 49                | ... | ...   | ...    |
| 50                | ... | ...   | ...    |
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| 52                | ... | ...   | ...    |
| 53                | ... | ...   | ...    |
| 54                | ... | ...   | ...    |
| 55                | ... | ...   | ...    |
| 56                | ... | ...   | ...    |
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| 58                | ... | ...   | ...    |
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| 64                | ... | ...   | ...    |
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| 70                | ... | ...   | ...    |
| 71                | ... | ...   | ...    |
| 72                | ... | ...   | ...    |
| 73                | ... | ...   | ...    |
| 74                | ... | ...   | ...    |
| 75                | ... | ...   | ...    |
| 76                | ... | ...   | ...    |
| 77                | ... | ...   | ...    |
| 78                | ... | ...   | ...    |
| 79                | ... | ...   | ...    |
| 80                | ... | ...   | ...    |
| 81                | ... | ...   | ...    |
| 82                | ... | ...   | ...    |
| 83                | ... | ...   | ...    |
| 84                | ... | ...   | ...    |
| 85                | ... | ...   | ...    |
| 86                | ... | ...   | ...    |
| 87                | ... | ...   | ...    |
| 88                | ... | ...   | ...    |
| 89                | ... | ...   | ...    |
| 90                | ... | ...   | ...    |
| 91                | ... | ...   | ...    |
| 92                | ... | ...   | ...    |
| 93                | ... | ...   | ...    |
| 94                | ... | ...   | ...    |
| 95                | ... | ...   | ...    |
| 96                | ... | ...   | ...    |
| 97                | ... | ...   | ...    |
| 98                | ... | ...   | ...    |
| 99                | ... | ...   | ...    |
| 100               | ... | ...   | ...    |

| NAME | TYPE |
|------|------|
|------|------|

| CHR            | CHR    |
|----------------|--------|
| 1. K. Estimate | 111111 |

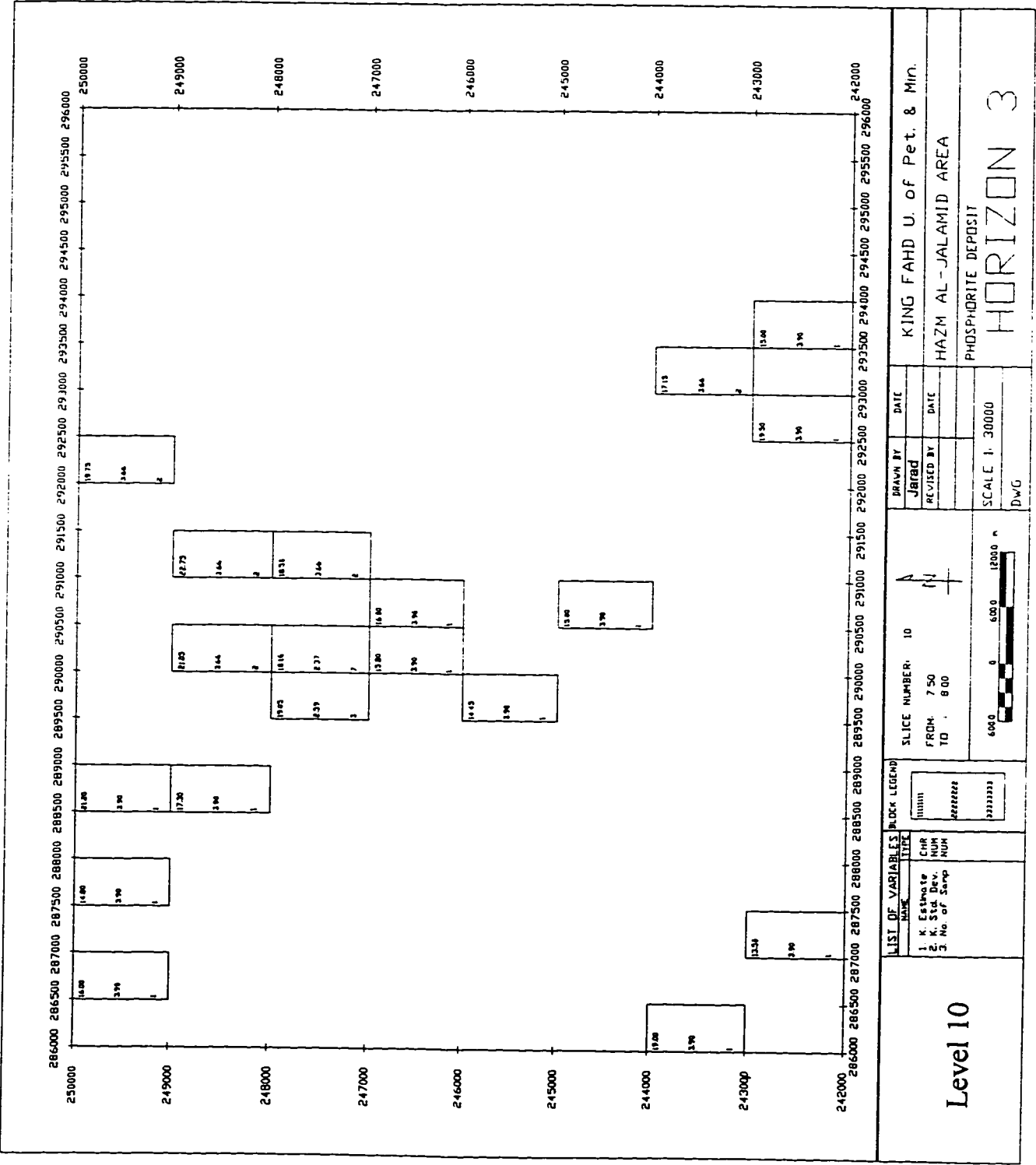
| 5. K. Sta | Dev    | NUM |
|-----------|--------|-----|
| 3. No of  | Sample | NUM |

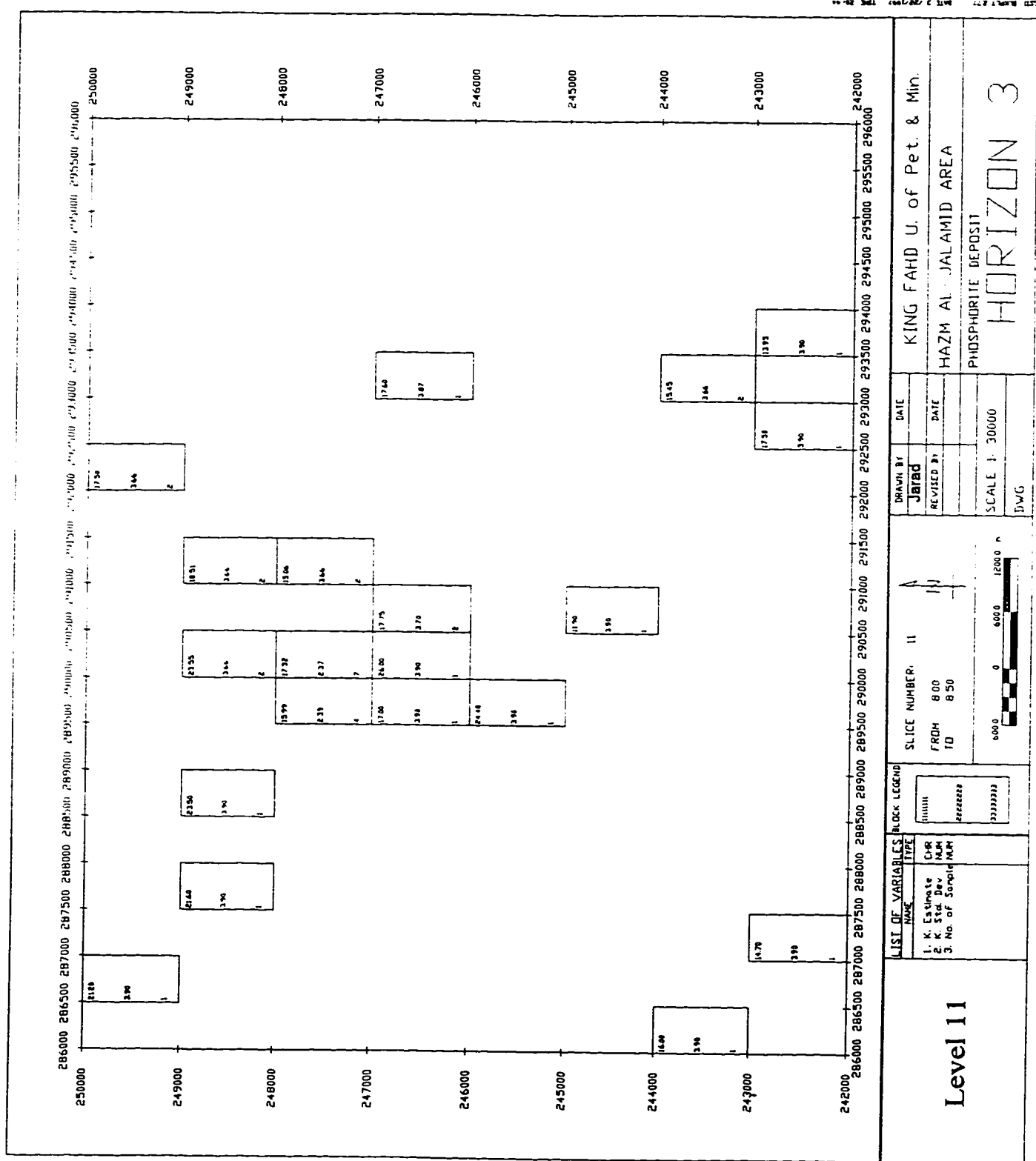
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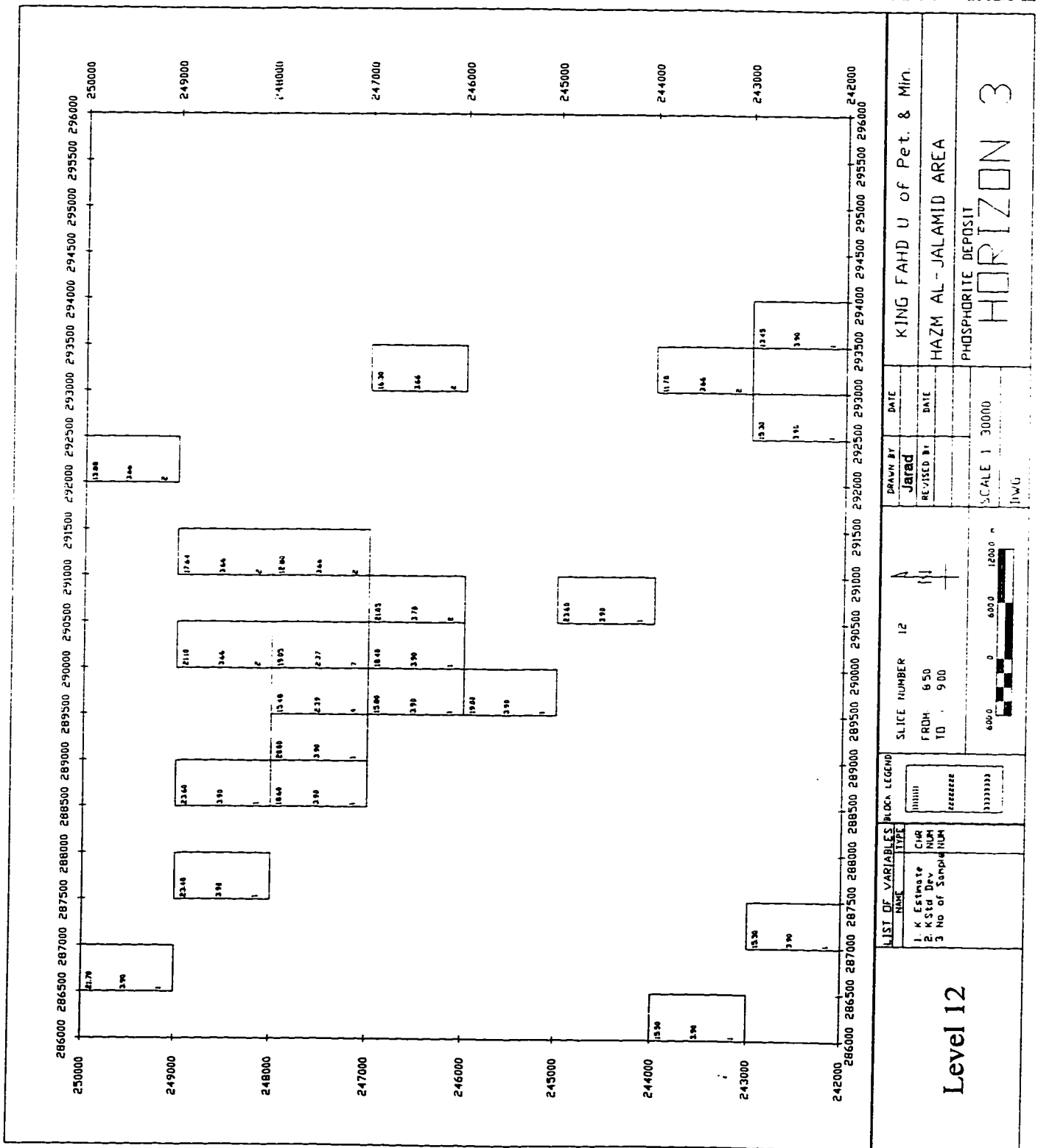
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CCCCC

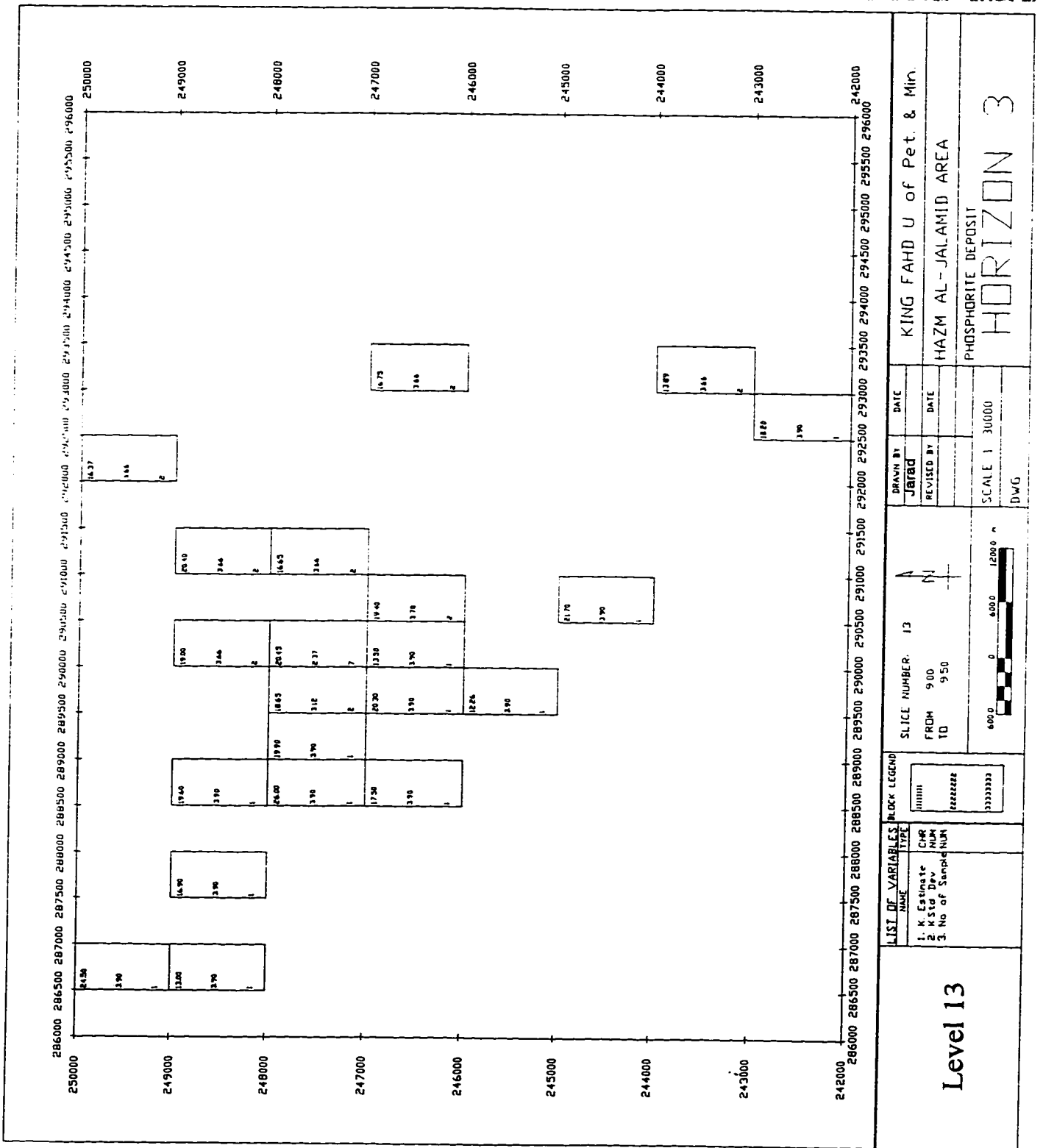
DATE: 11/11/03 BY: JAB/

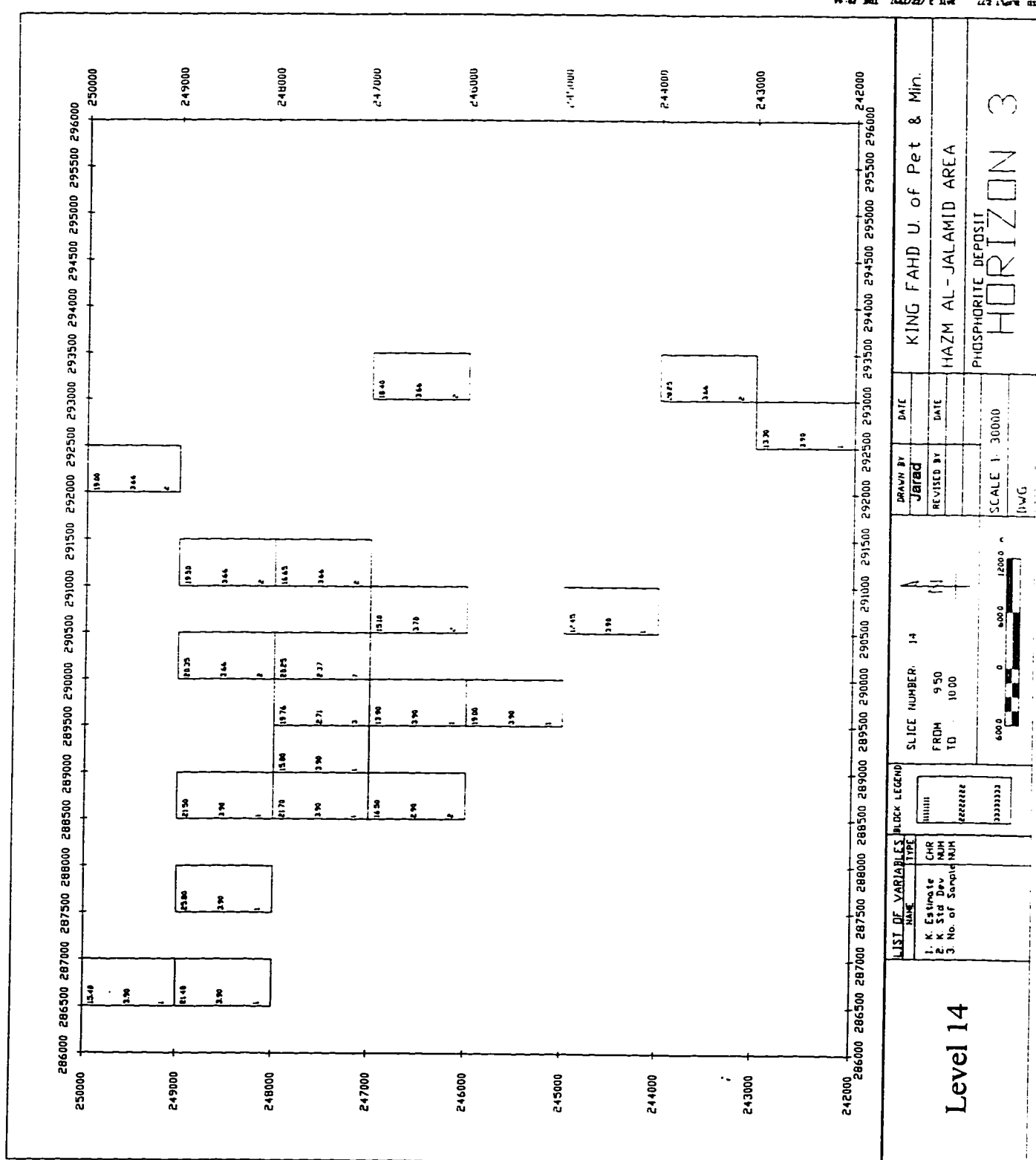




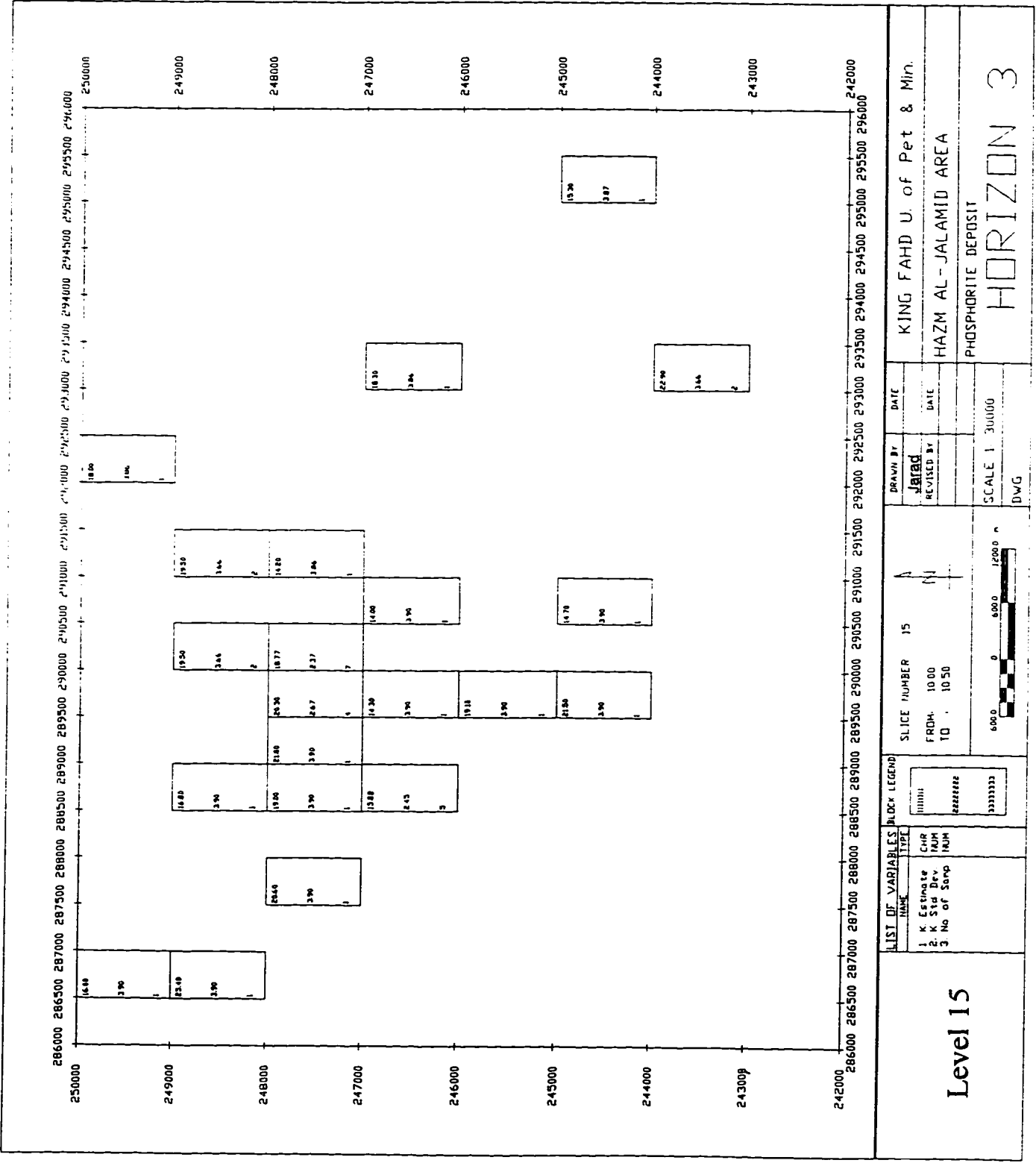




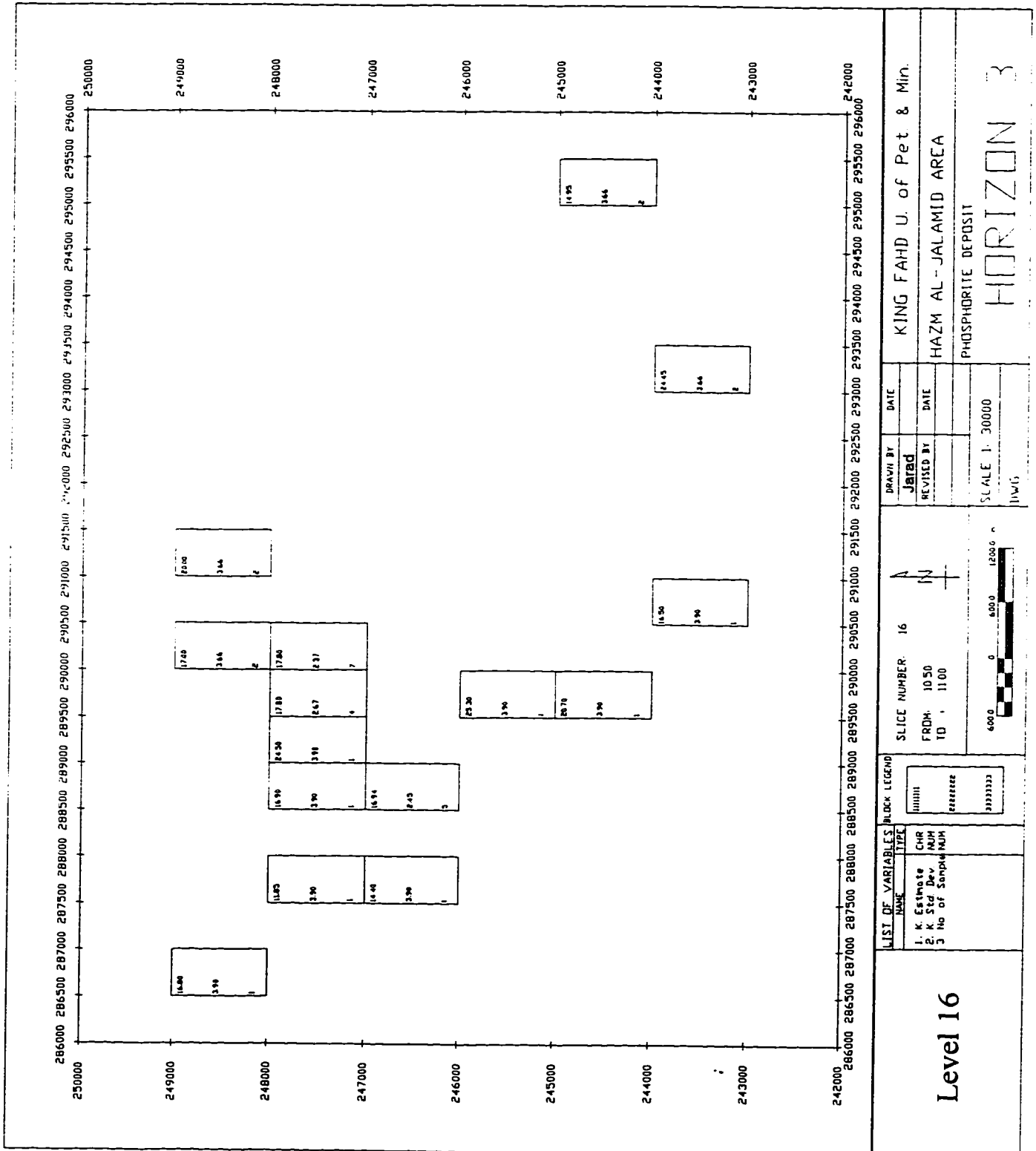


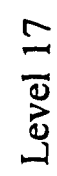


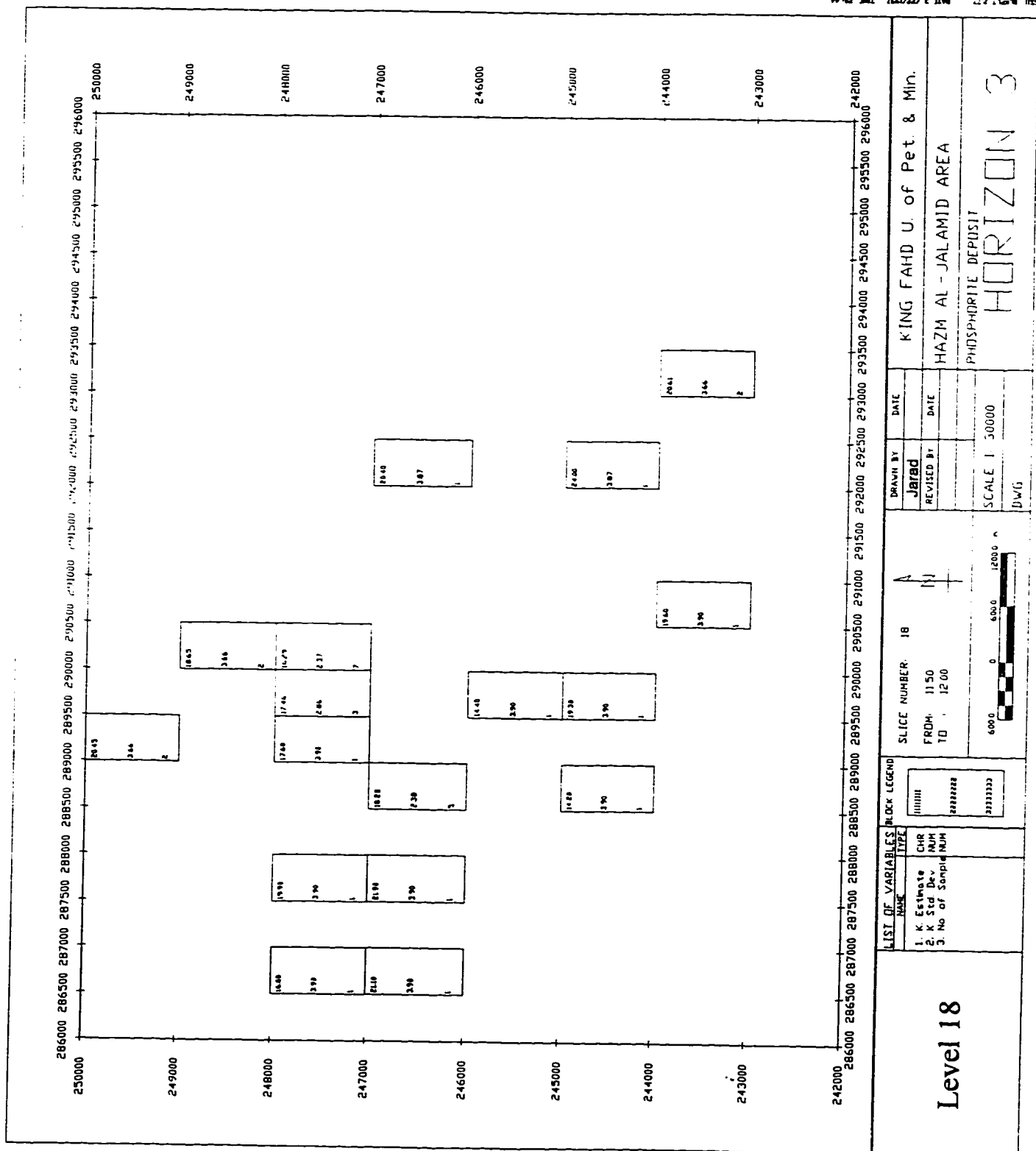
CSO 10/11/77 12:17 PM 12/12/77 12:17 PM



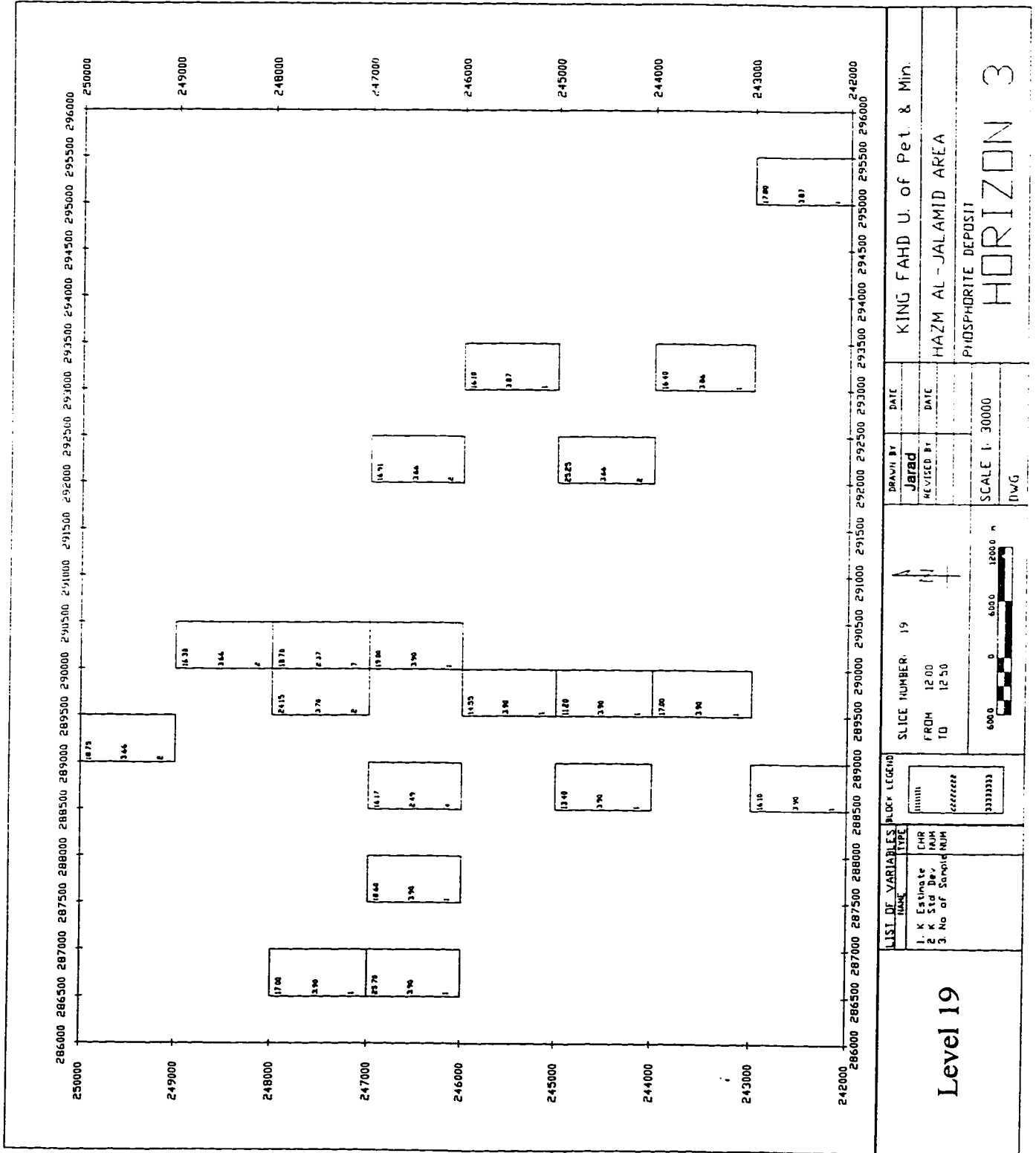
ED 10/11/17 DATE 10/11/17 TIME 09:44

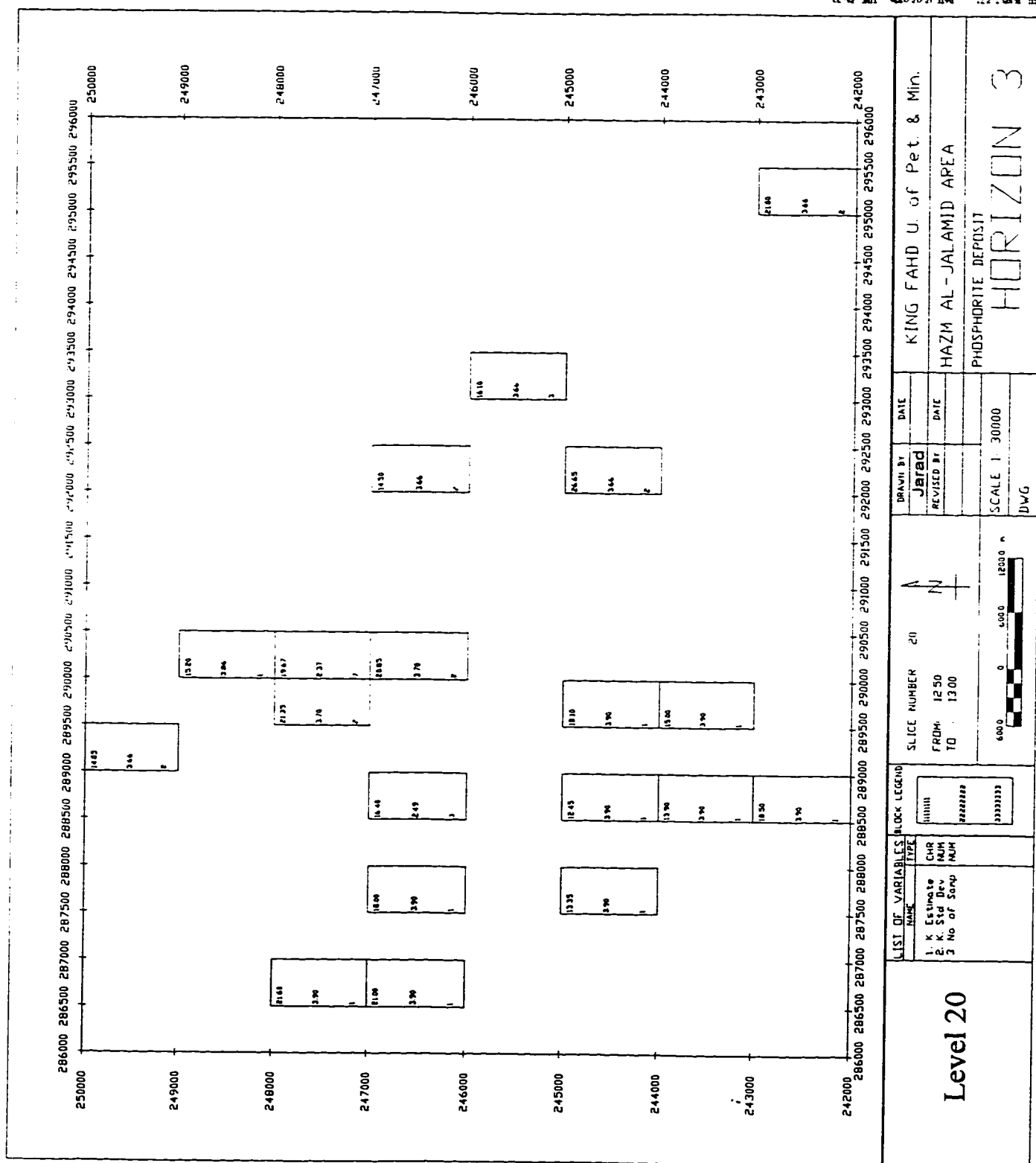




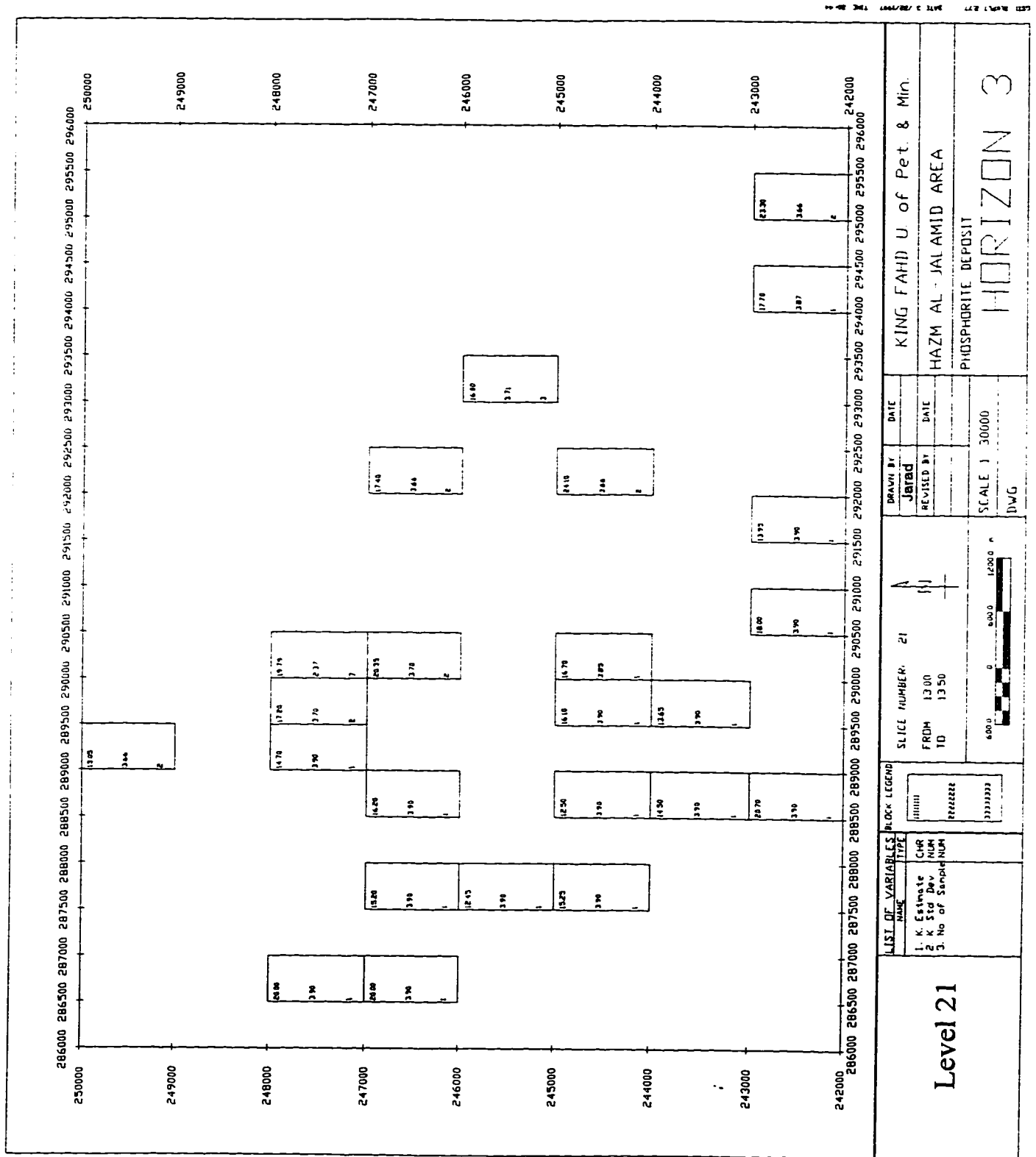


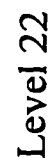
DATE 3/22/99 TIME 10:44

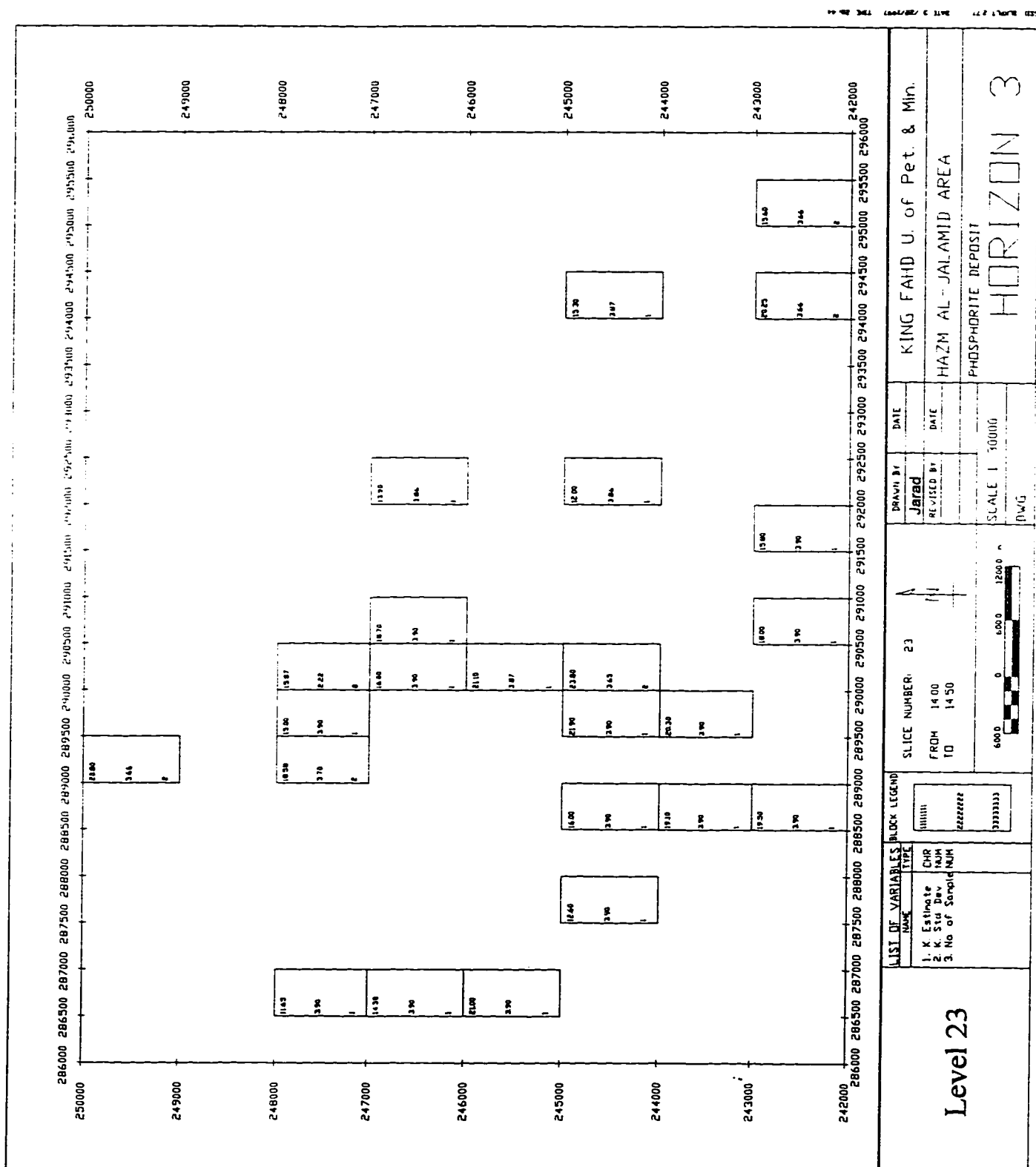


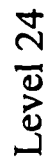


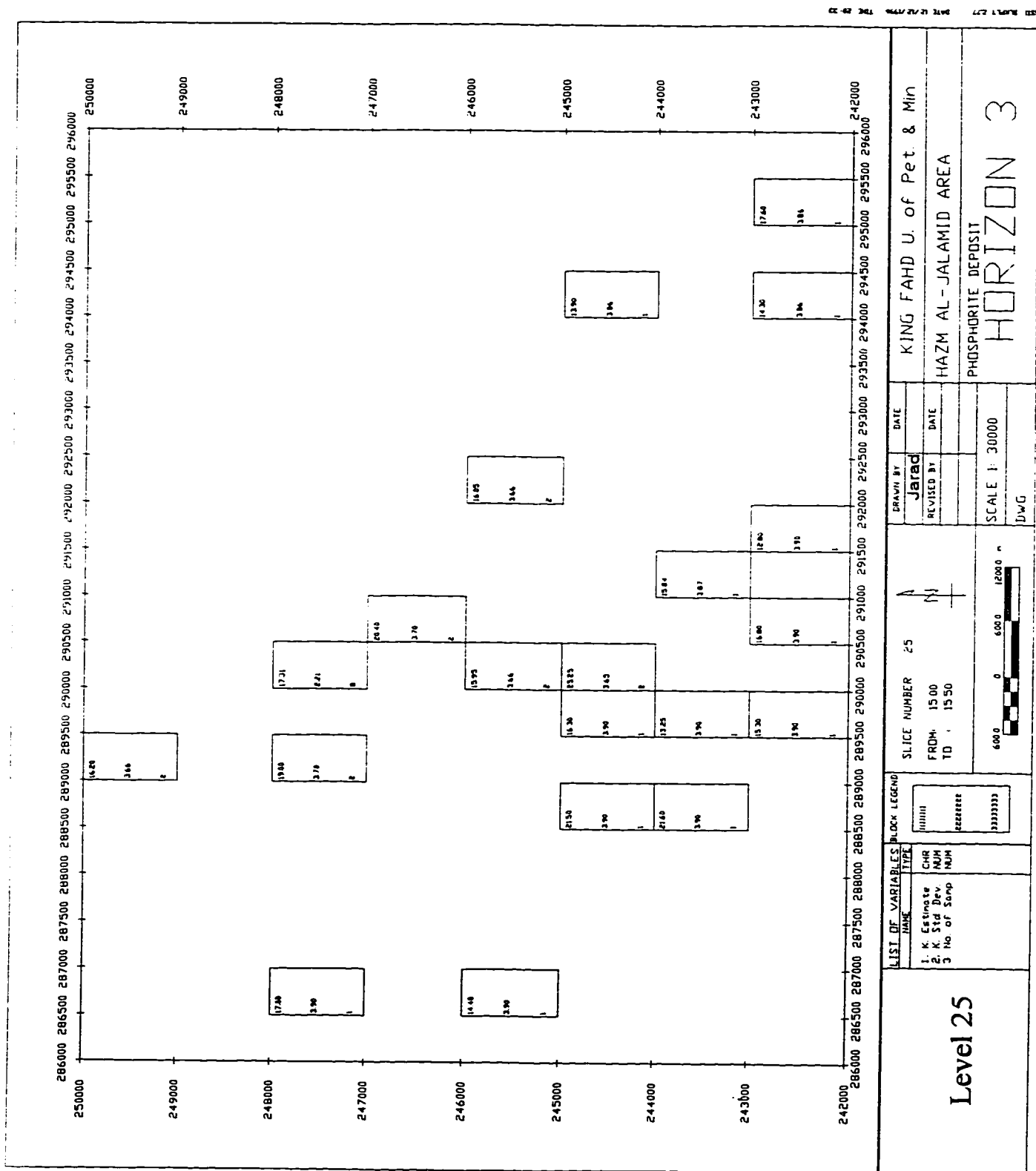


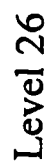


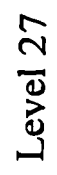


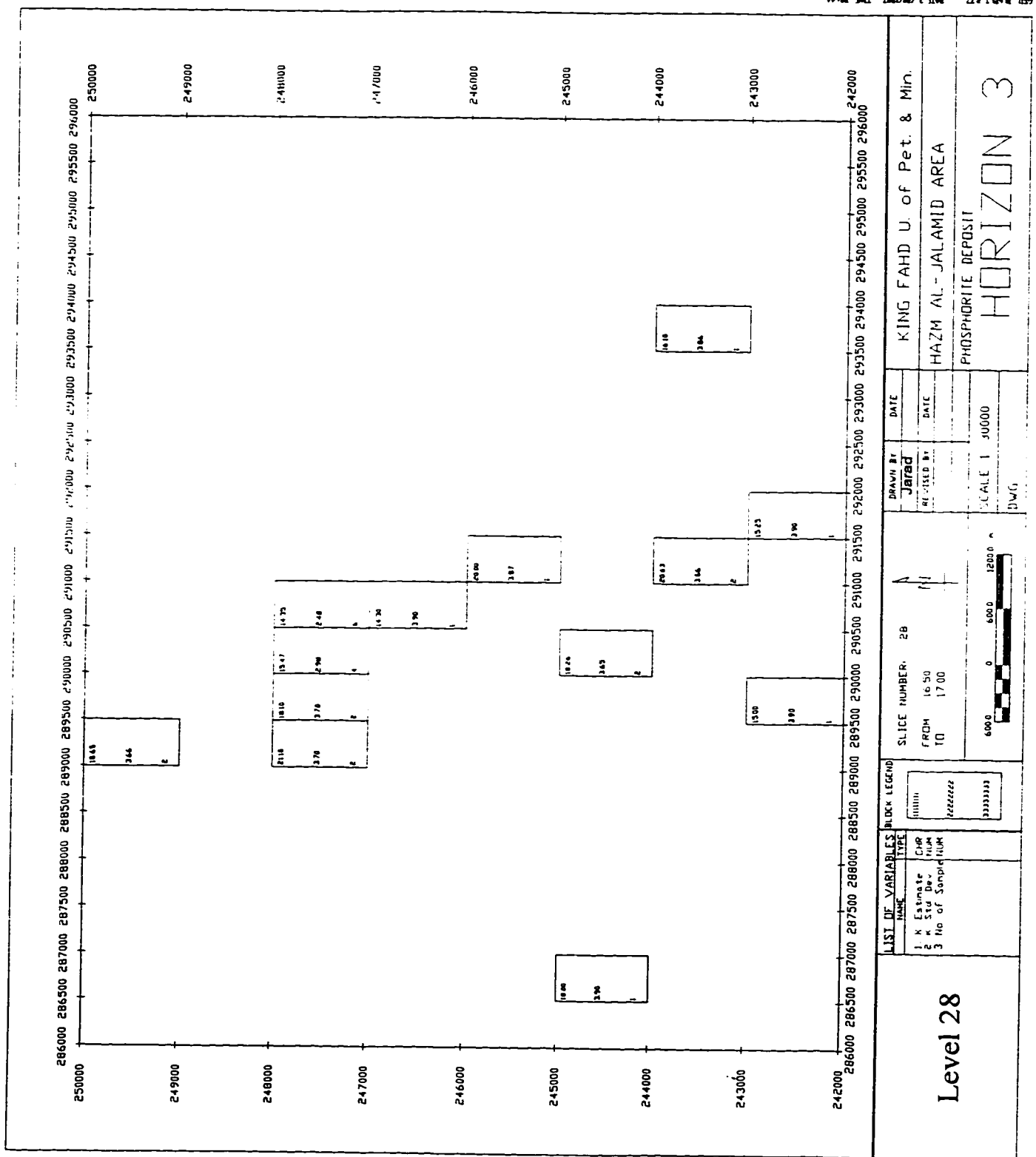




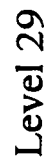




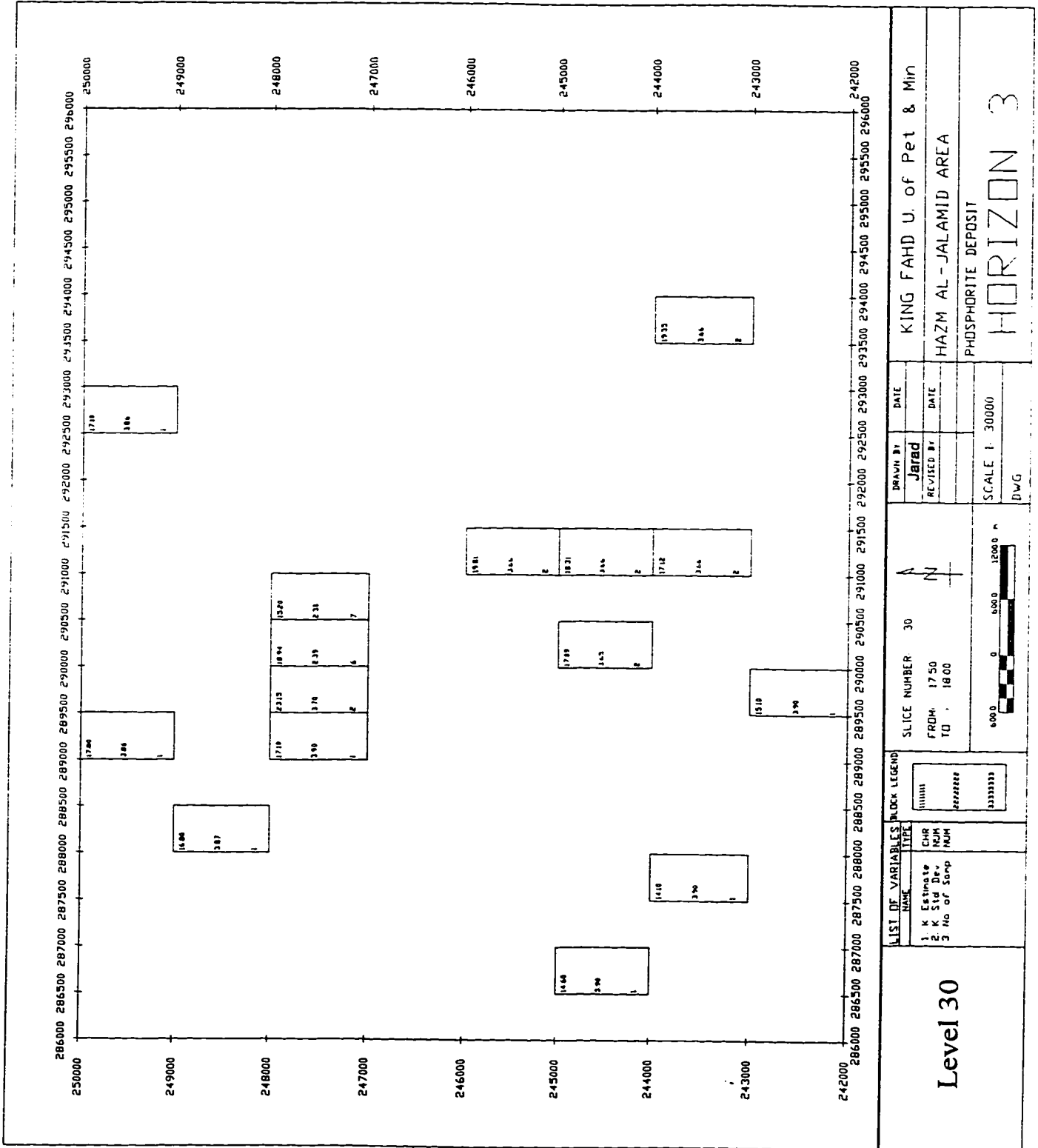


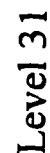


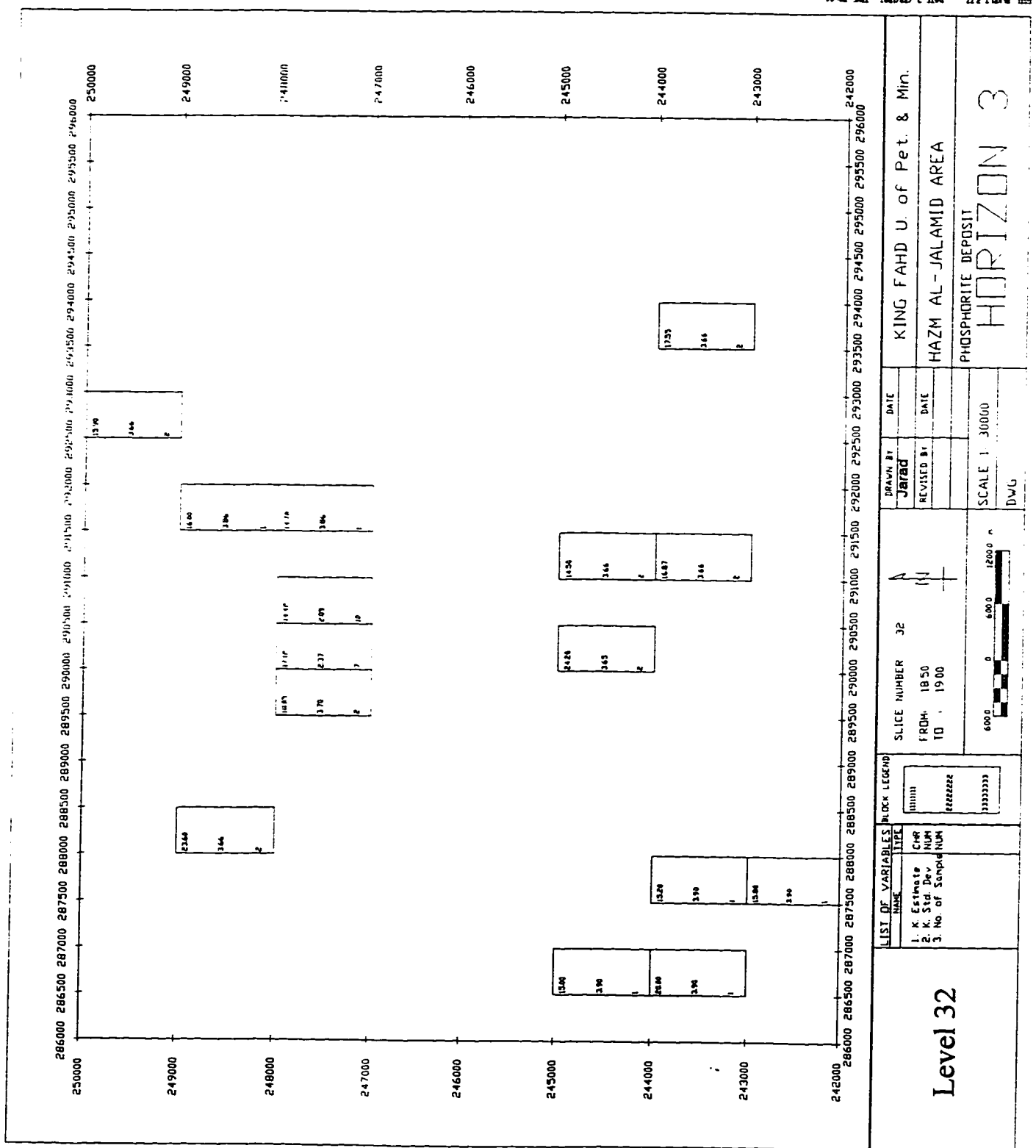


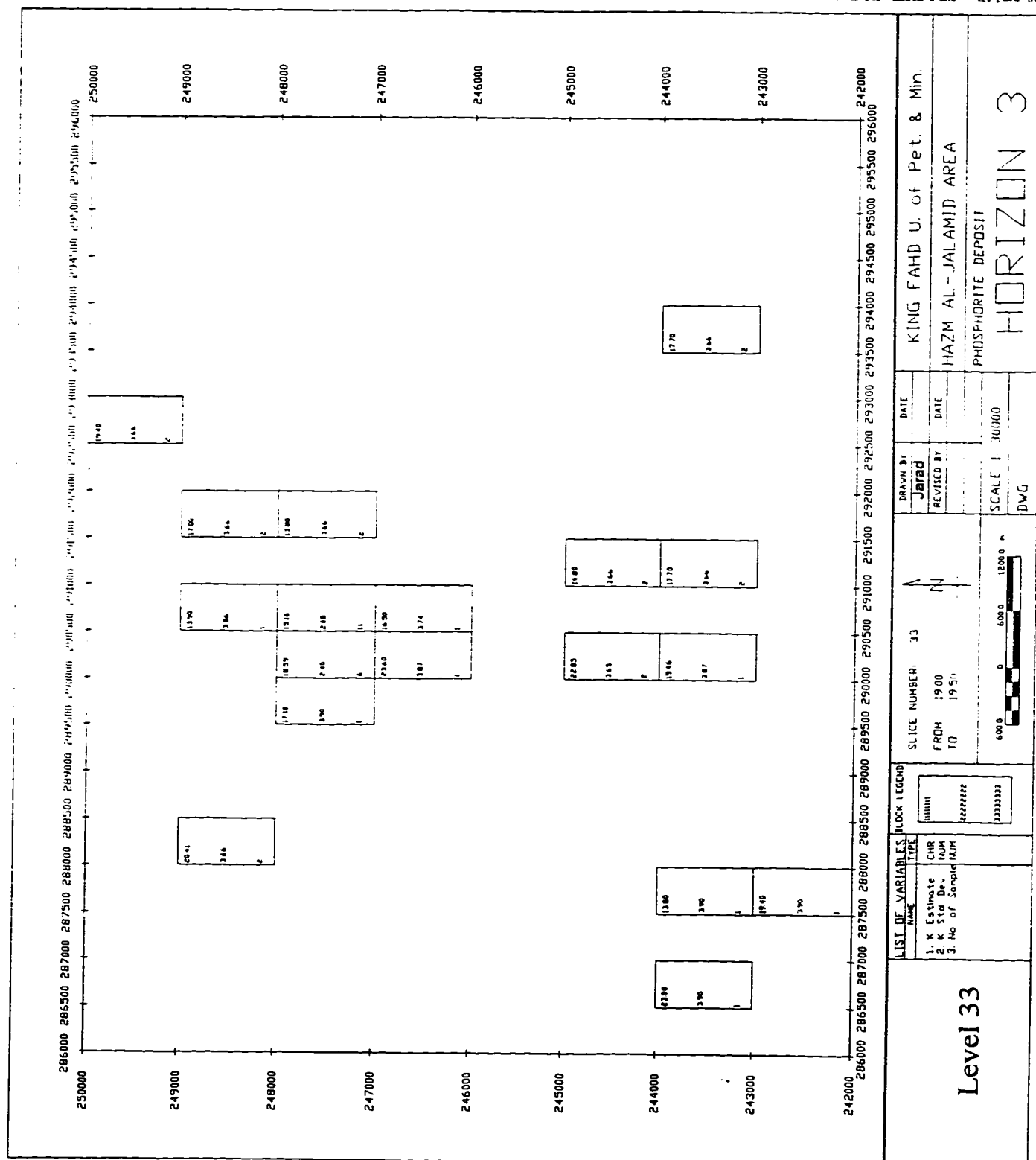


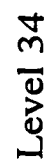
CSO MAP 1-27  
DATE 12-22-09  
THE 27-30

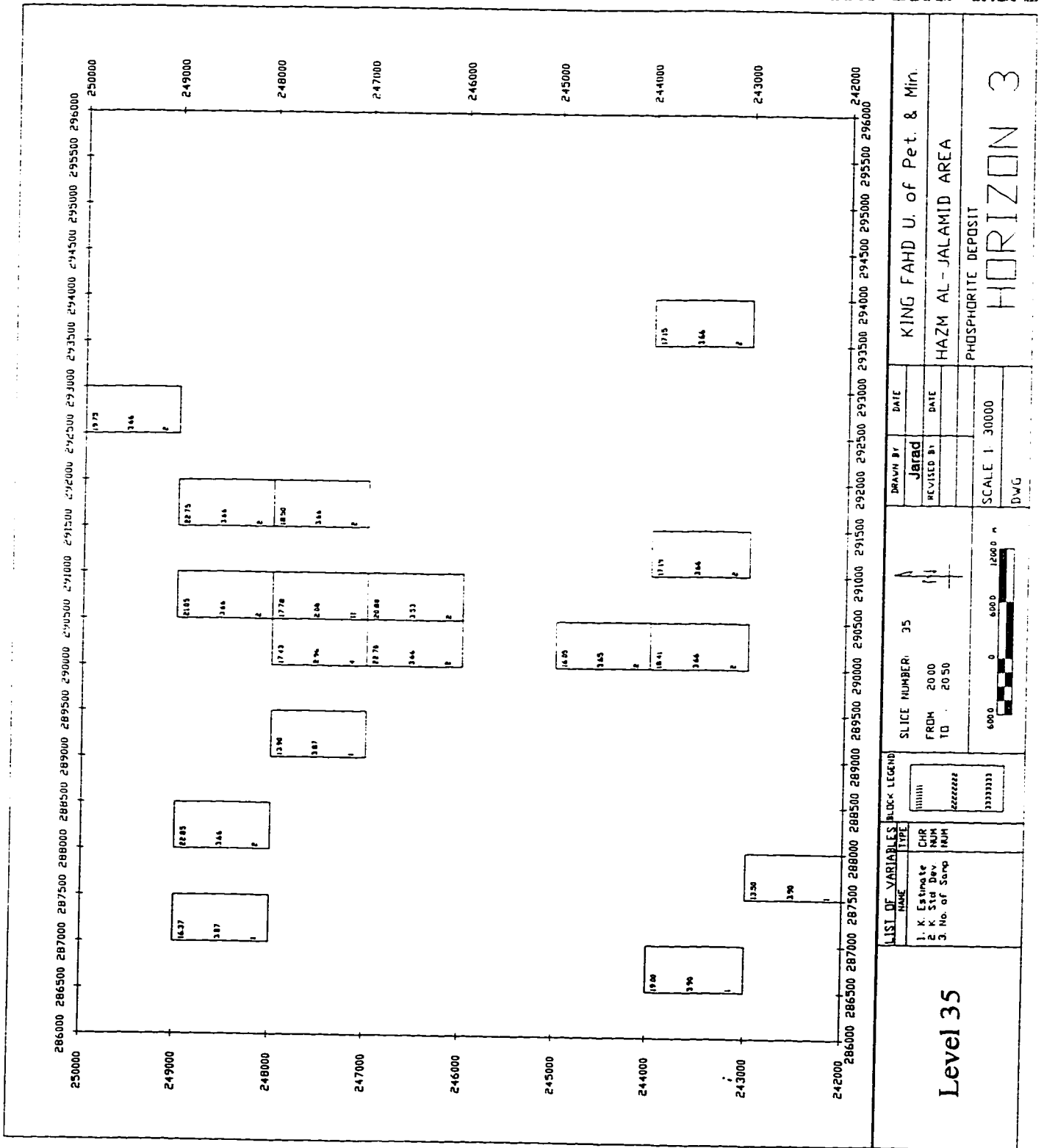


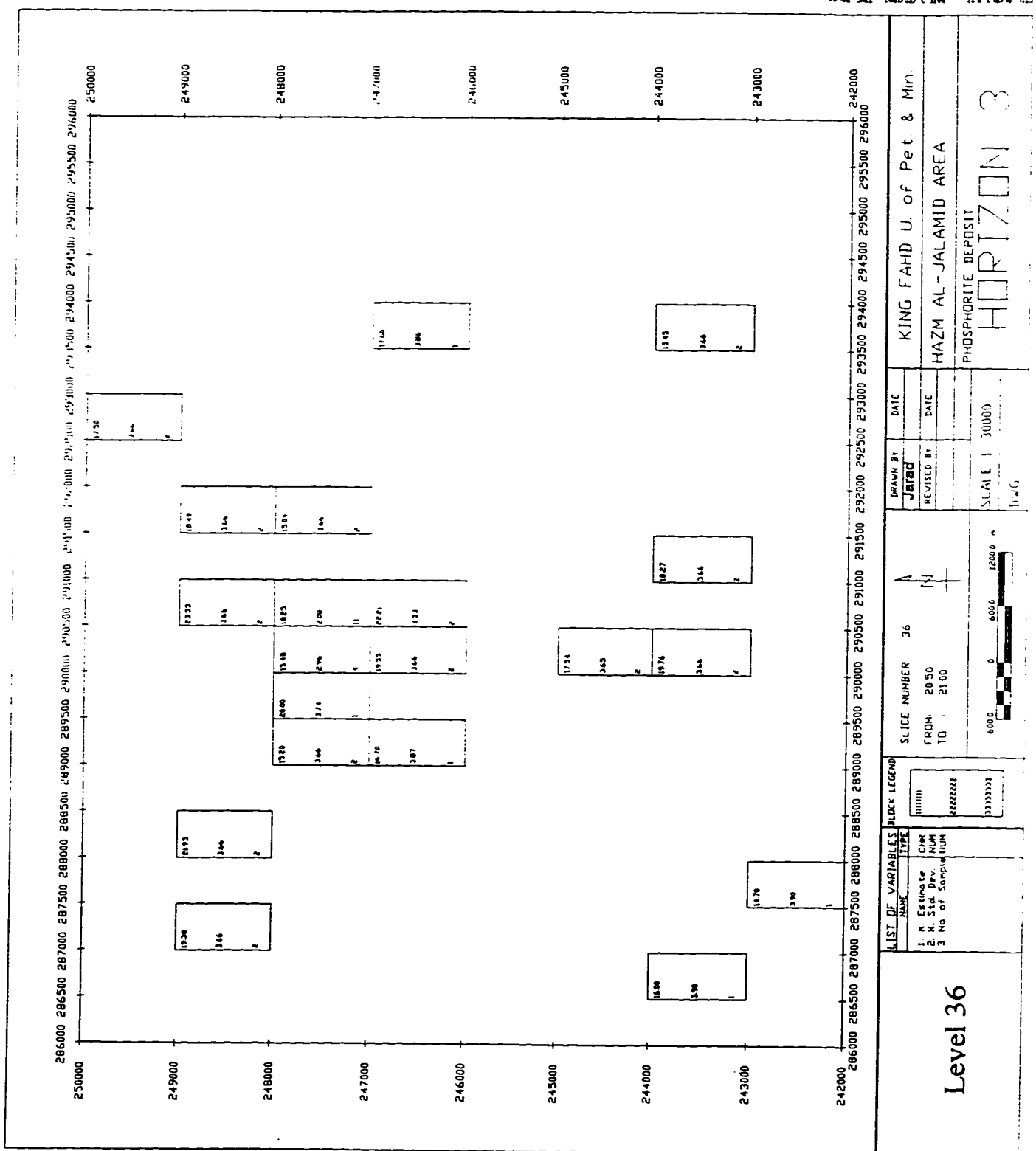




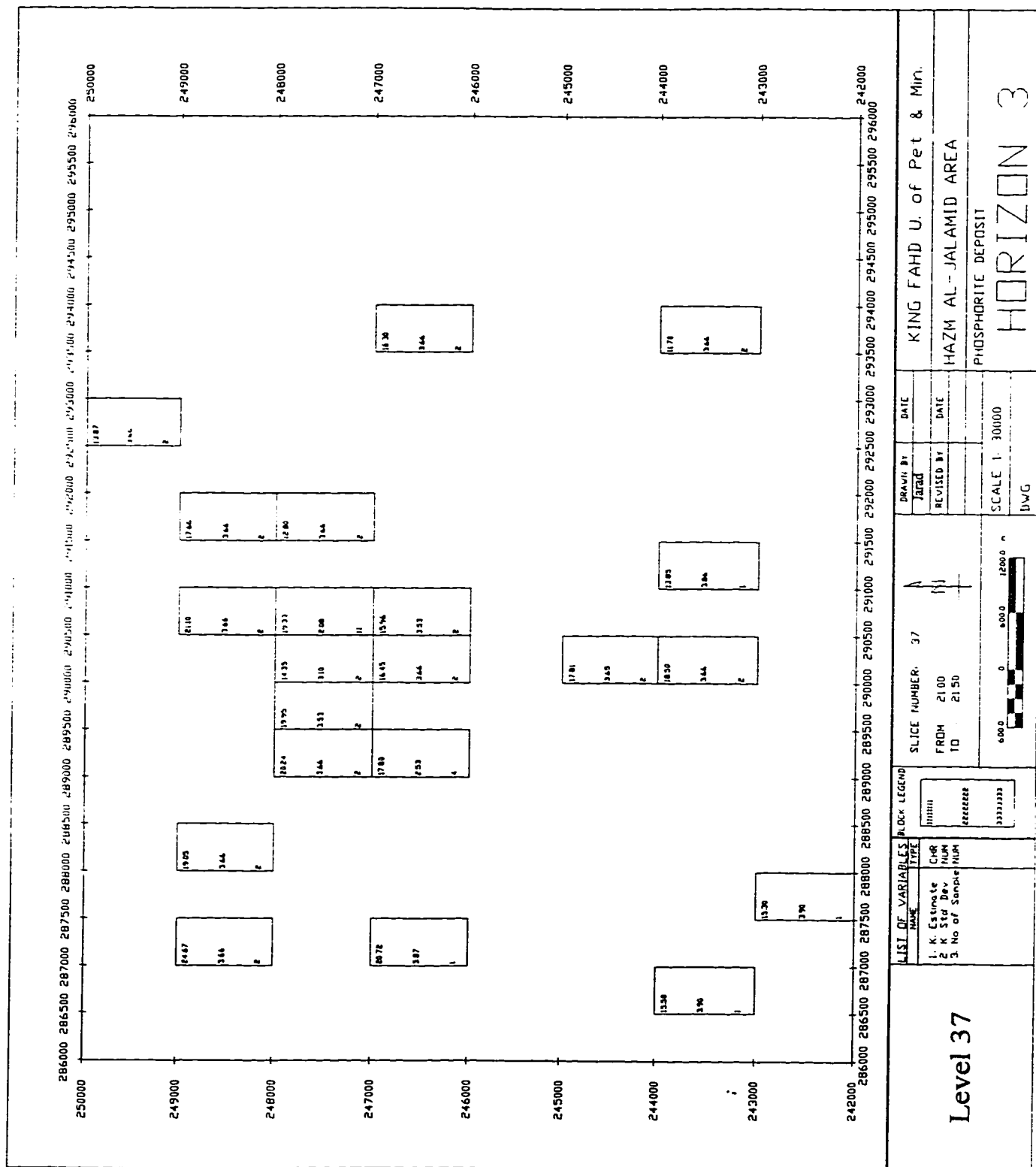


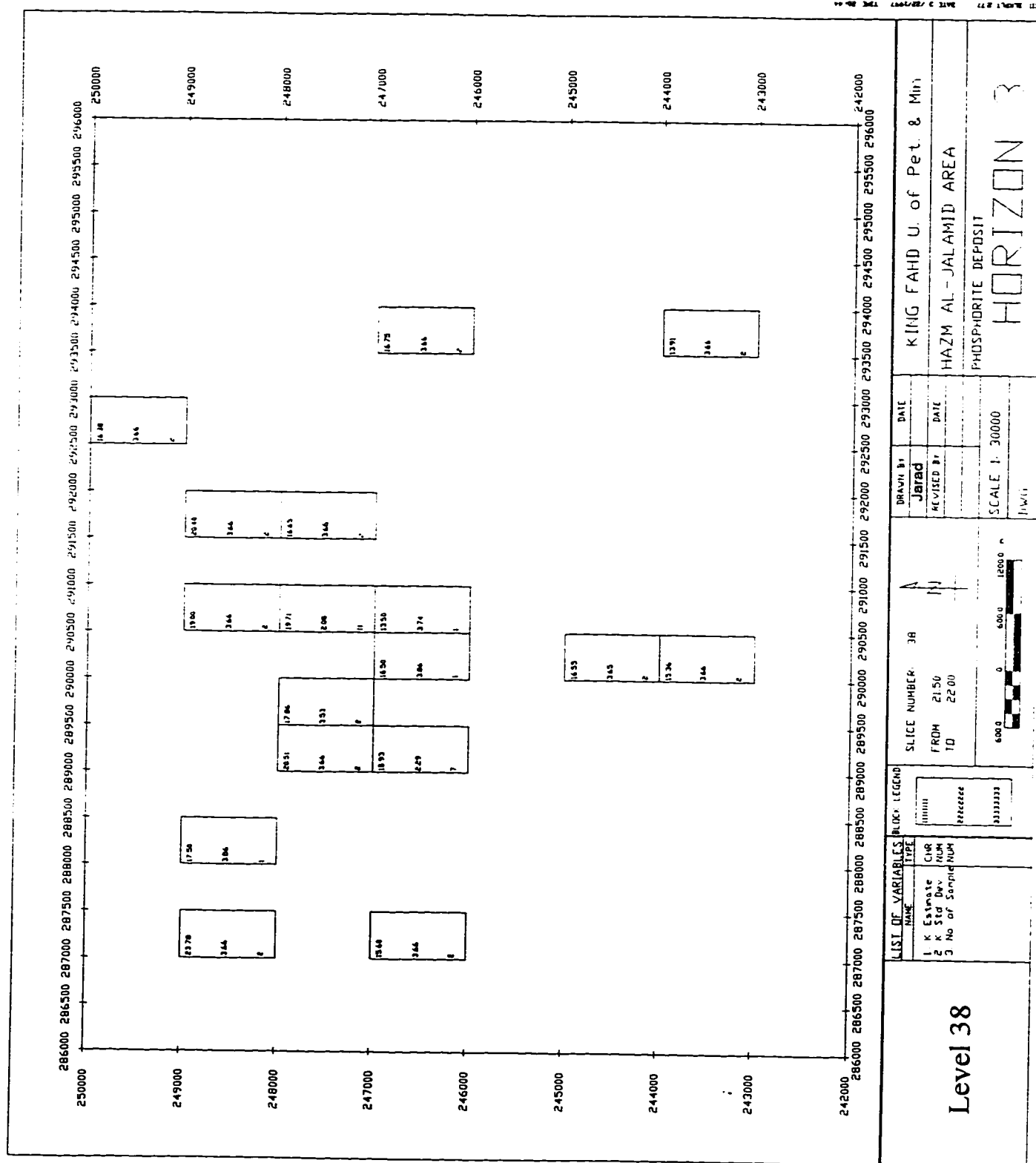


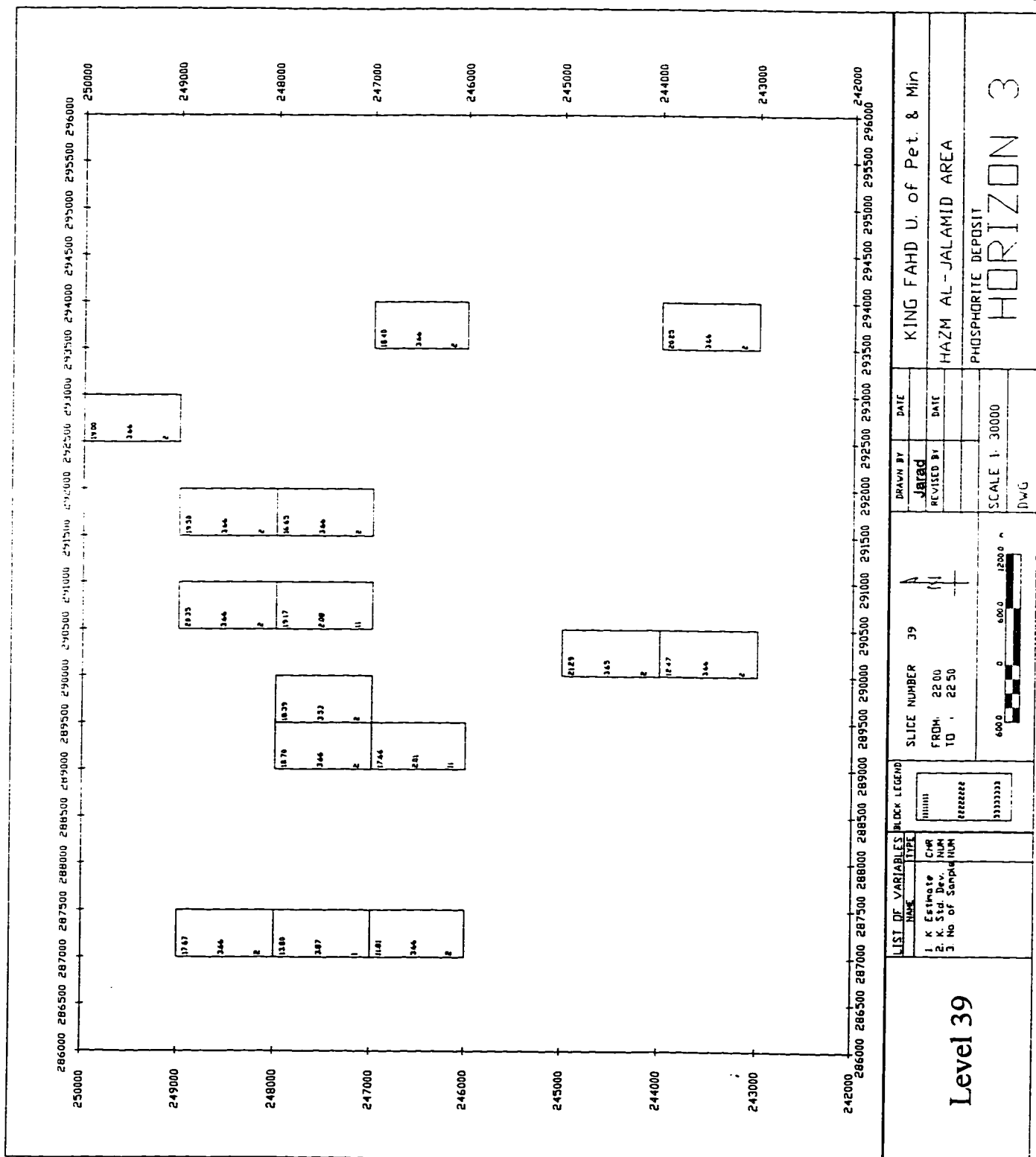


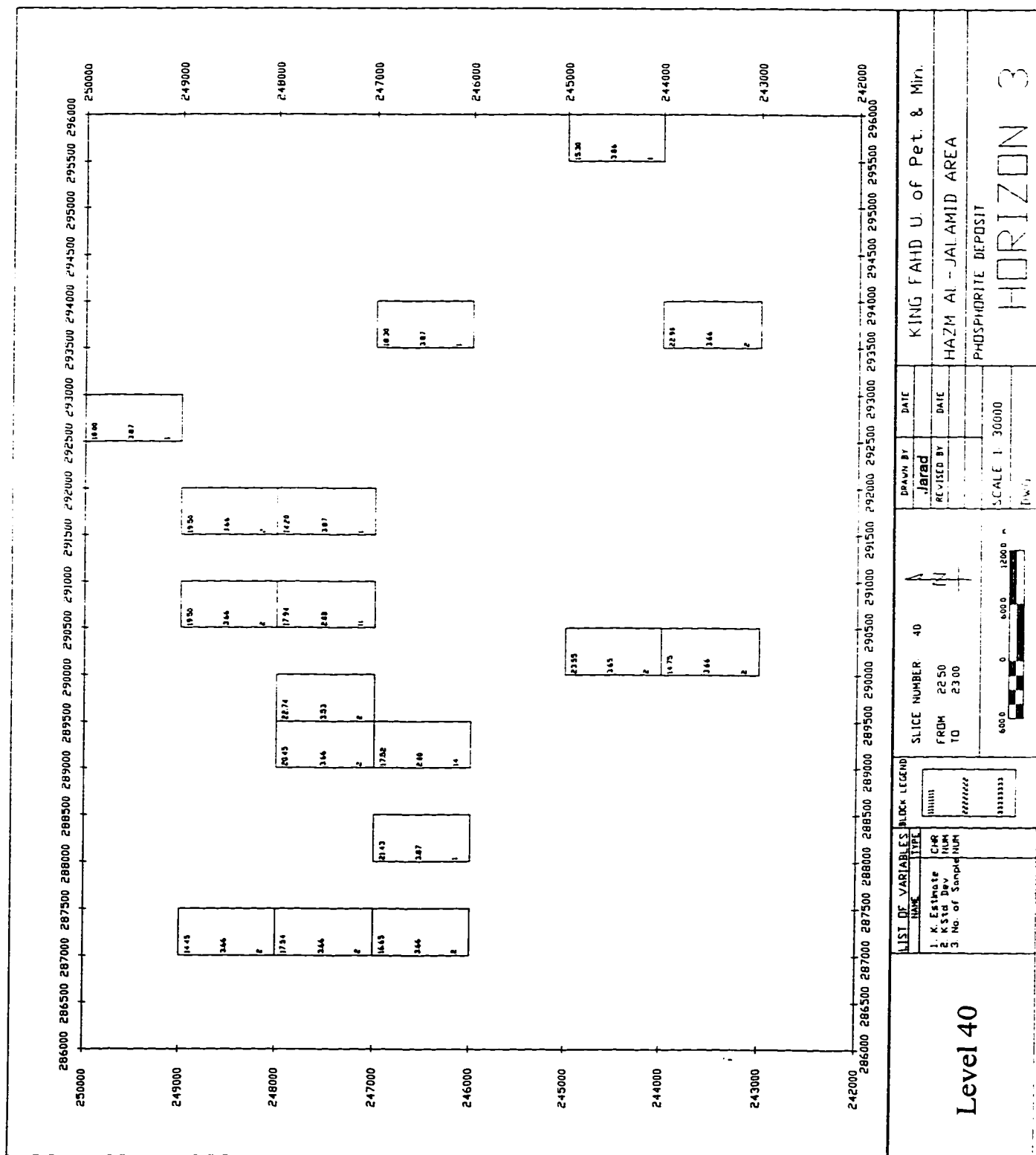


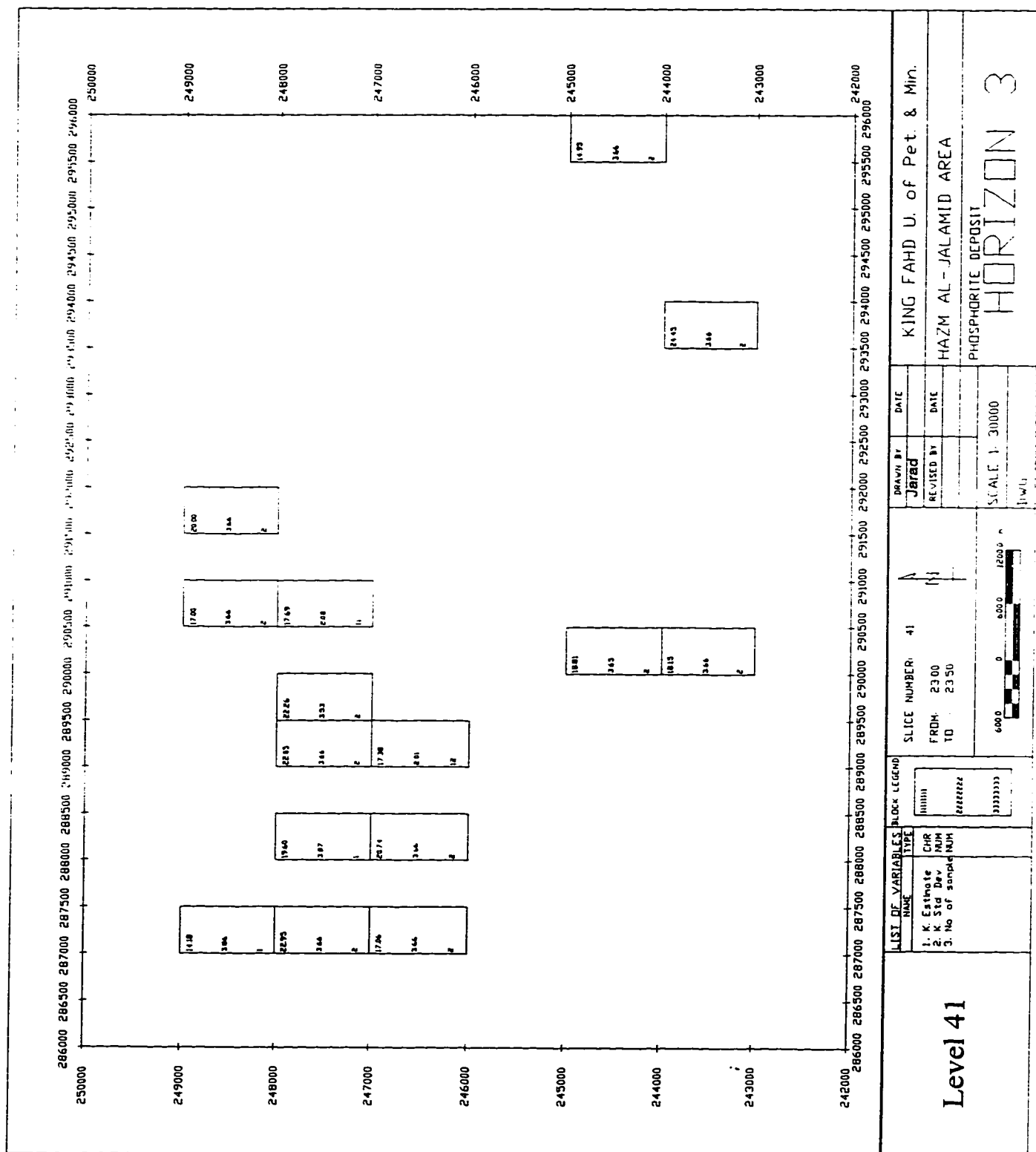


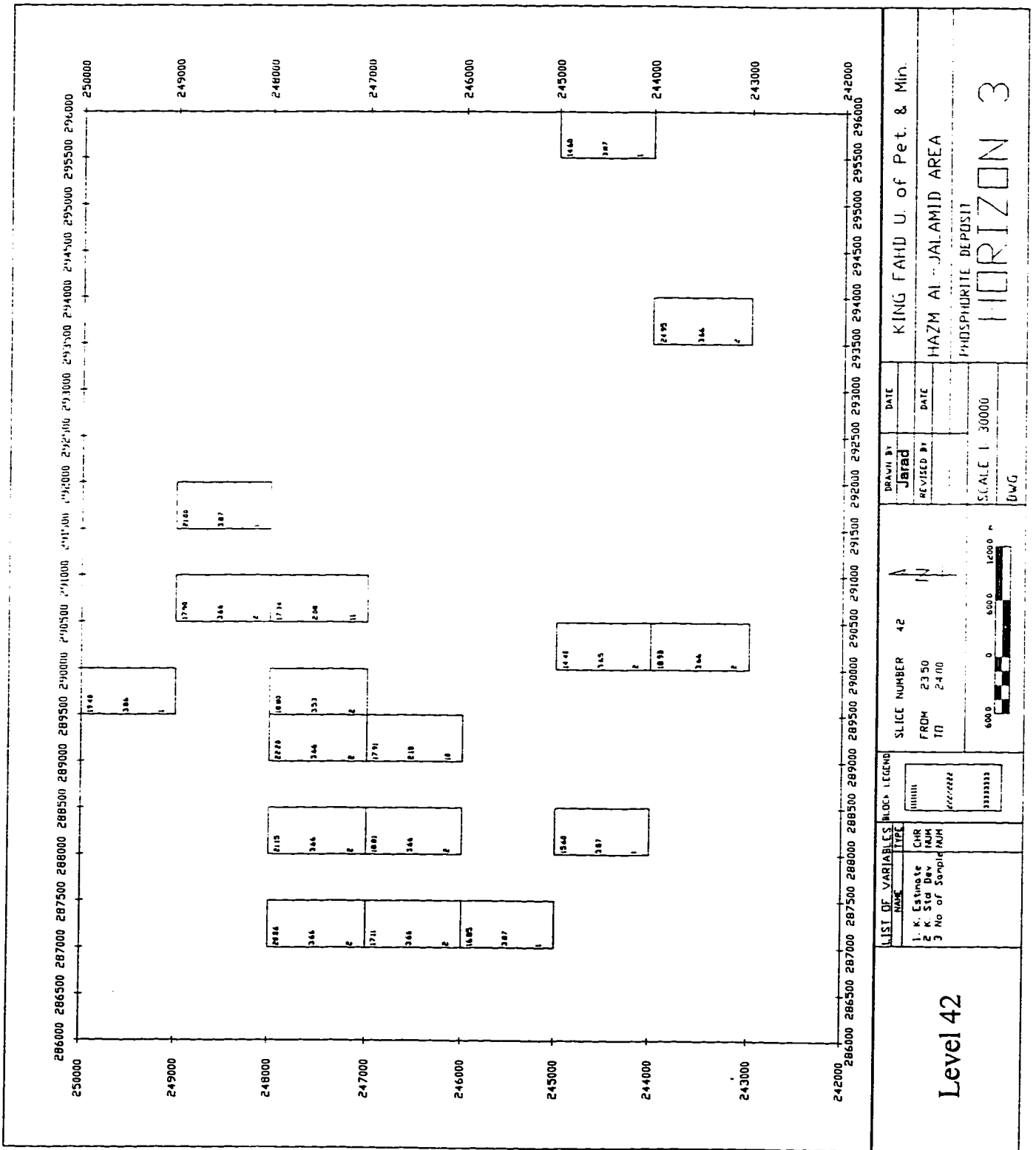


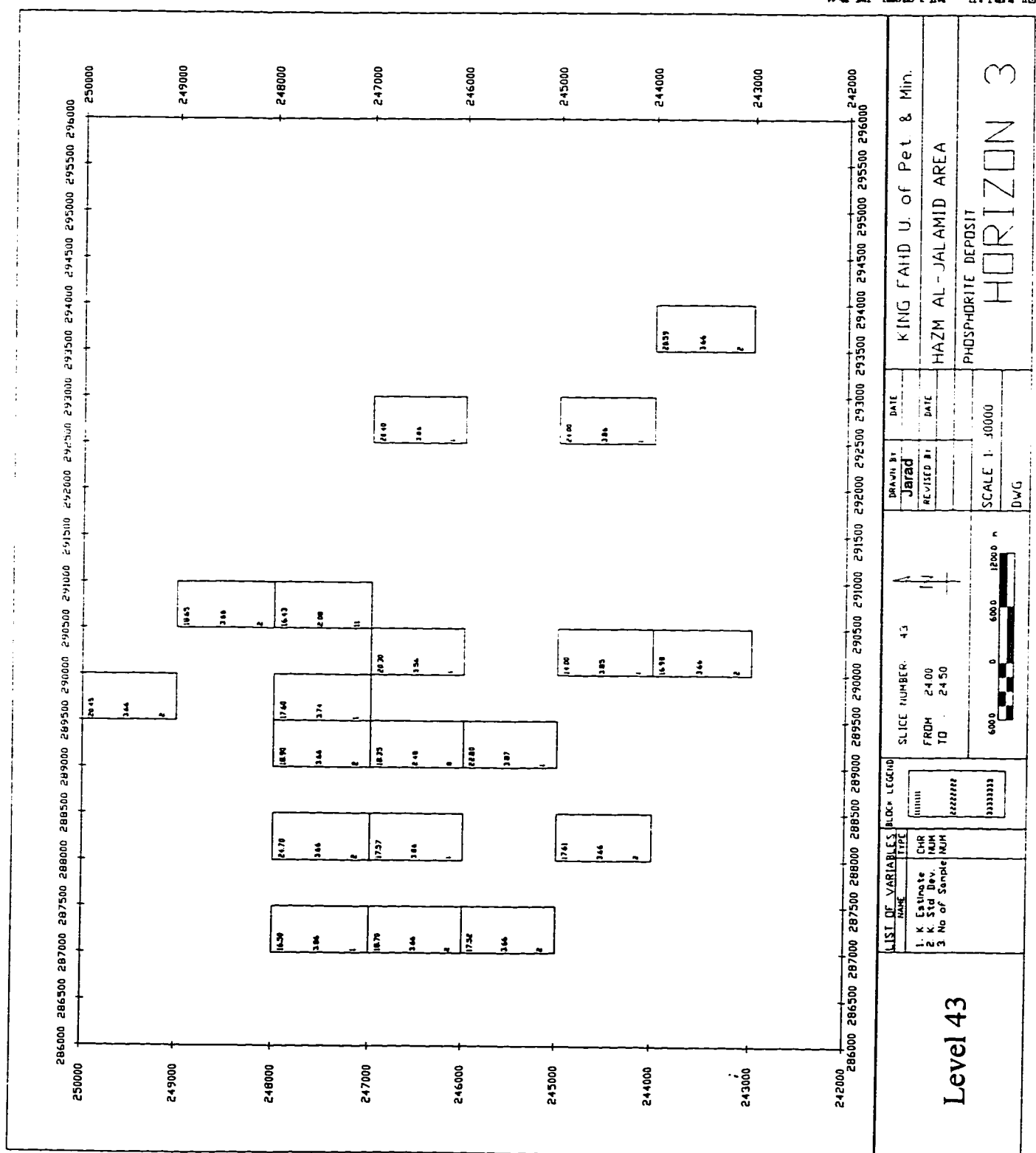


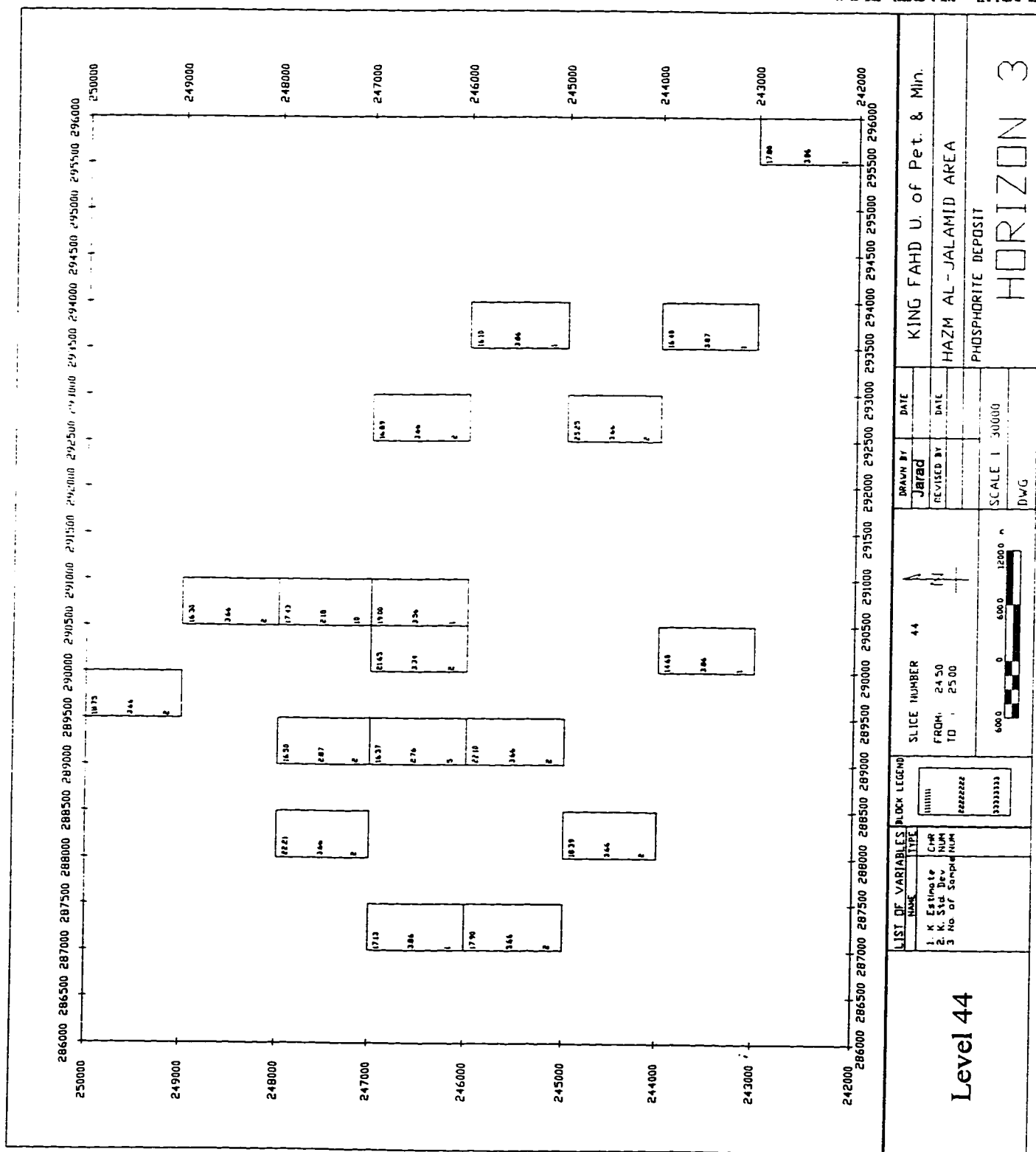




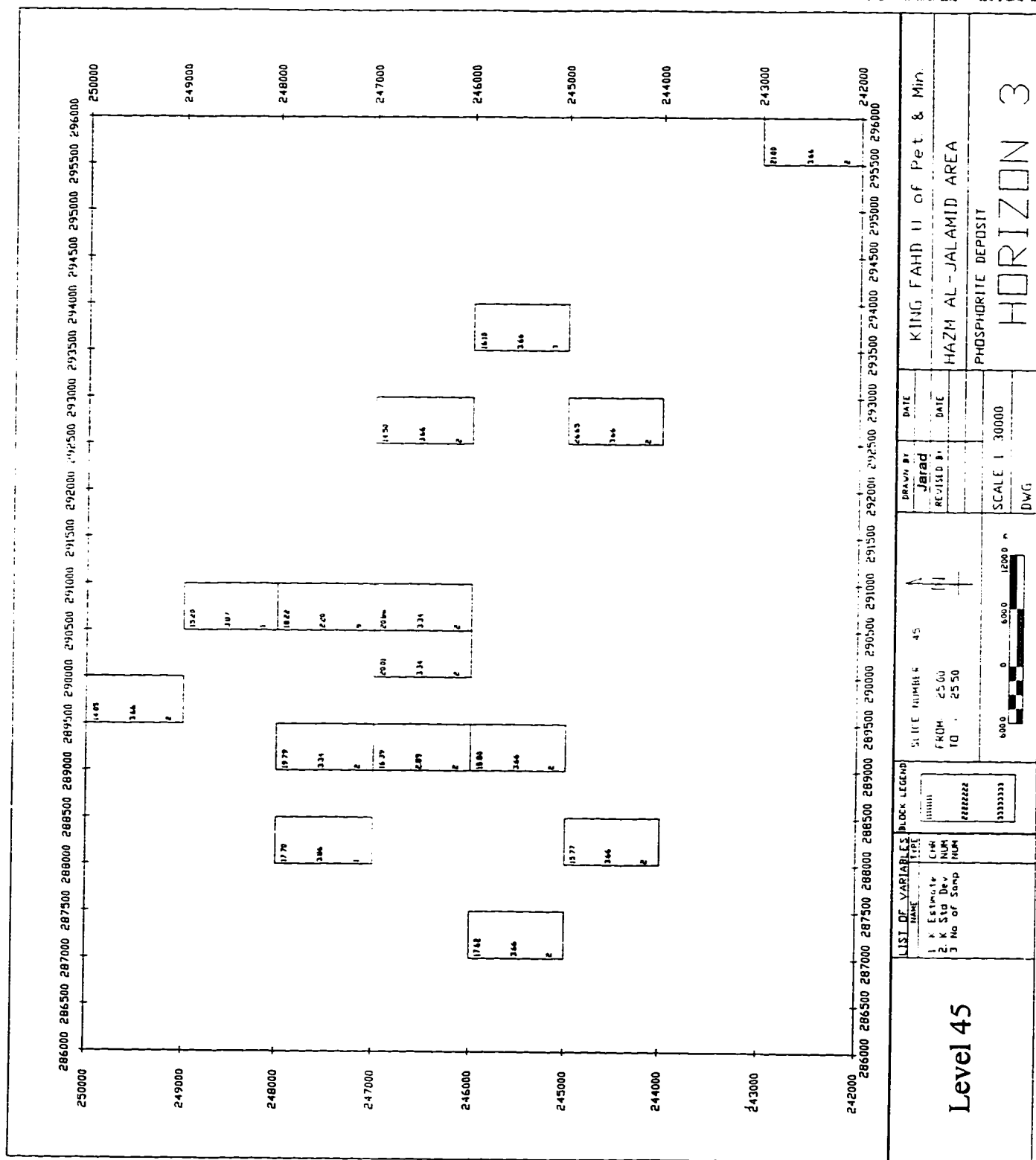


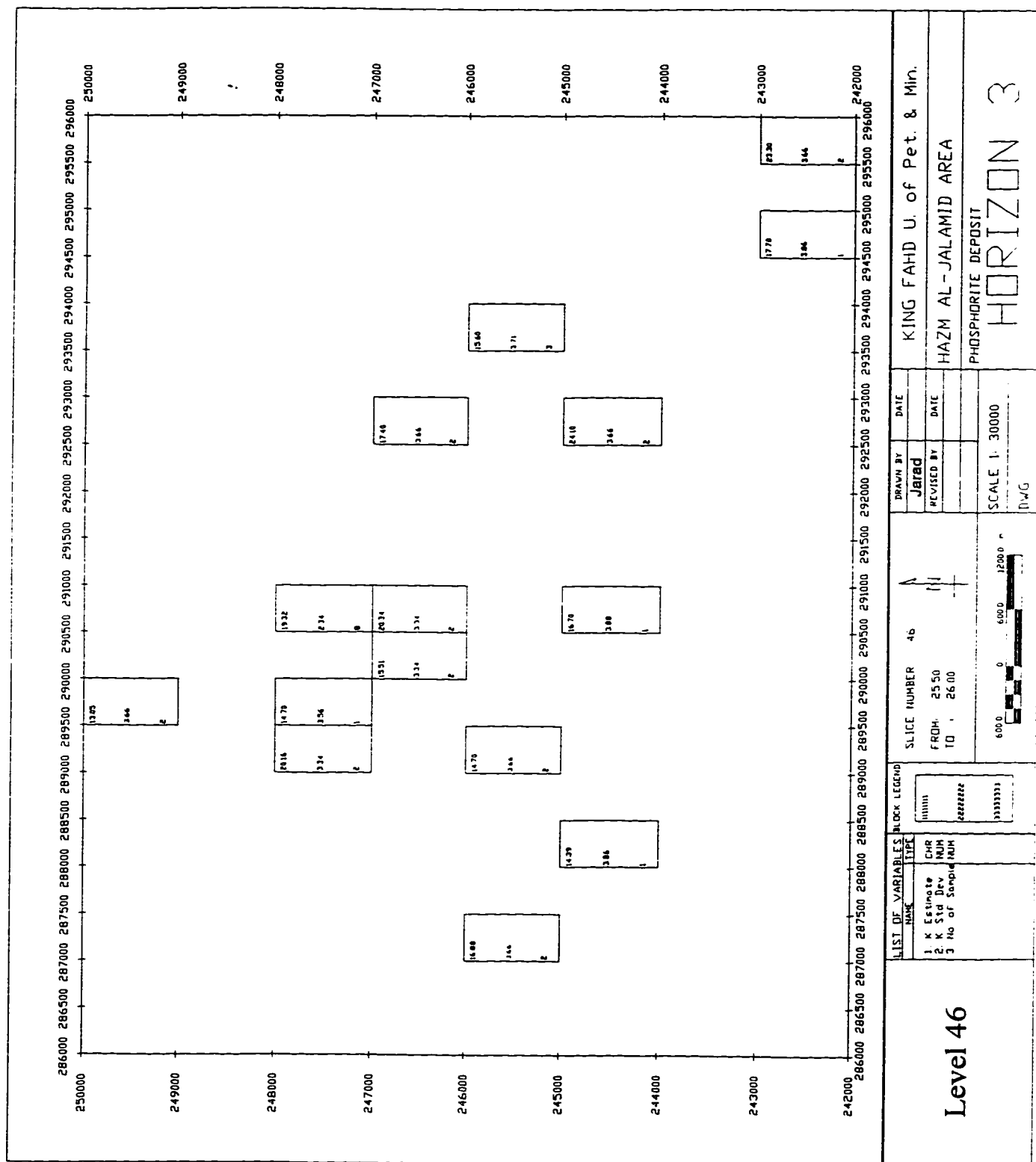


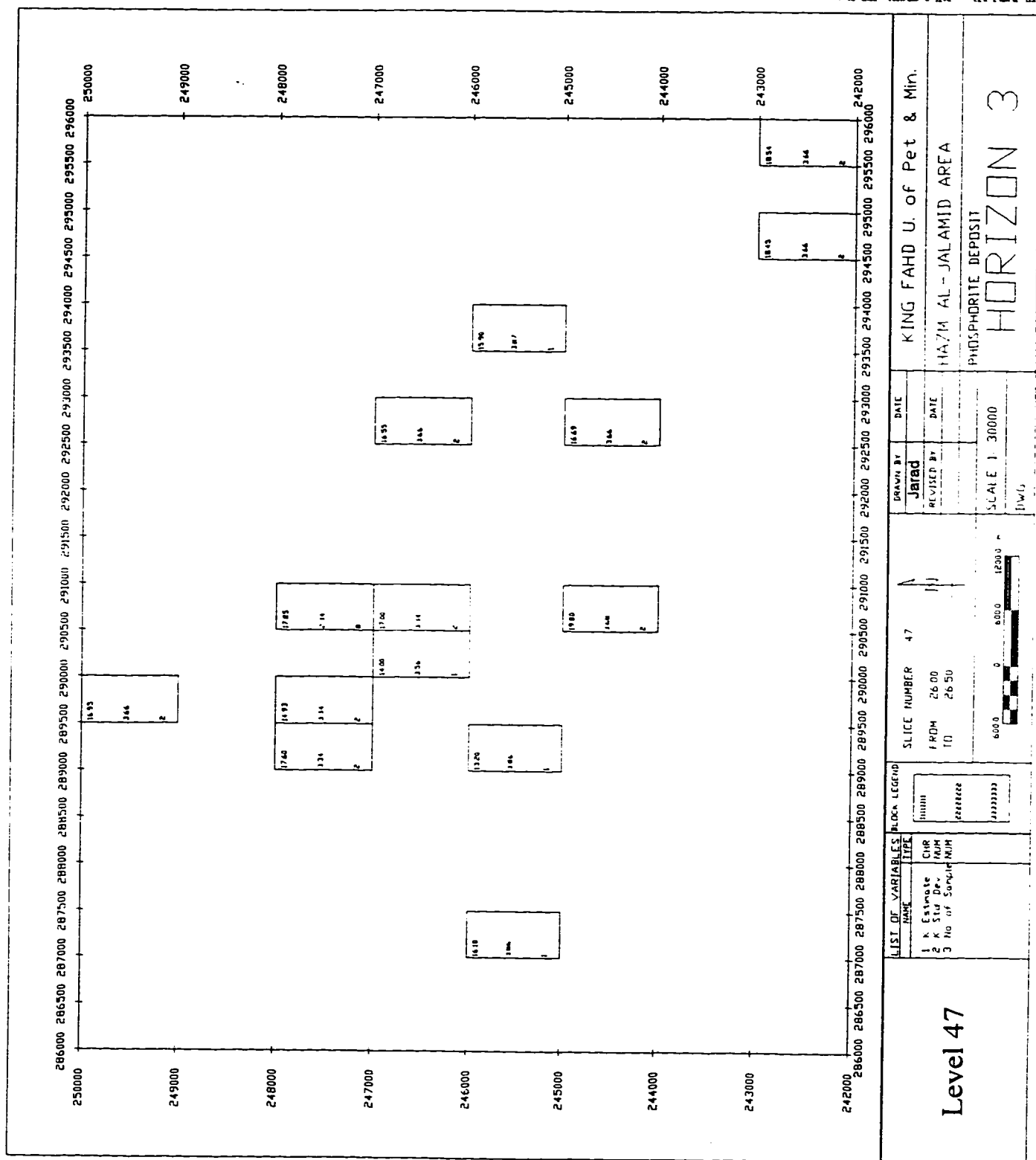


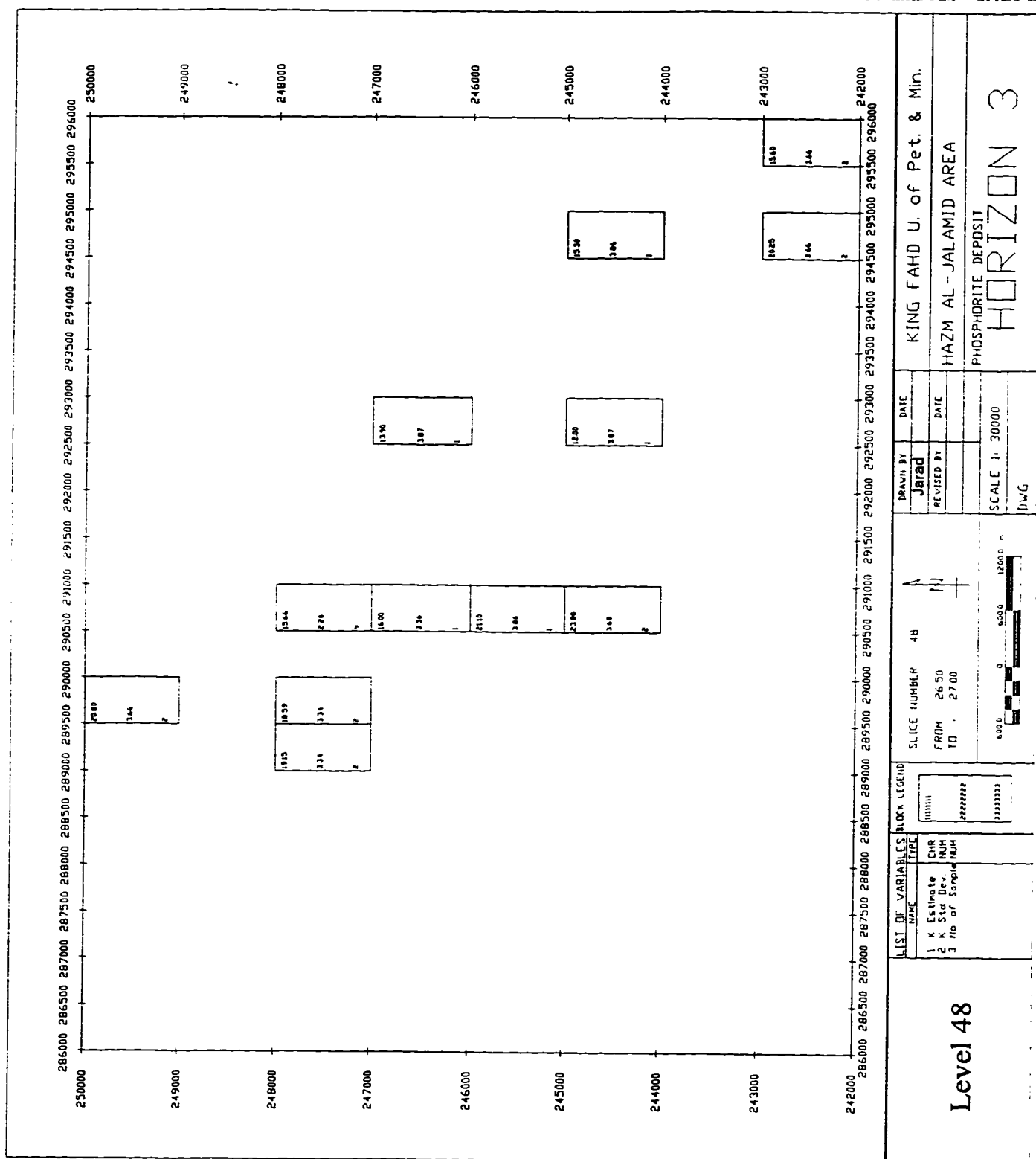


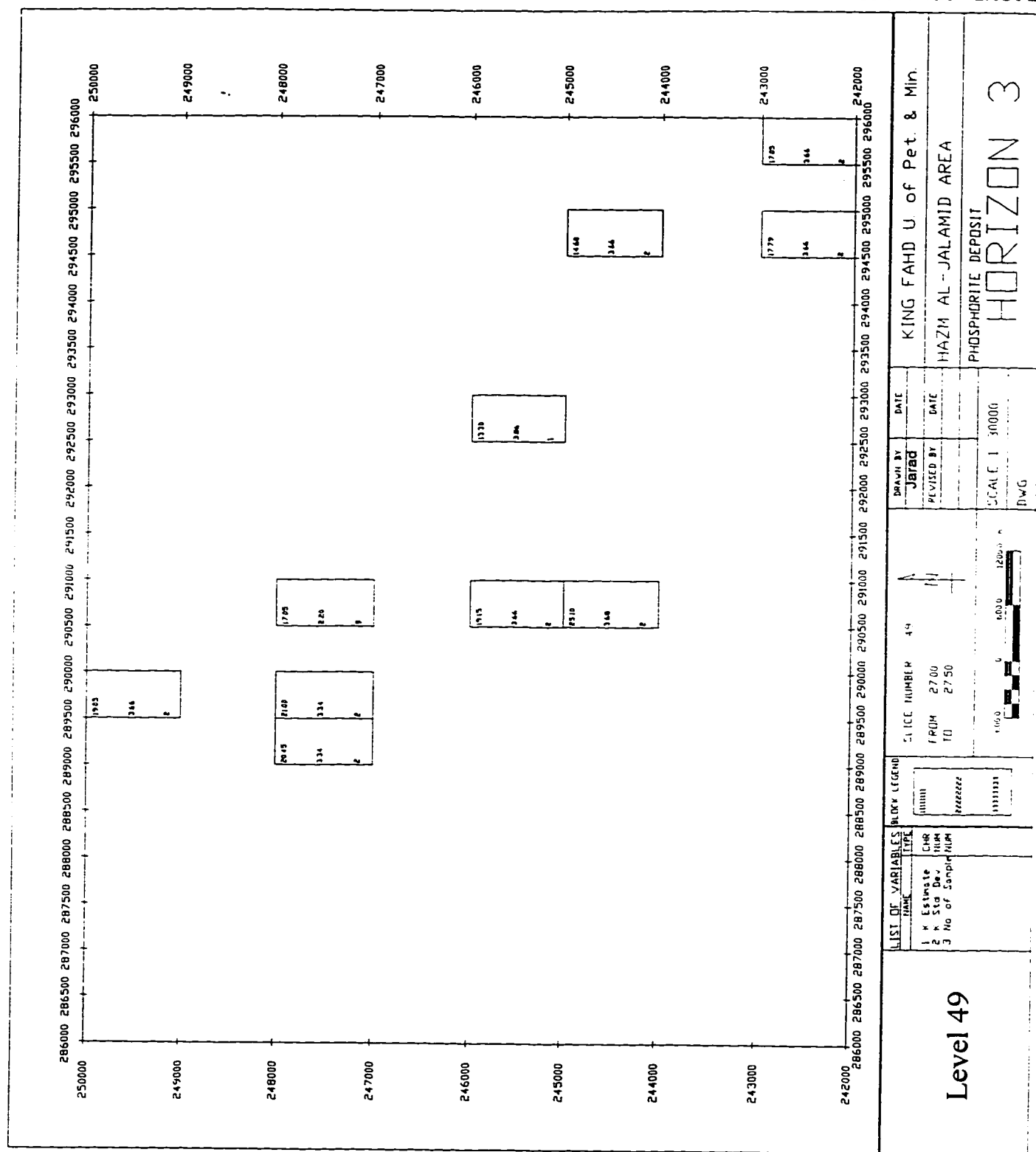


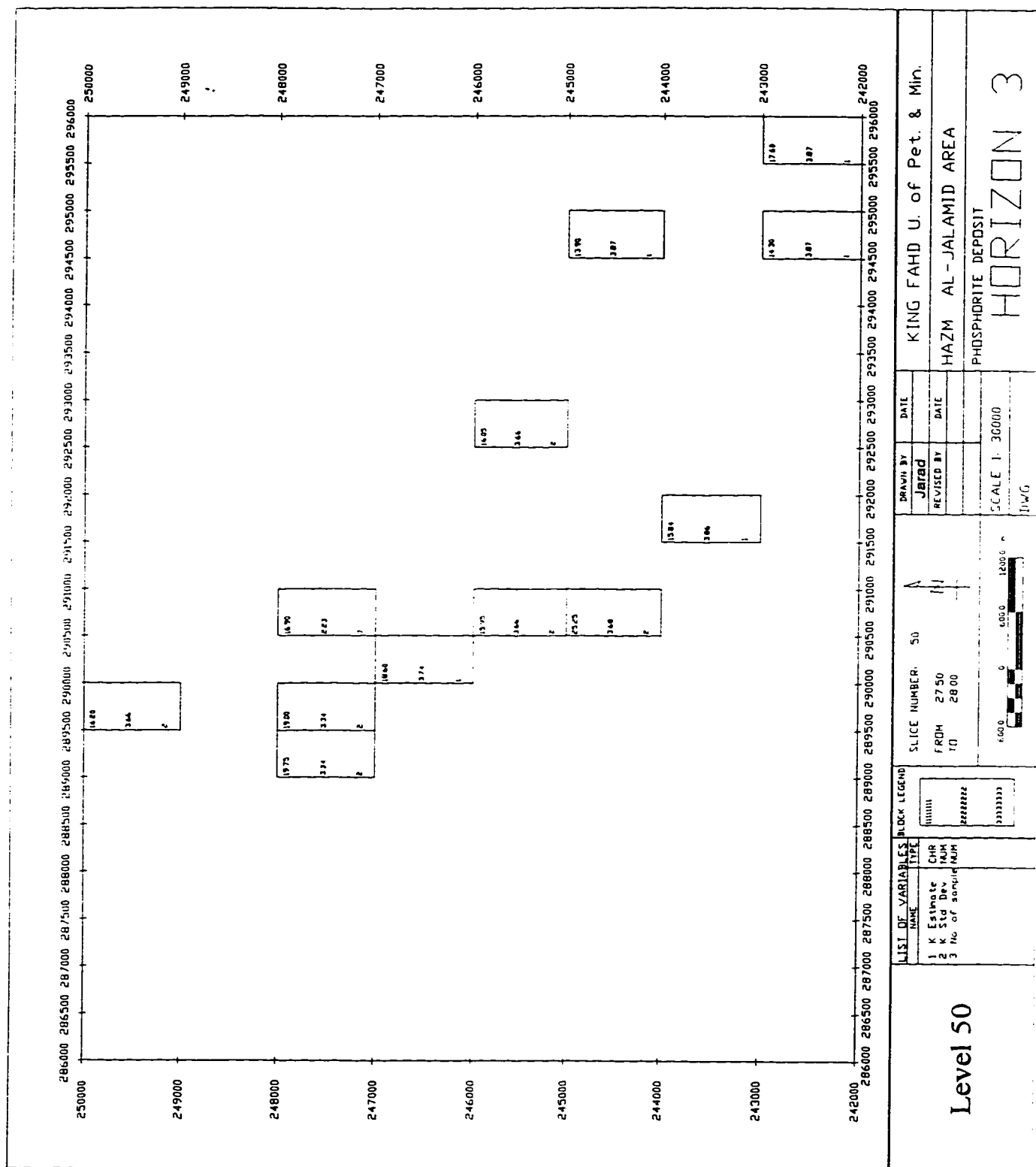


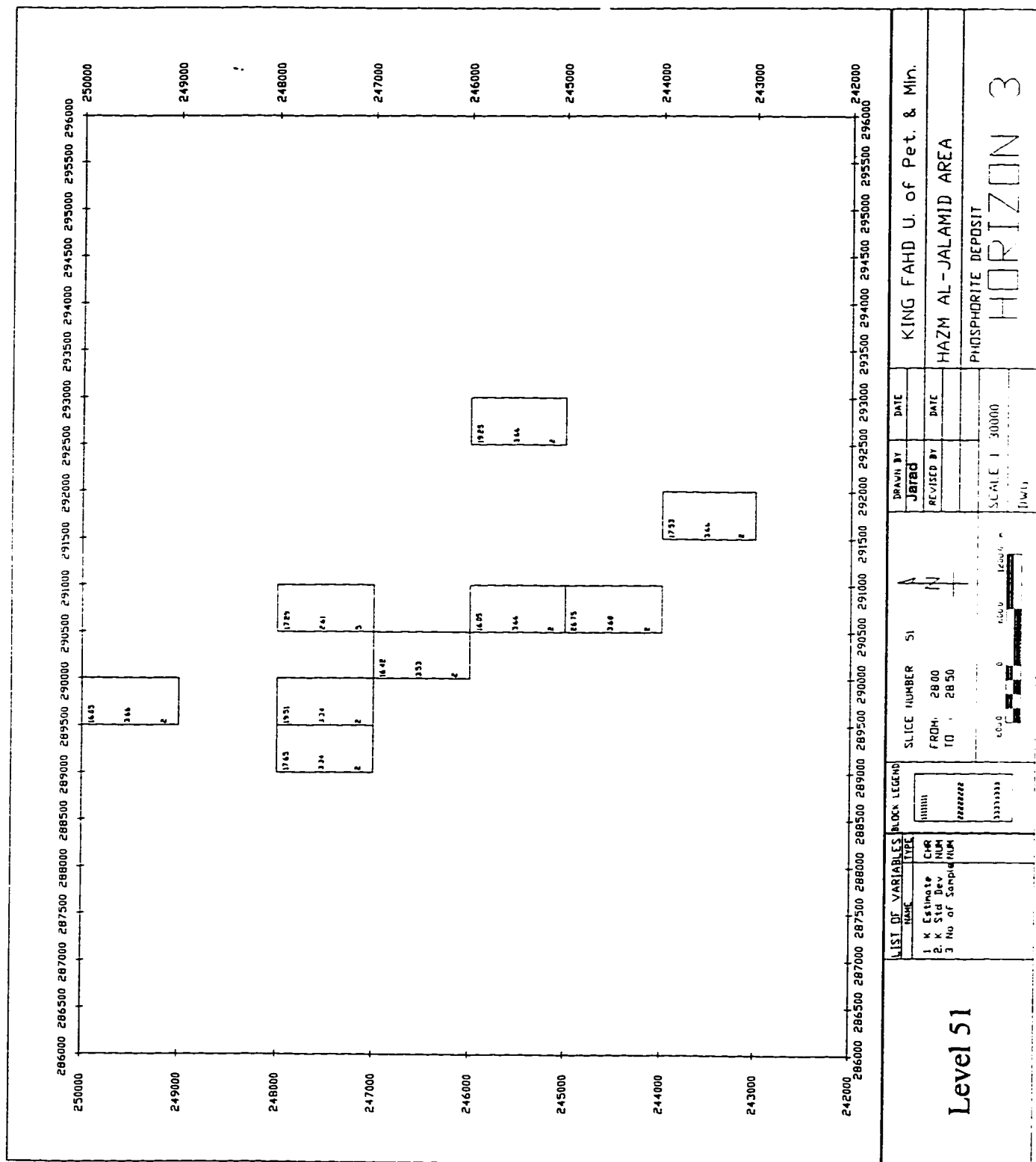


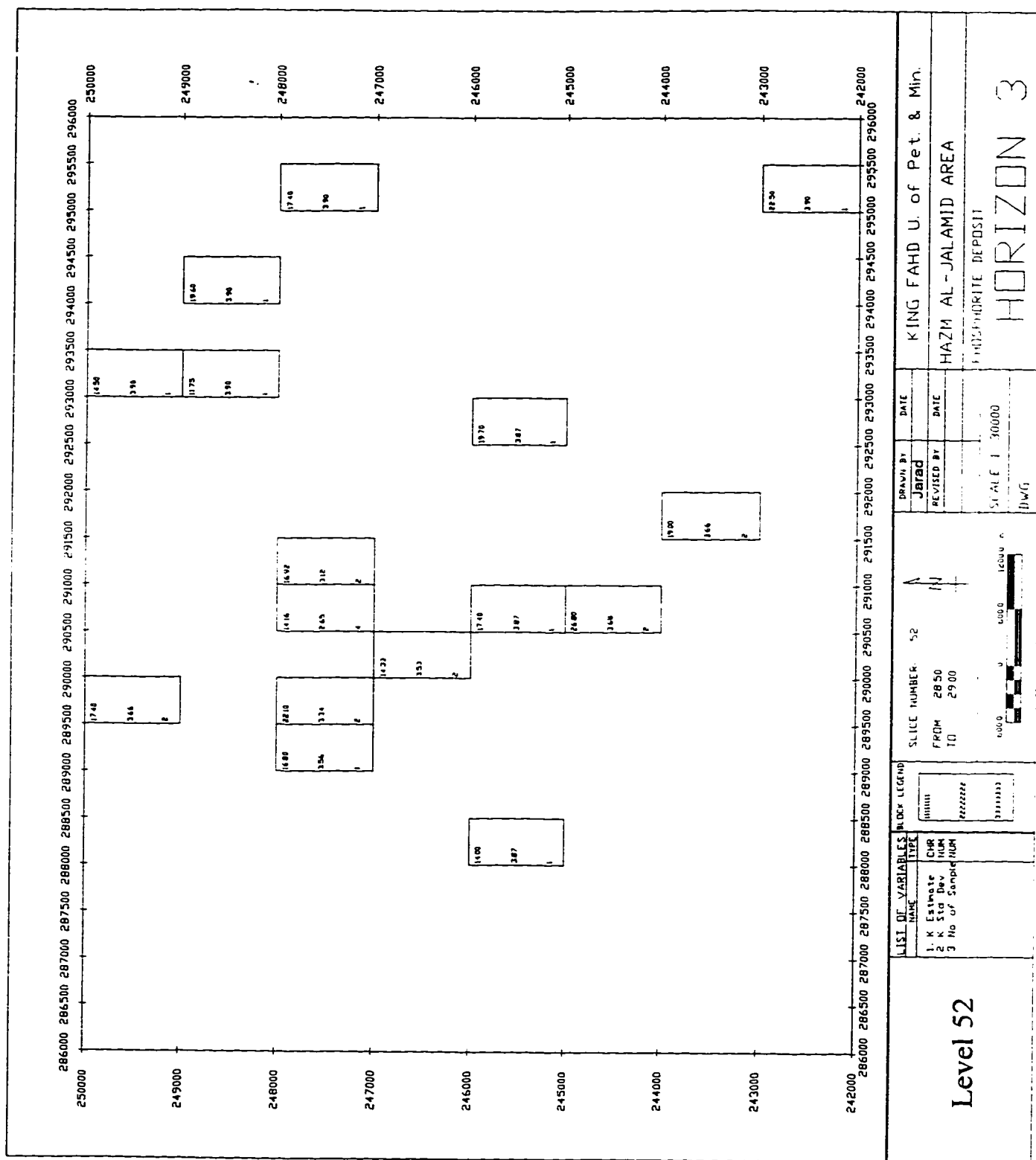




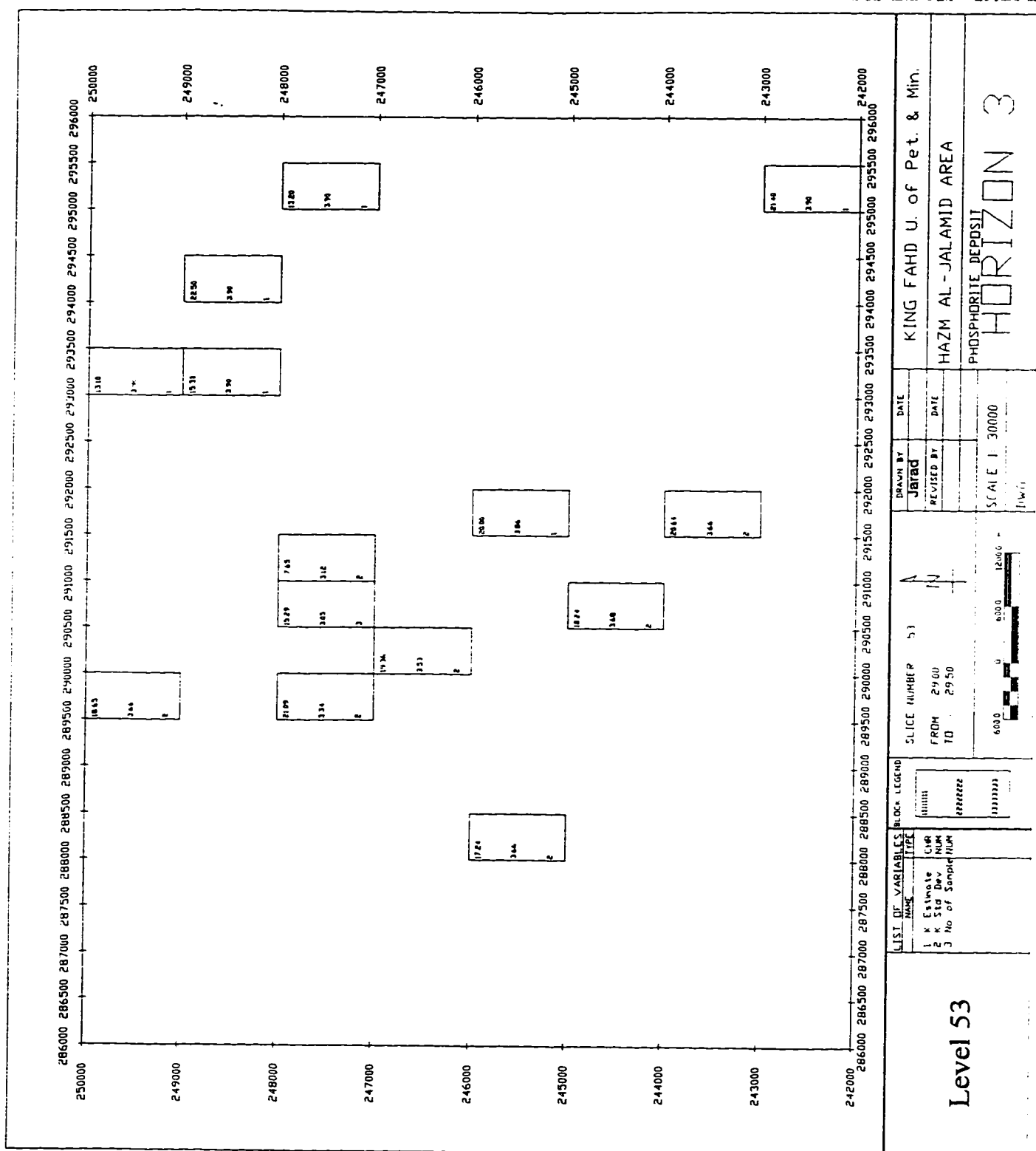


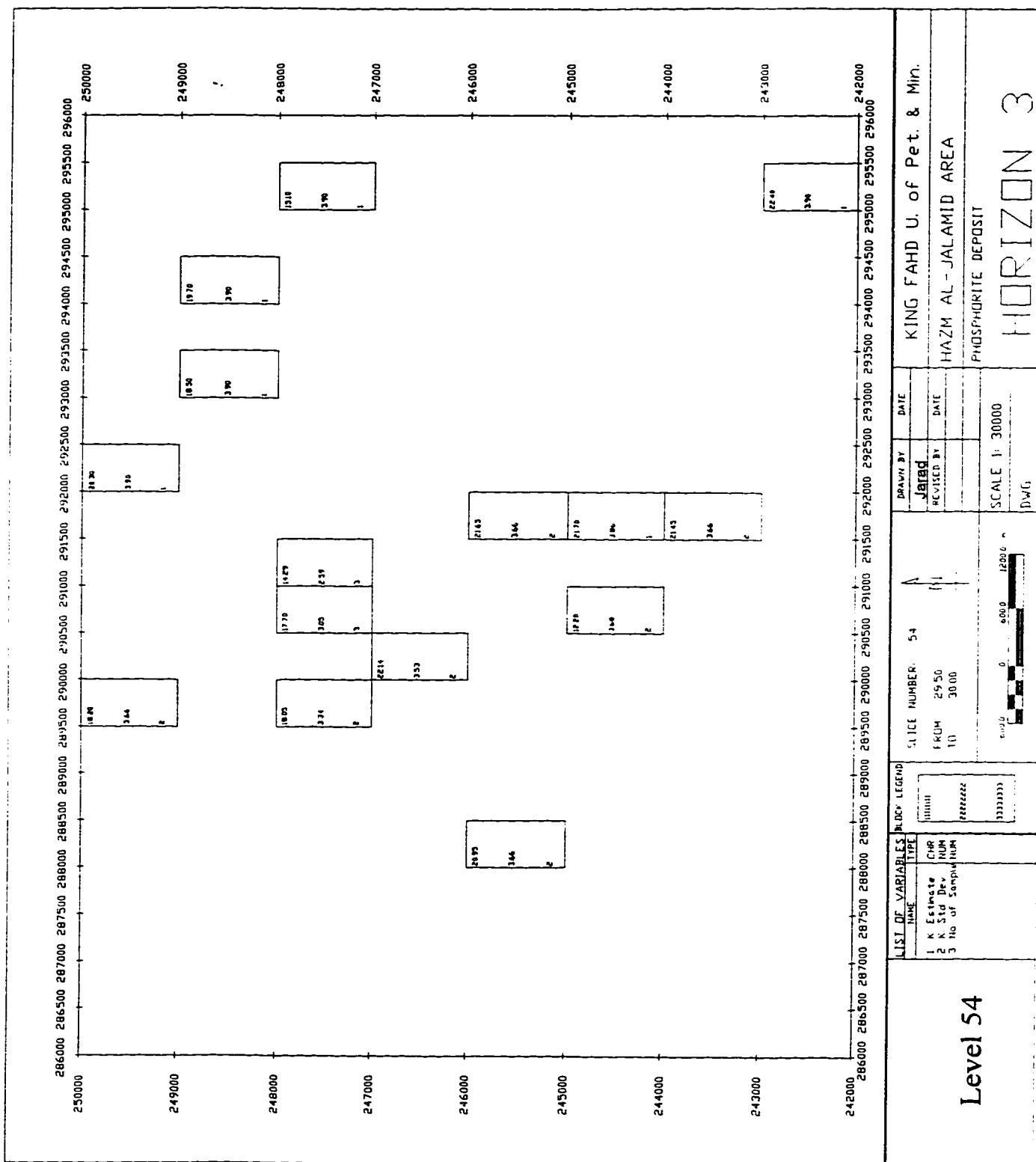




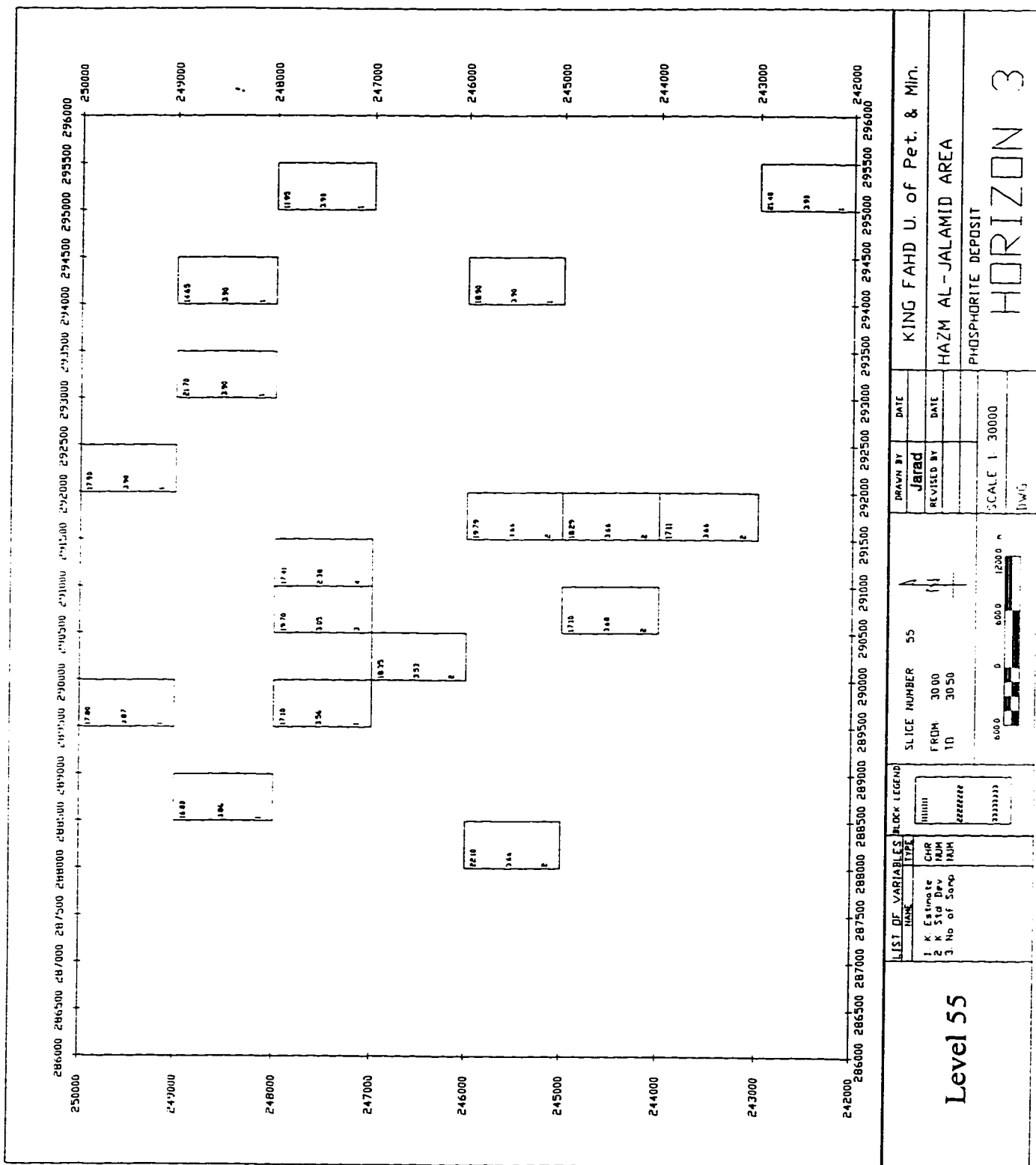




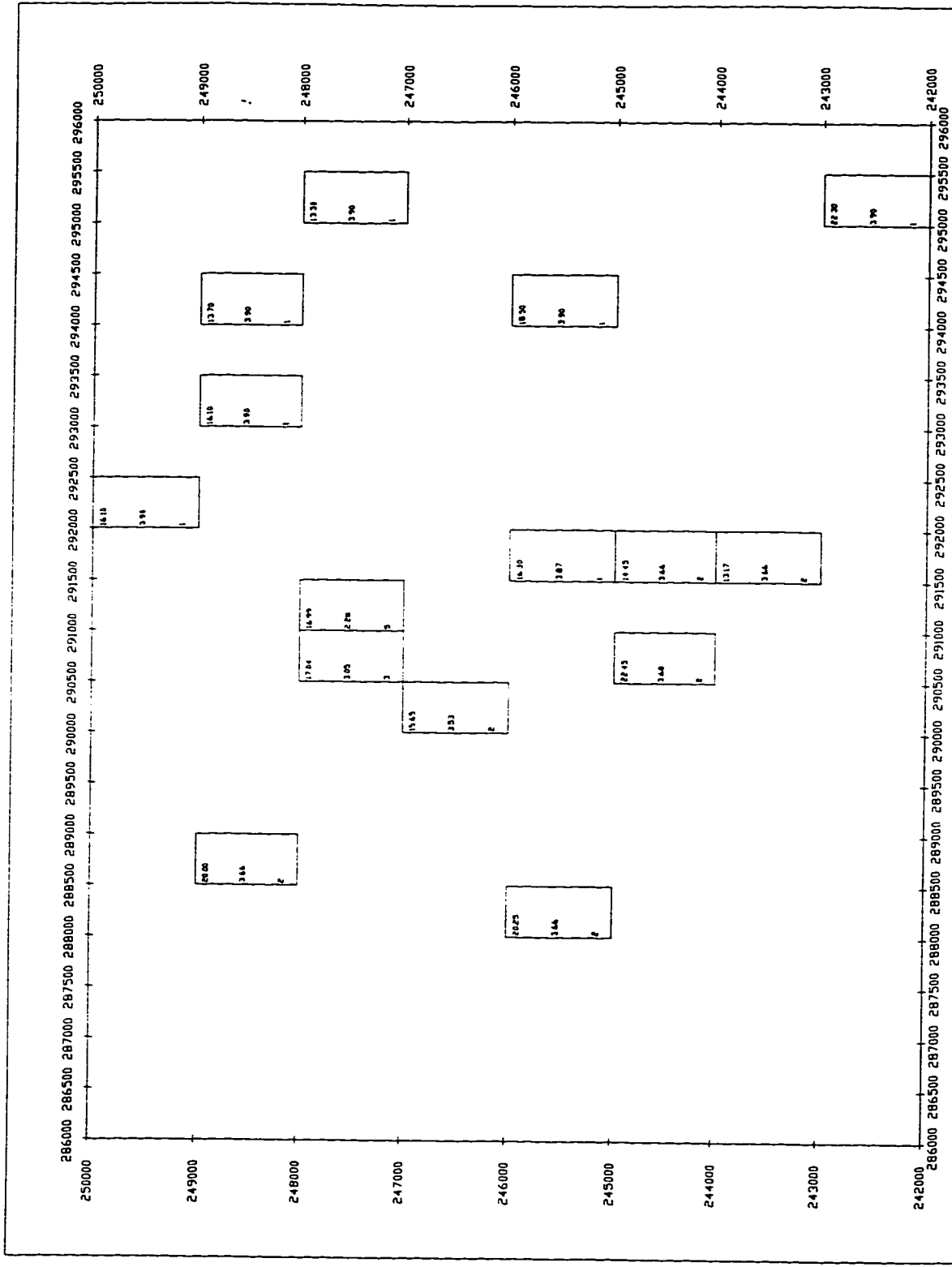




CSB MAP 127 DATE 3/22/99 THE CH 4



DATE 2/28/97 THE 20-44



|                 |                          |              |                                                |                                                                                                                                                                                |                                         |                      |                                        |
|-----------------|--------------------------|--------------|------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------|----------------------|----------------------------------------|
| <b>Level 56</b> | <b>LIST OF VARIABLES</b> |              | <b>SLICE NUMBER</b> 56<br>FROM 3050<br>TO 3100 | <br> | <b>DATE</b><br>Jatad<br>REVISOR<br>DATE | <b>DATE</b>          | <b>KING FAHD U. of Pet. &amp; Min.</b> |
|                 | <b>NAME</b>              |              |                                                |                                                                                                                                                                                |                                         |                      |                                        |
|                 | <b>TYPE</b>              |              |                                                |                                                                                                                                                                                |                                         |                      |                                        |
|                 | <b>CHG</b>               |              |                                                |                                                                                                                                                                                |                                         |                      |                                        |
| 1. K Estimate   |                          | 2. K Str Dev |                                                | 3. No of Samples                                                                                                                                                               |                                         | HAZM AL-JALAMID AREA |                                        |
| 22222222        |                          | 22222222     |                                                | 22222222                                                                                                                                                                       |                                         | PHOSPHORITE DEPOSIT  |                                        |
| 22222222        |                          | 22222222     |                                                | 22222222                                                                                                                                                                       |                                         | HORIZON 3            |                                        |
| 22222222        |                          | 22222222     |                                                | 22222222                                                                                                                                                                       |                                         | SCALE 1:30000        |                                        |
| 22222222        |                          | 22222222     |                                                | 22222222                                                                                                                                                                       |                                         | DWG                  |                                        |

## **APPENDIX J**

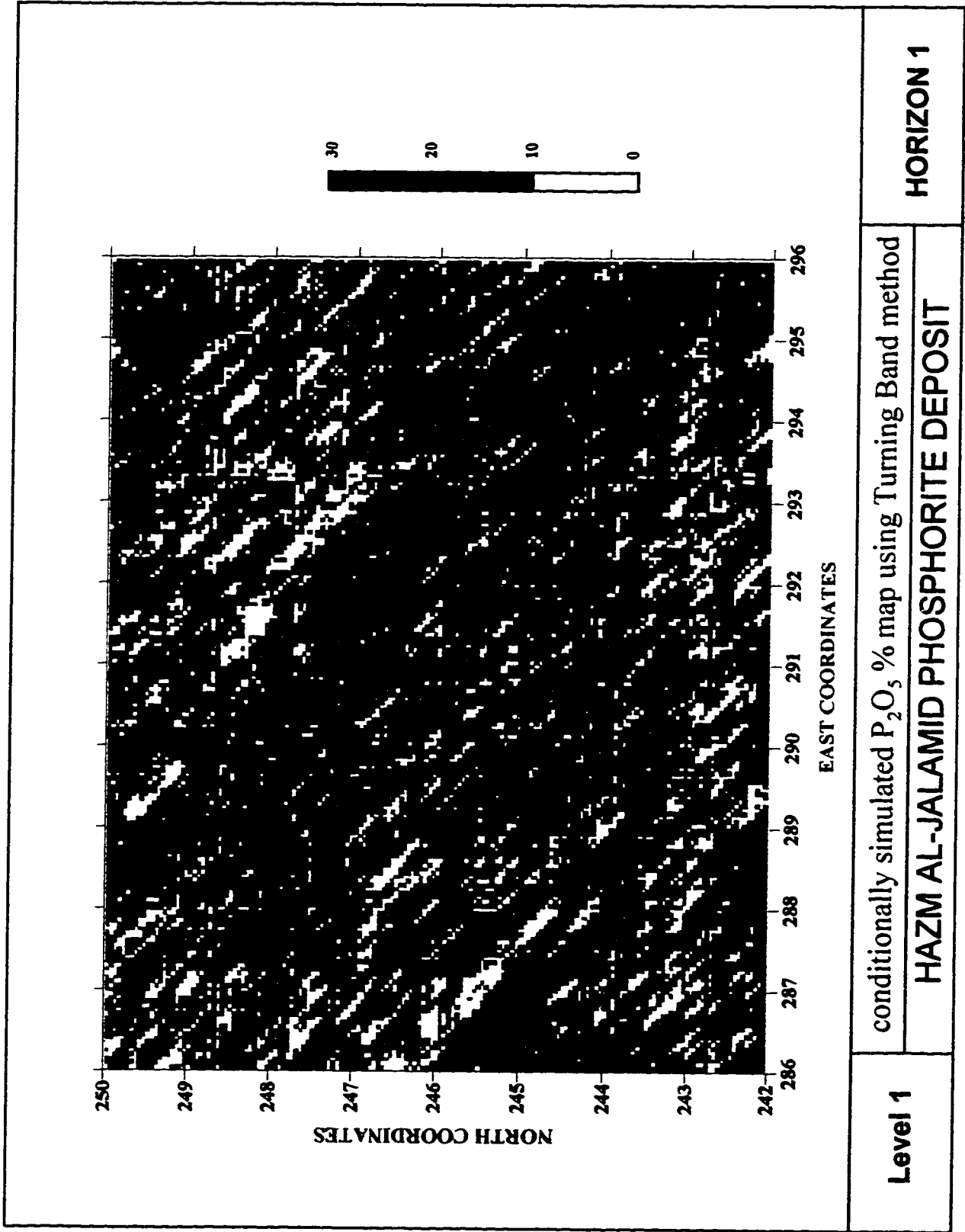
An excerpt from the simulation output file

| <b>X-index</b> | <b>Y-index</b> | <b>Z-index</b> | <b>Simulated values</b> |
|----------------|----------------|----------------|-------------------------|
| 1              | 81             | 1              | 21.3679                 |
| 2              | 81             | 1              | 19.0071                 |
| 3              | 81             | 1              | 14.7056                 |
| 4              | 81             | 1              | 11.9010                 |
| 5              | 81             | 1              | 12.1478                 |
| 6              | 81             | 1              | 16.7185                 |
| 7              | 81             | 1              | 15.1789                 |
| 8              | 81             | 1              | 14.3437                 |
| 9              | 81             | 1              | 12.9894                 |
| 10             | 81             | 1              | 9.6187                  |
| 11             | 81             | 1              | 10.8128                 |
| 12             | 81             | 1              | 13.5960                 |
| 13             | 81             | 1              | 11.7811                 |
| 14             | 81             | 1              | 10.7370                 |
| 15             | 81             | 1              | 10.4248                 |
| 16             | 81             | 1              | 14.4103                 |
| 17             | 81             | 1              | 16.2705                 |
| 18             | 81             | 1              | 19.8237                 |
| 19             | 81             | 1              | 12.6076                 |
| 20             | 81             | 1              | 11.1241                 |
| 21             | 81             | 1              | 10.3683                 |
| 22             | 81             | 1              | 13.6555                 |
| 23             | 81             | 1              | 11.9053                 |
| 24             | 81             | 1              | 16.6702                 |
| 25             | 81             | 1              | 18.2532                 |
| 26             | 81             | 1              | 21.0313                 |
| 27             | 81             | 1              | 23.9997                 |
| 28             | 81             | 1              | 14.9585                 |
| 29             | 81             | 1              | 15.8174                 |
| 30             | 81             | 1              | 14.6068                 |
| 31             | 81             | 1              | 17.6576                 |
| 32             | 81             | 1              | 16.3796                 |
| 33             | 81             | 1              | 17.3303                 |
| 34             | 81             | 1              | 18.9025                 |
| 35             | 81             | 1              | 19.7574                 |
| 36             | 81             | 1              | 20.1221                 |
| 37             | 81             | 1              | 20.4963                 |
| 38             | 81             | 1              | 15.2334                 |
| 39             | 81             | 1              | 18.2629                 |
| 40             | 81             | 1              | 16.7393                 |
| 41             | 81             | 1              | 21.8592                 |
| 42             | 81             | 1              | 8.3287                  |
| 43             | 81             | 1              | 15.1773                 |
| 44             | 81             | 1              | 21.3548                 |
| 45             | 81             | 1              | 22.0208                 |
| 46             | 81             | 1              | 27.8035                 |
| 47             | 81             | 1              | 18.7133                 |

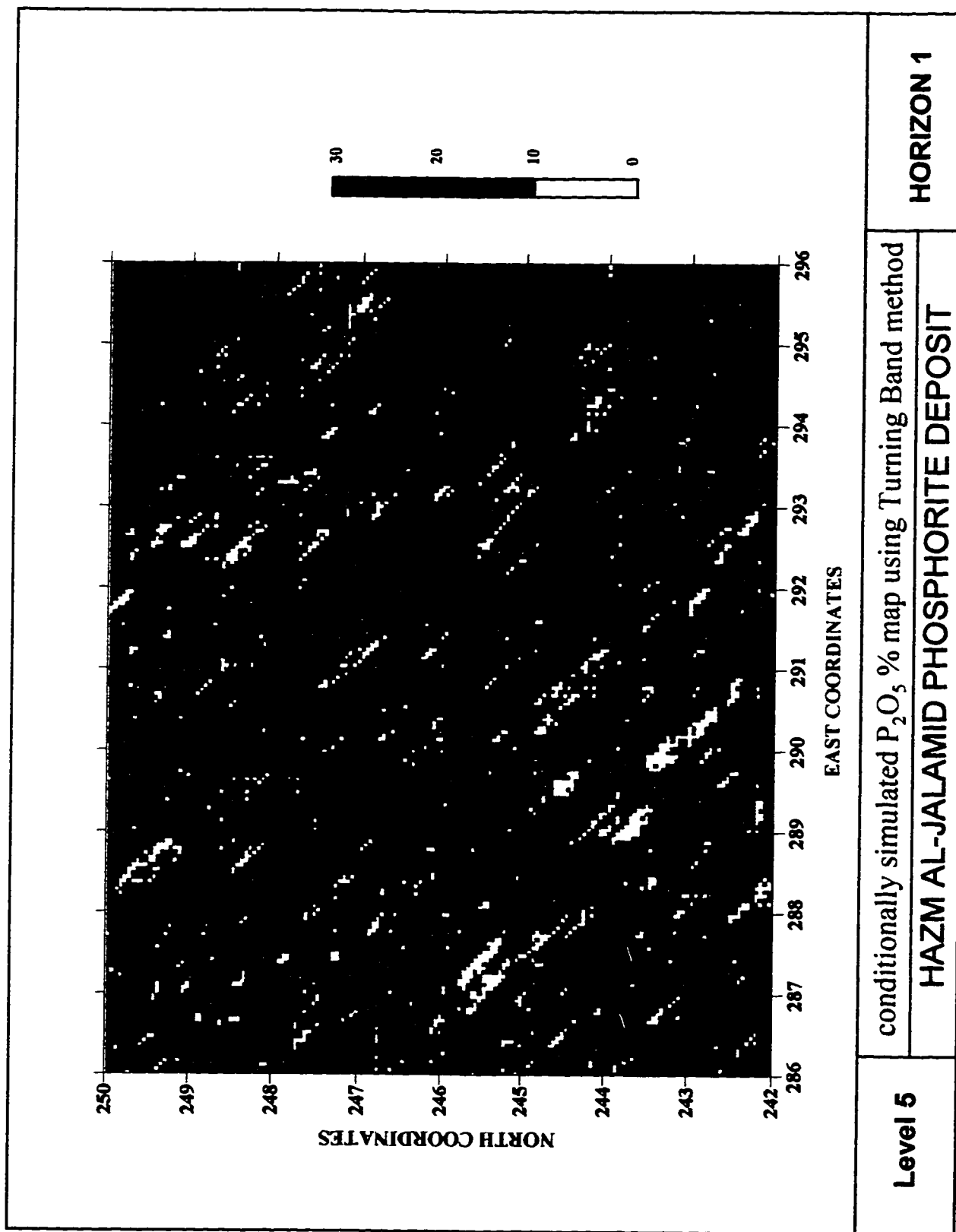
..

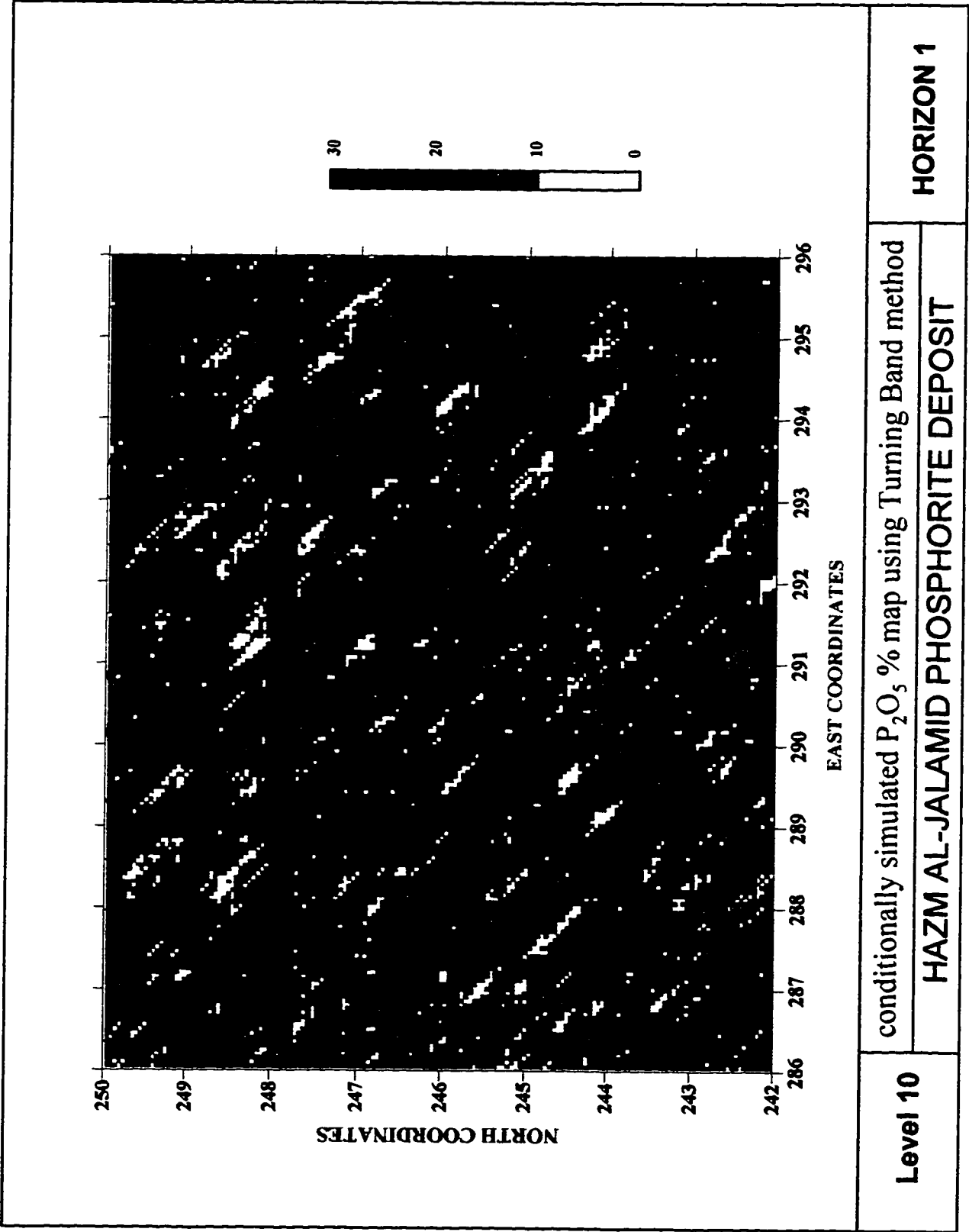
## **APPENDIX K**

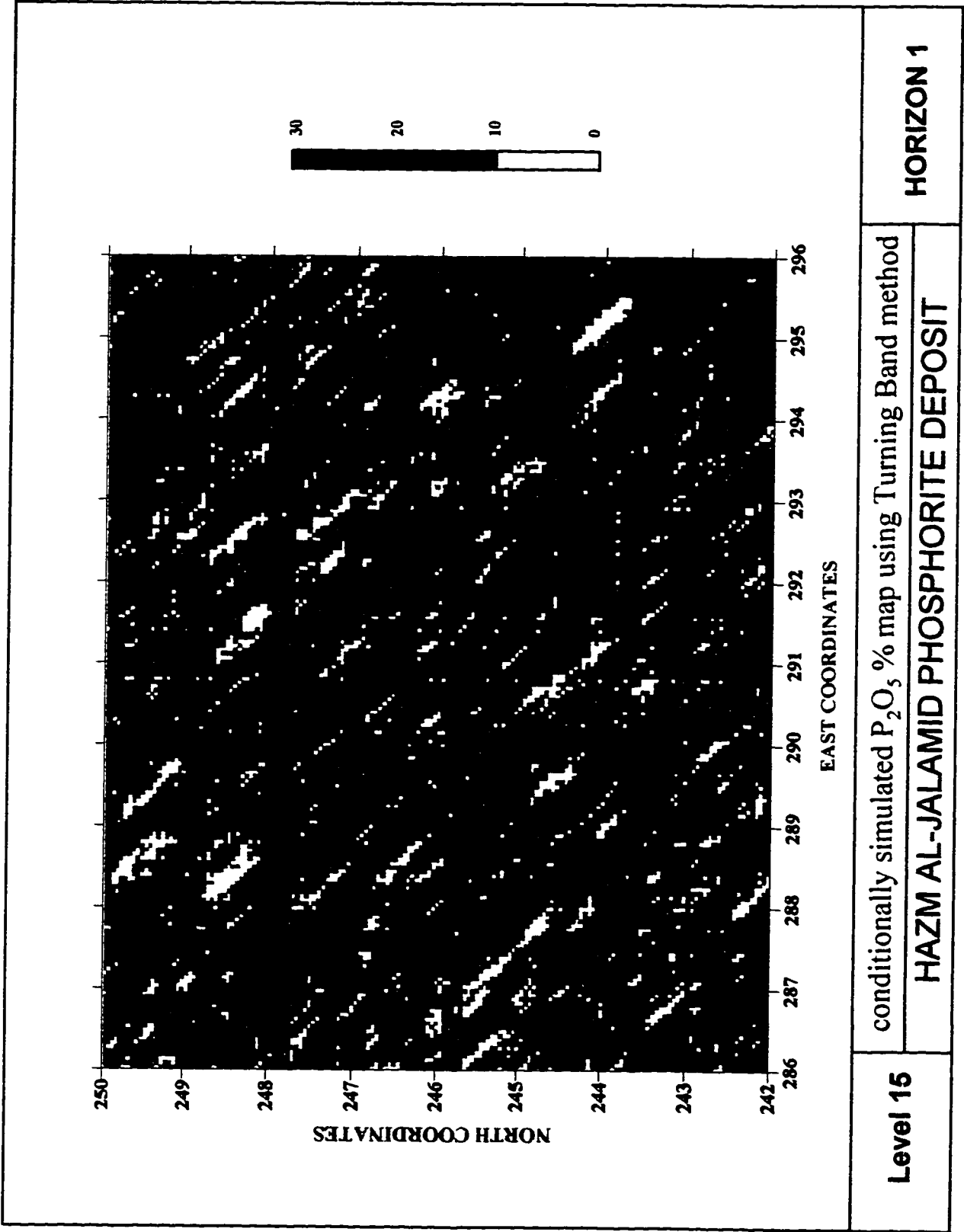
Simulation output maps for Horizon 1

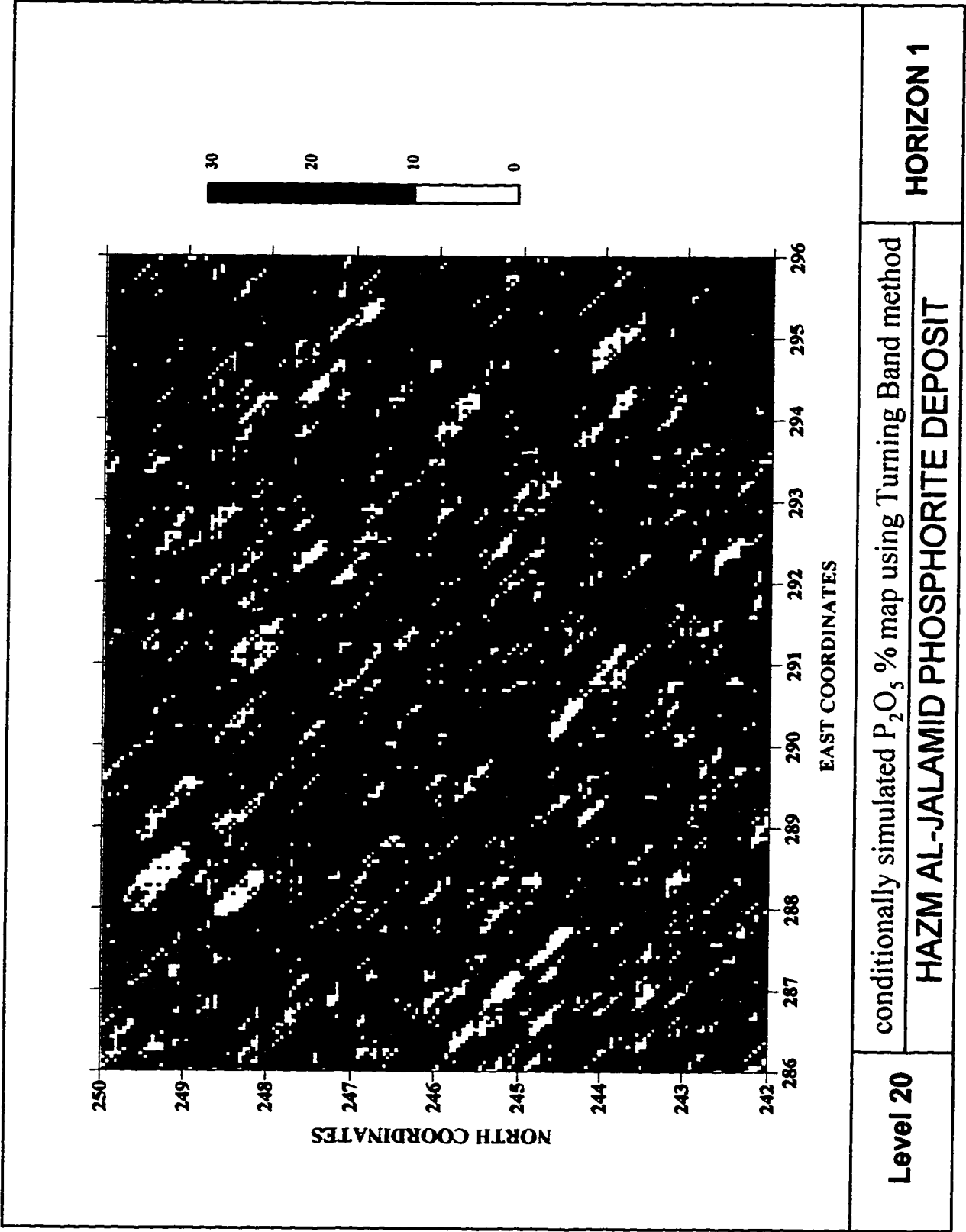


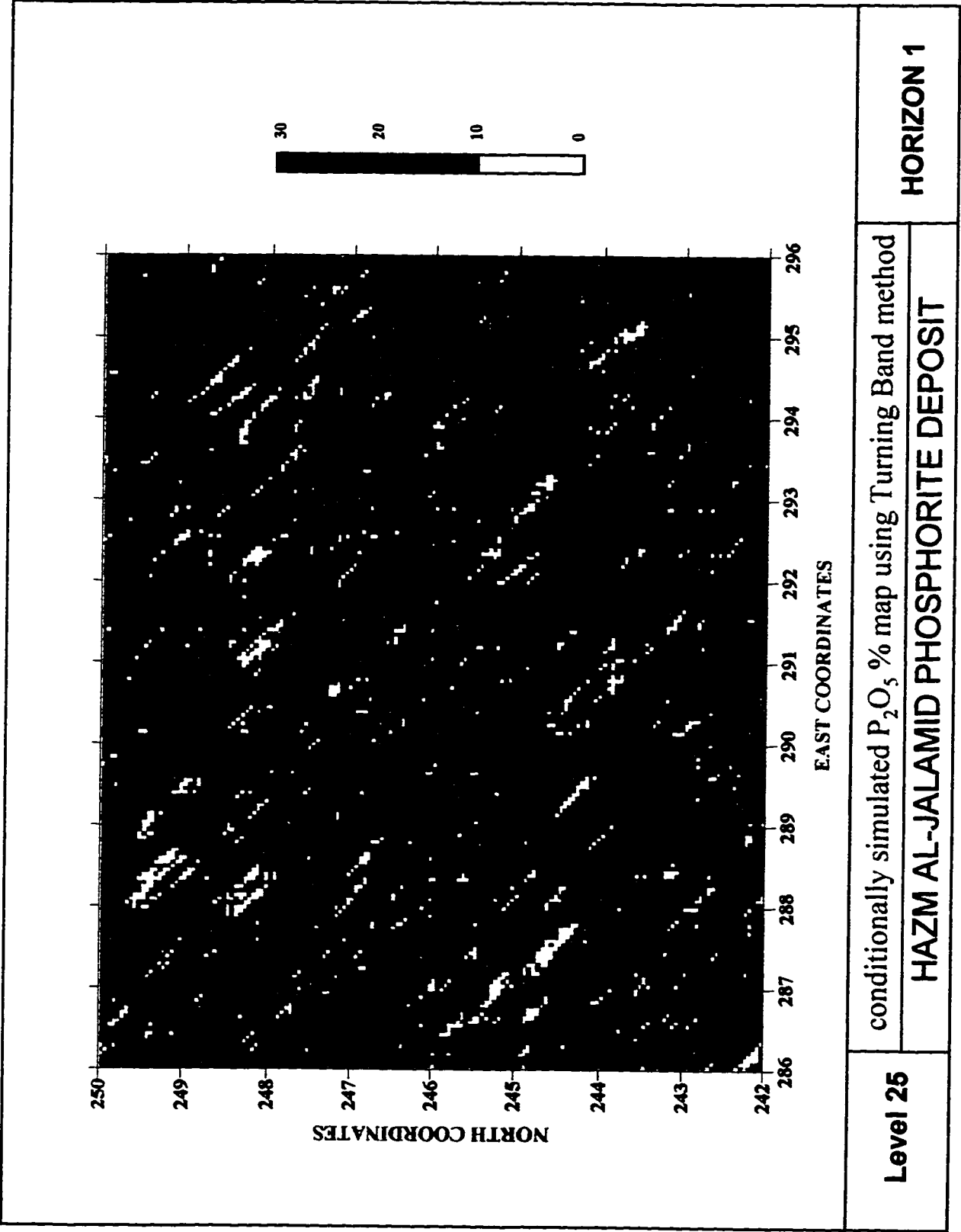


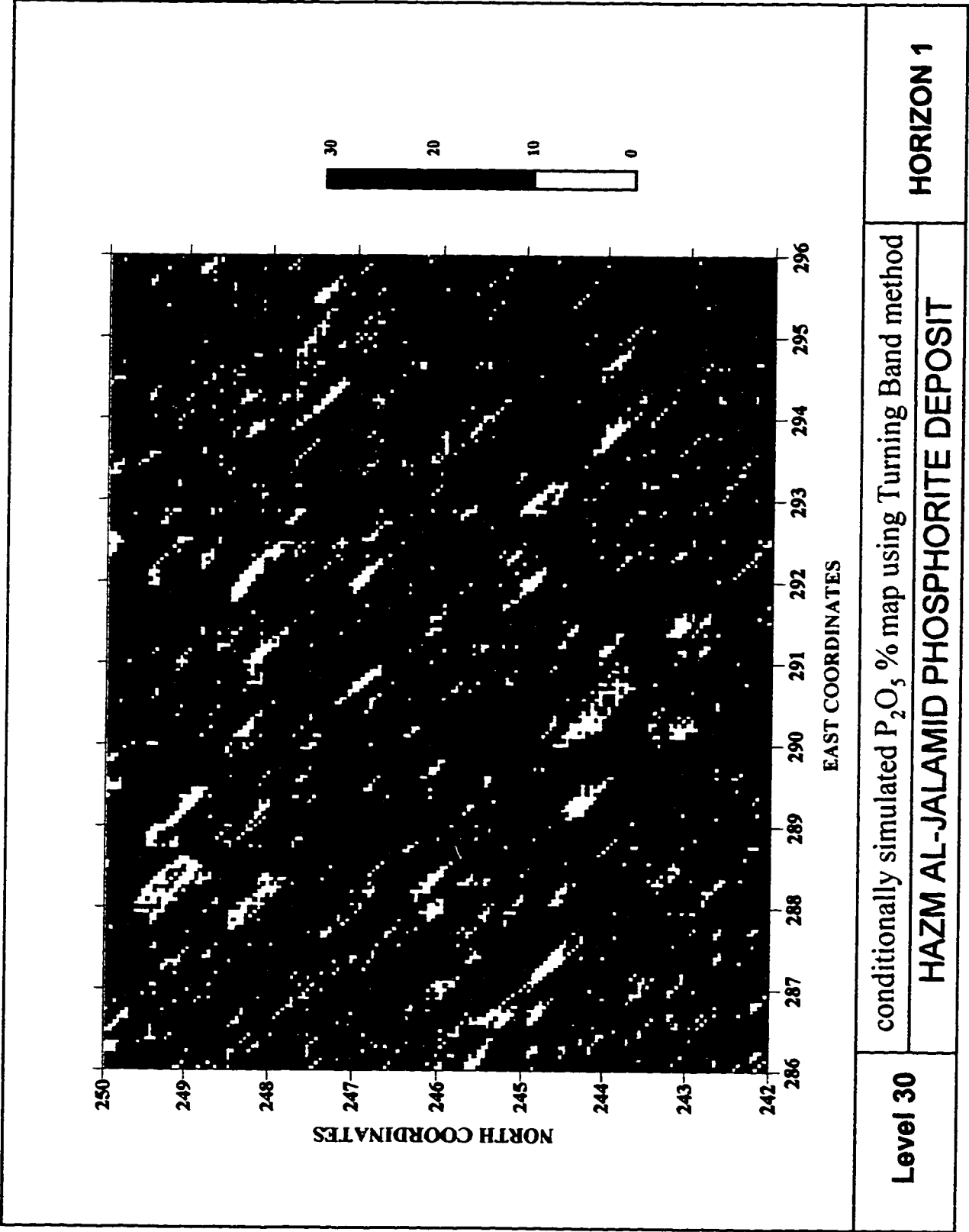


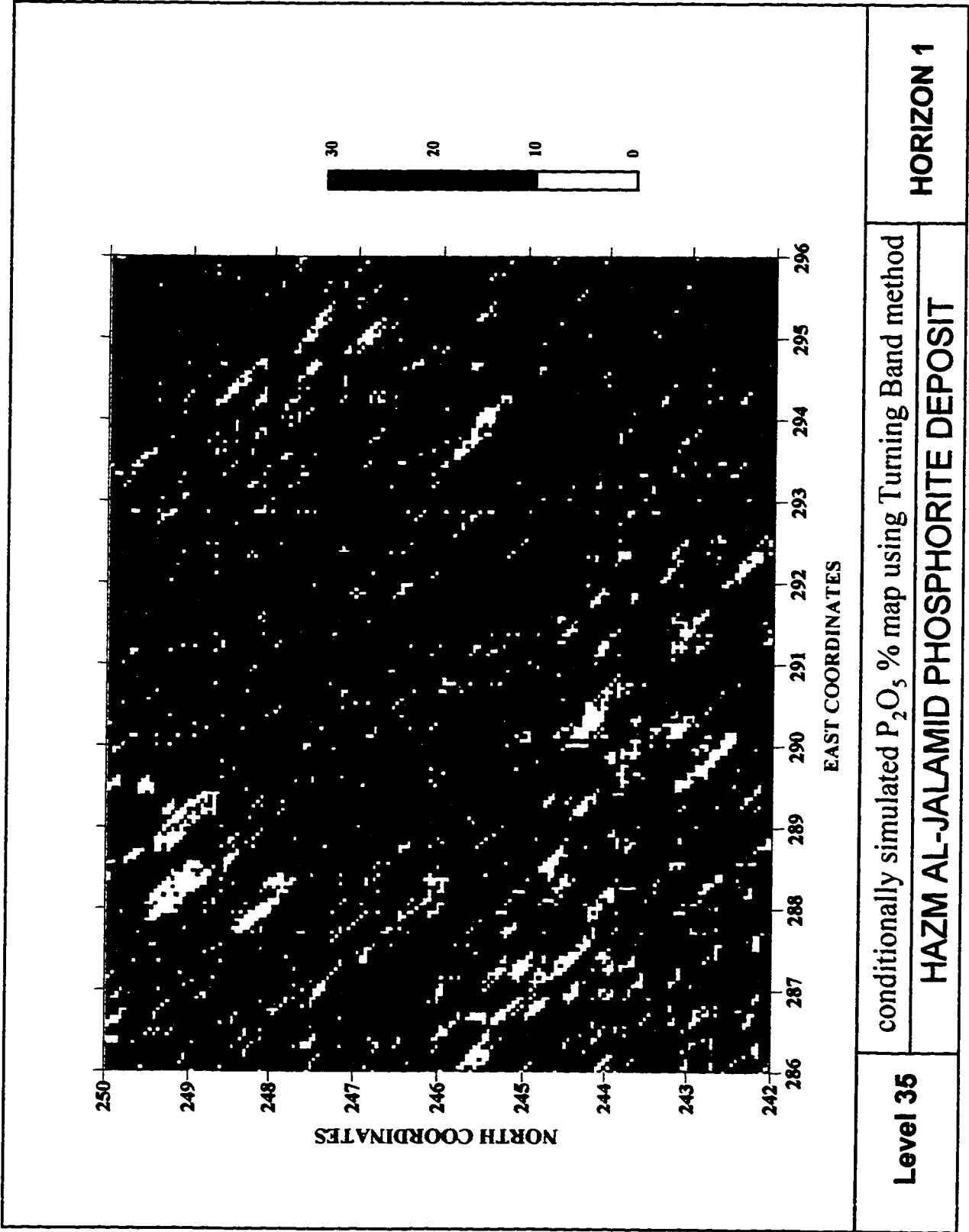


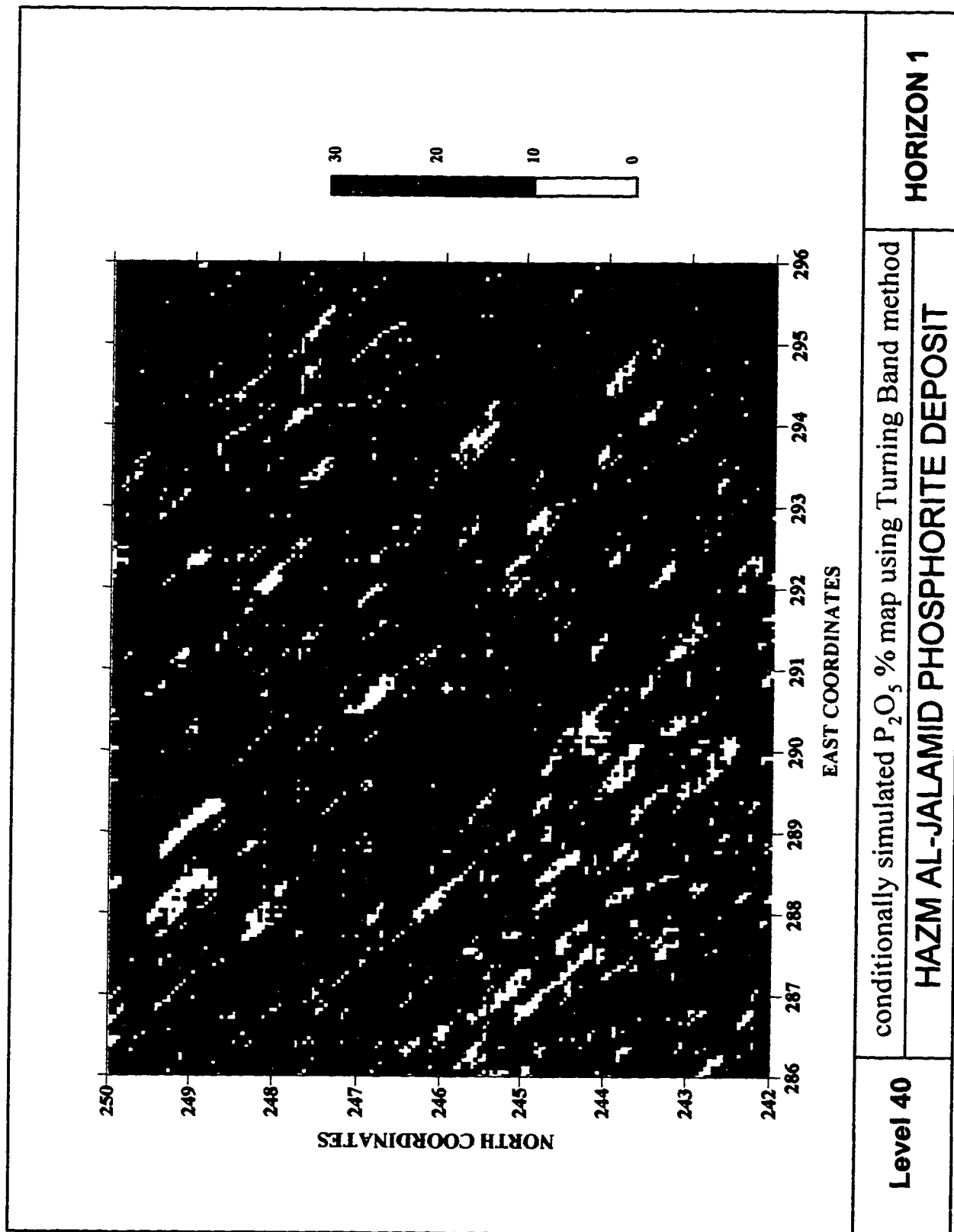




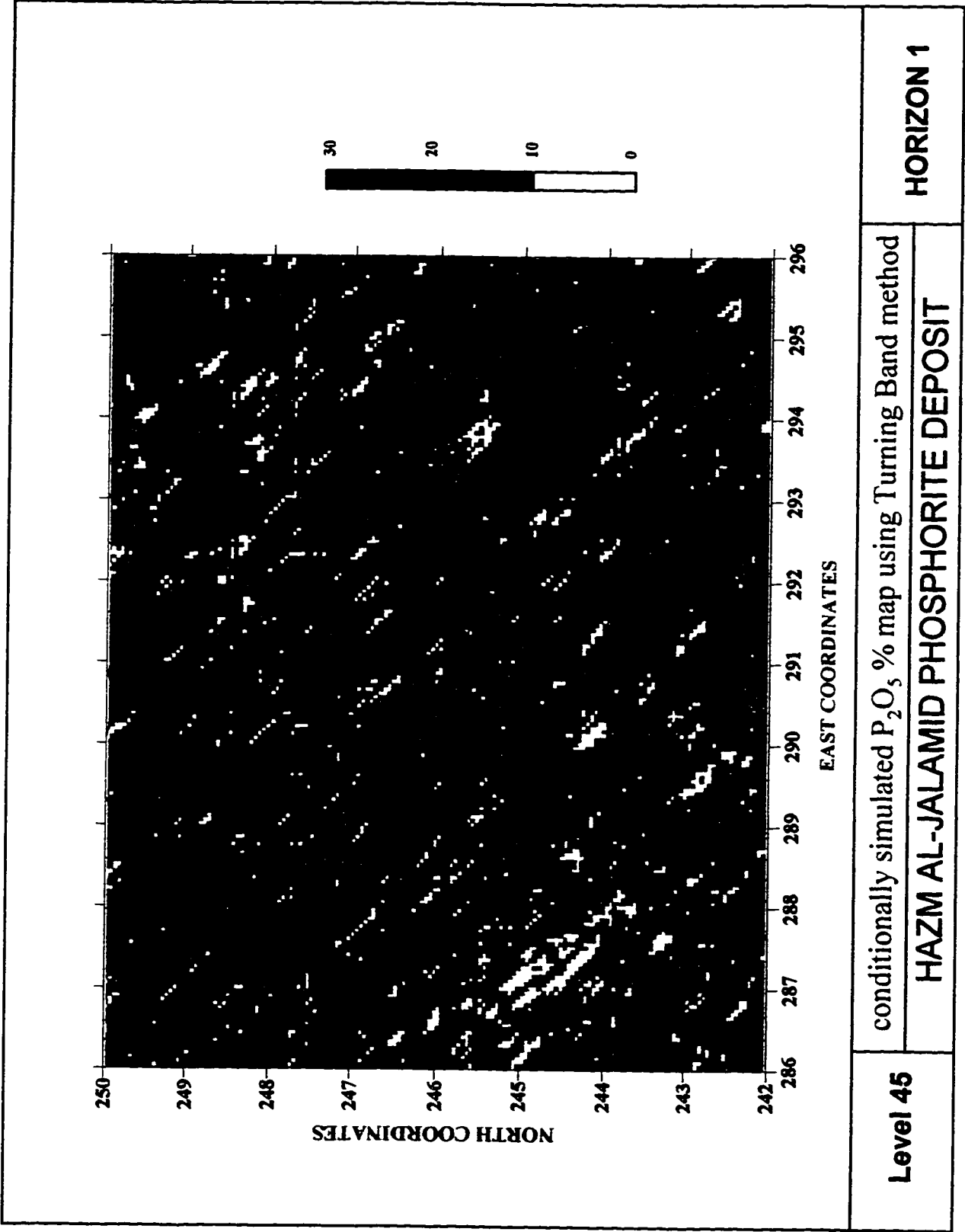


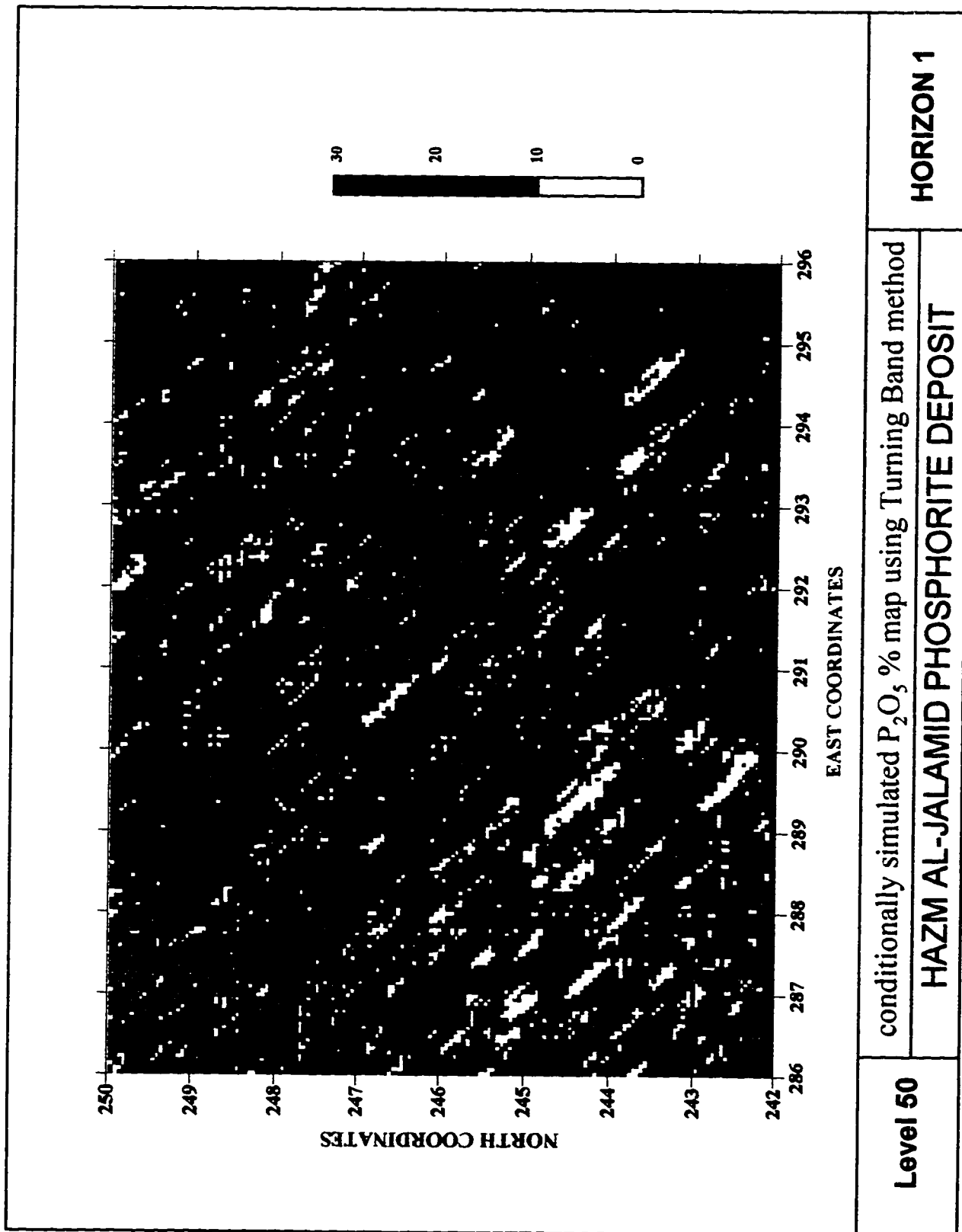


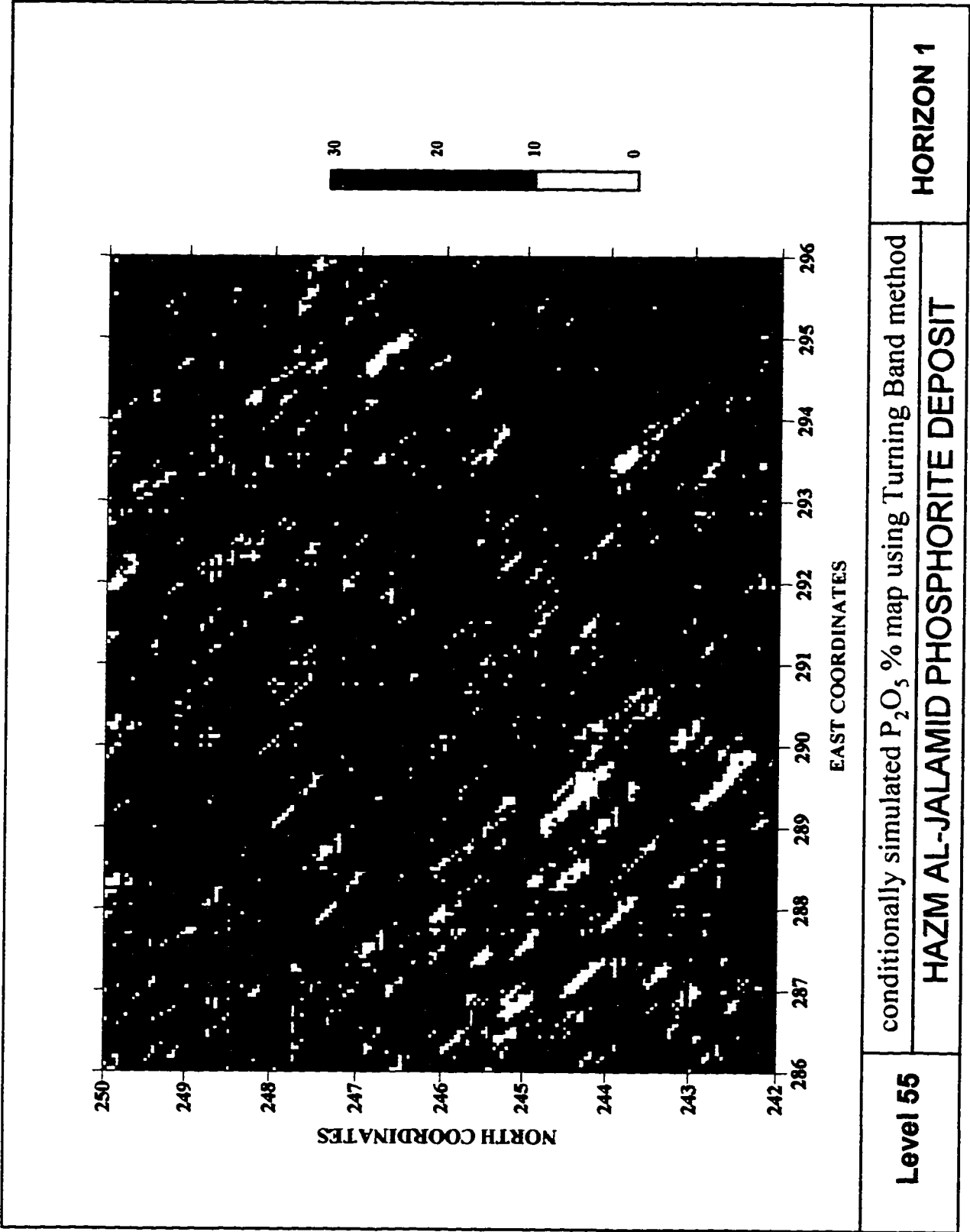


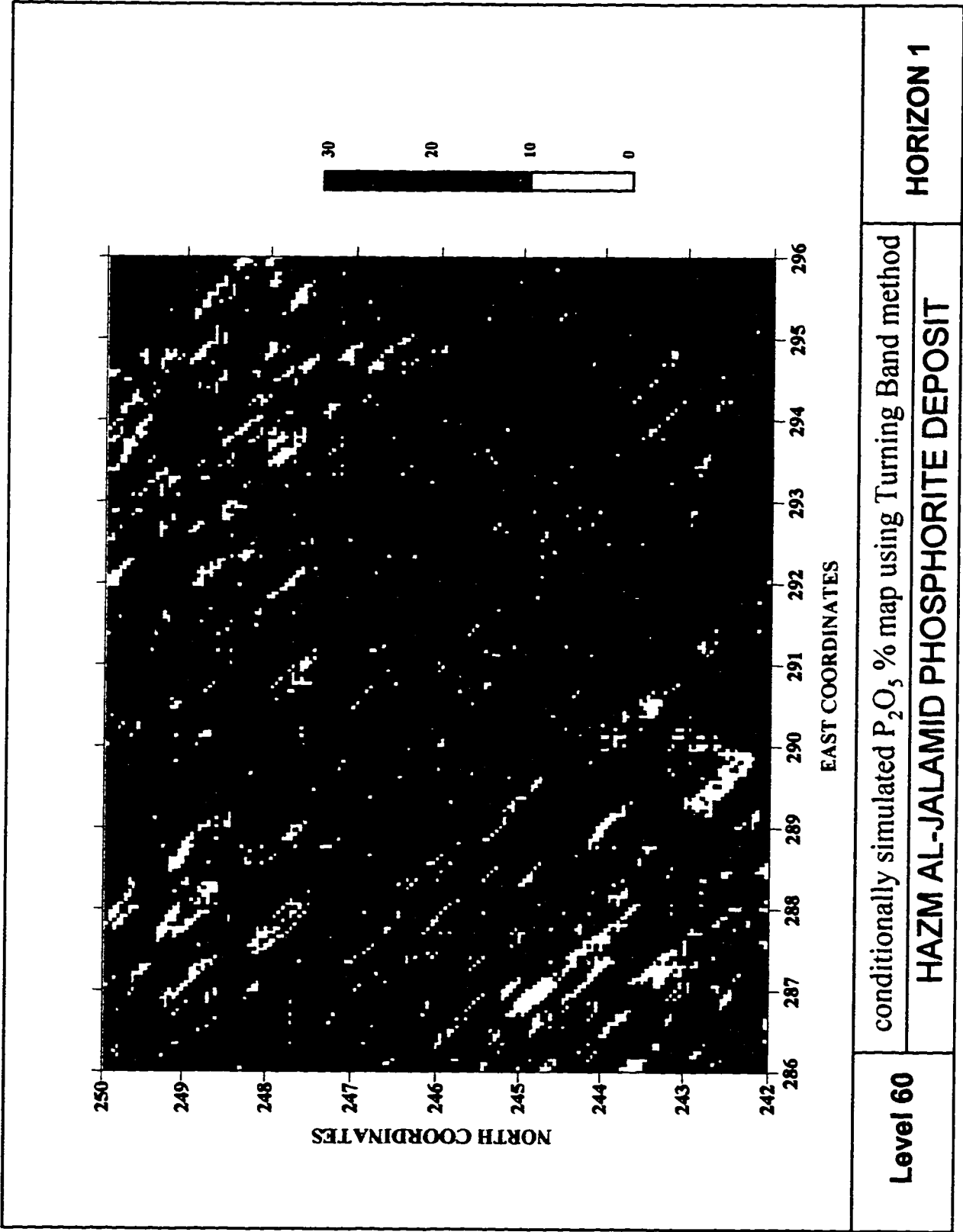


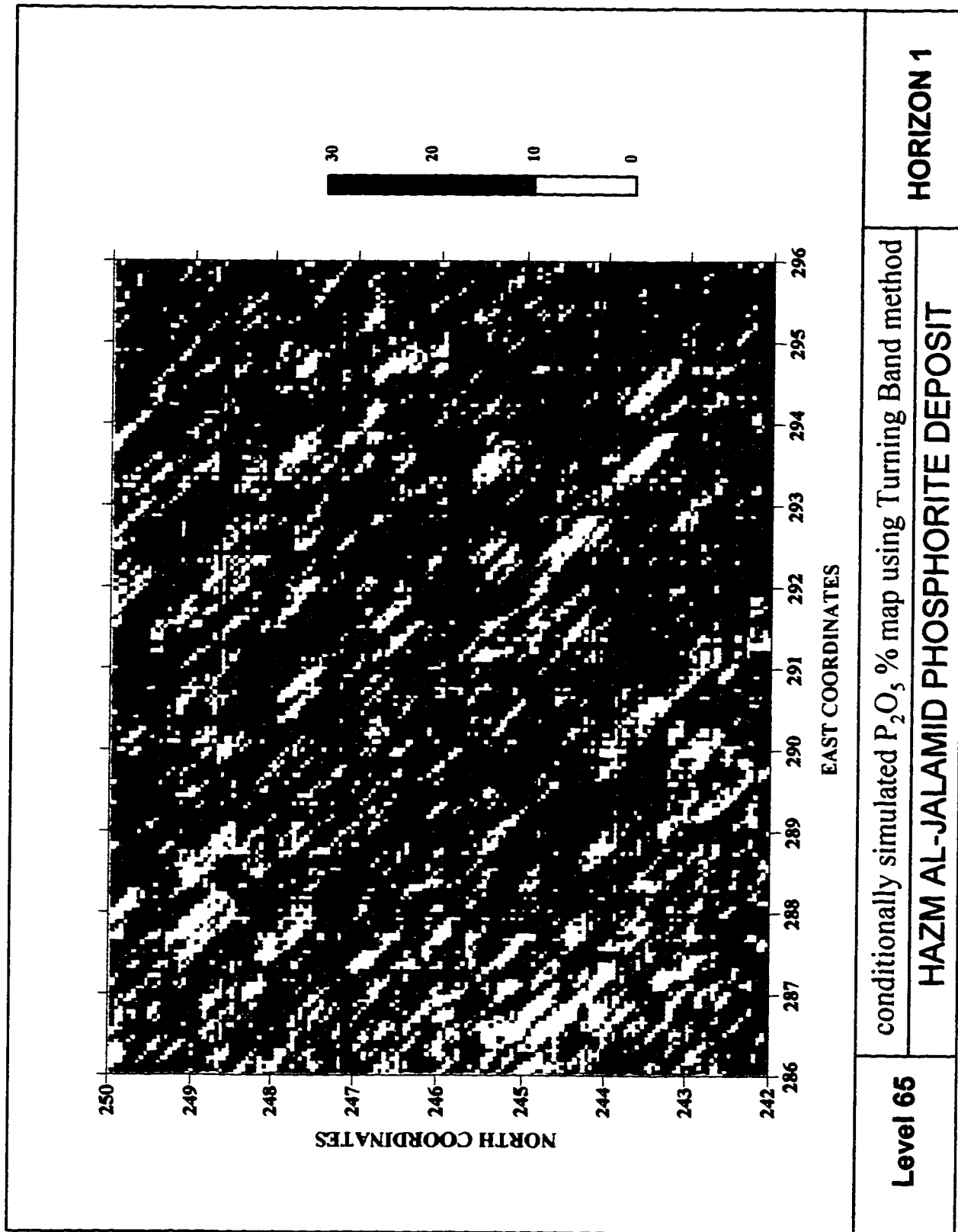












## **APPENDIX L**

Simulation output maps for Horizon 3

