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Upper Carboniferous of the Cleaverbank High

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Author(s)
B.M. Schroot (also editor)
H.B. de Haan
S.D. Nio

Richard Holkade 10
P.O.Box 157
2000 AD Haarlem
The Netherlands

Phone +31 23 530 03 00
Fax +31 23 535 16 14

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Netherlands Institute of Applied Geoscience TNO has main offices in Delft and Haarlem and branch locations in Haarlem, Heerlen, Nuenen, IJmuiden and Zwolle.

The Institute is the central geoscience institute in the Netherlands for information and research on the sustainable management and use of the subsurface and its natural resources.

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Summary

The exploration for gas in the Carboniferous on the Dutch continental shelf has been hampered by the complexity of the petroleum geology in relation to the available data. The occurrence of hydrocarbon traps and the presence of reservoir sandstones are the two critical factors, which are difficult to predict in this deep play. The quality of 2D seismic data at the depths of about 3500 - 4000m, beneath the Zechstein evaporites, was not high enough to adequately model the subtle structures.

Advances in exploration technology, such as the use high quality 3D seismic surveys together with modern software-based high resolution well log interpretation and correlation tools, have been applied on the Carboniferous play of the Dutch Cleaverbank High. The detailed well log interpretation was done using new software, which performs frequency analysis on log-curves, with a sequence stratigraphic approach. The result was a high resolution stratigraphic framework using more than 40 wells with a substantial Carboniferous section, both on the Dutch side and on the UK side of the median line.

This geological framework was input for a large seismic interpretation study of the Carboniferous in an area of some 5000 km^2, which has been covered by 3D seismic surveys during the last few years. For the first time it was possible to interpret intra-Carboniferous horizons within seismic surveys consistently over such a large area.

The resulting maps show prospective structures at top Carboniferous level, and result in a better understanding of the distribution of the sand-prone units of the Upper Carboniferous.

An overview of the remaining prospectivity is given. There are still structures to be drilled, but the traditional concept with structural closure at top Carboniferous level will probably only yield marginal fields. There is, however, scope for more gas in stratigraphic traps, but this concept still has to be proven in the area. Proof of the occurrence of an intra-Carboniferous seal would make a lot of difference.

To study these higher risk play-concepts it is important to have to best available 3D data, and work in highly multidisciplinary manner with new geological tools. As more data will become available in the near future, it will be possible to integrate this data, and update the current maps and models. With respect to the regional framework and overview, NITG-TNO has an important position, because it is the only party which has access to all of the 3D surveys.

Contents

List of figures

List of tables

List of enclosures

1 Introduction

1.1 Administrative

This report presents a study on the Upper Carboniferous of the Cleaverbank High, which was proposed to the Ministry of Economic Affairs by the Geological Survey of the Netherlands (RGD) on March 26th 1996 (ref. PJ/YA-961220). In his letter of August 14th 1996 (ref. E/EOG/MW 96047998) the minister furnished a contribution to perform the study, which has been given project code FAS61232. The RGD has started to work on the project in September 1996, and finished the project within 10 months according to the original proposal. A first presentation of the results has been given to a delegation from the ministry on June 17th 1997 in Haarlem.

For the study three seismic interpreters have worked simultaneously on the interpretation of the 3D surveys. One of RGD's geologists was responsible for the interpretation of the stratigraphy in the wells. It was decided to do thorough sequence and cyclostratigraphic work on the Carboniferous portions of wireline logs of the wells, using the expertise and proprietary software of the geologic consultant ENRES. A minor contribution to the project came from one of RGD's biostratigraphic experts in analysing palynological slides from a few UK wells. The ministry's contribution of NGL 180,000,- was used to hire expertise (one of the seismic interpreters for 4 months and the sequence stratigraphic expertise of ENRES), and to acquire digital log data of 12 released UK wells.

During the course of the project the RGD has merged into the new institute "Netherlands Institute of Applied Geoscience TNO - *National Geological Survey* , which took over the role of RGD in 1997. The study has been performed within the department "Deep Subsurface/Oil and Gas" of the new institute.

1.2 Purpose of the study

The purpose of the study was to evaluate the occurrence and character of the Upper Carboniferous sediments in the Dutch Cleaverbank High (CBH) in view of their petroleum geological potential, and thus achieve a better understanding of the prospectivity of the Upper Carboniferous reservoirs in the area. Efforts were focused mainly on sequence and cyclostratigraphic wireline-log analyses and correlation and seismic interpretation. The objectives were to establish a new and reliable zonation of the Carboniferous sequences, using both well-log and 3D seismic data, and subsequently complete a new integrated seismic interpretation and mapping of that part of the Cleaverbank High that had recently been covered by 3D seismic surveys (see figure 1.1). Furthermore the aim was to identify structural traps and (if possible) stratigraphic traps on the new maps, and to produce maps which show the distribution of the younger Westphalian sediments.

In addition an integrated geological and basin model had to be constructed in order to predict the distribution of sand-prone units.

It was deciced that in spite of the regional character of the study, the density and accuracy of the seismic interpretation of the 3D data should be at the scale of a field evaluation. Reasons to set this rather high goal, were the structural complexity within the Carboniferous and the fact that at least the relatively simple overburden (above the base of the Zechstein) would not have to be reinterpreted again in future field studies. All digital grids will then be immediately available. Another benefits of this approach will be the fact that this work has been done in a consistent way within a regional framework.

1.3 Petroleum geological background

The area known as the Cleaverbank High in the northern part of the Dutch continental shelf of the North Sea, consisting of the southern D and E blocks and northernmost J and K blocks has proved to be a fairway for gas in the Upper Carboniferous sandstones. In this Carboniferous play just north of the classical Rotliegend fairway, some gas discoveries have been made since the mid 1980's. Compared to the nearby Carboniferous play in the UK sector, the exploration of the area after the initial discoveries, has not been as successful as in the UK sector. The high complexity of the petroleum geology plays an important role in this relative lack of success, and oil companies have for some time considered the play to be a high risk one.

During the last few years technological advances, such as high quality 3D seismic surveys and the introduction of frequency analysis of well-log curves, are offering challenges to better understand the complex petroleum geological problems. At the same time new discoveries on the UK side of the median line seem to indicate border-crossing fields. These two developments have lead to an increased interest in this Carboniferous play, both from the side of the industry and from the Netherlands Ministry of Economic Affairs. Recently the exploration based on 3D seismic data has resulted in some new discoveries.

In terms of petroleum geological conditions needed for gas accumulations to occur, the two most critical factors in the area are the distribution of reservoir sandbodies and the presence of hydrocarbon traps. The difficulties the exploration industry has encountered so far, while trying to answer the questions where the good Carboniferous reservoir sands are present, and where structural or stratigraphic traps occur, have severely hampered successful exploration until recently high quality 3D seismic data became available. The technical challenge now is to use this data in a modern and multidisciplinary way and integrate it with other types of data such as borehole measurements and biostratigraphic interpretations in order to resolve these two important questions.

1.3.1 History

The Southern part of the Cleaverbank High is situated at the northern fringe of the Rotliegend Slochteren gas-play. During exploration and development of some gas-fields (e.g. in blocks K4 and K5) of this play the operators have found out that also the Upper Carboniferous sandbodies can be gasbearing. In the D and E blocks exploration started with a few wells aimed at Triassic or Zechstein, which were not successful. One of the first wells aimed at the Carboniferous was E13-1 in 1984, which found gas (and minor oil) in reservoirs of Westphalian C and D age. A little later the wells D12-03 (1985) and D15-03 (1986) found the D12/D15 gasfield, where the equivalent of the Caister sandstones of early Westphalian B age contains gas. These Carboniferous wells of the mid 1980's were based on maps from 2D seismic interpretations, and most probably were drilled at high features at base Zechstein level. The 2D data does not often show a lot of detail within the Carboniferous, and if it does, the reflectors are difficult to correlate across faultblocks.

In 1989 a regional seismic interpretation of the 2D spec survey N86 was done within RGD, which resulted in a depthmap of the top of the Carboniferous. After the biostratigraphic analysis of some well data from the D and E wells, this work was summarised in RGD report 91PTG01 entitled "Het Boven Carboon van de D&E blokken".

In the meantime exploration on the UK side of the median line had been more successful, and the idea was raised that exploration for the Carboniferous on the Dutch part of the continental shelf started to lag behind. In 1994 the Netherlands Ministry of Economic Affairs took the initiative for a new study within the scope of the research programme "Energy in the Subsurface", and a group of consultants together with RGD started a multi-disciplinary project to evaluate new tools and concepts, which could play a role in further exploration of the Upper Carboniferous of the central part of the Dutch continental shelf. The results of the study "Permo-Carboniferous gas reservoirs on the central continental shelf of the Netherlands" (RGD report 30028) were presented in 1995. In that study it was demonstrated that the availability of higher quality data (particularly 3D seismic surveys) and of modern workstation based software-tools (e.g. seismic amplitude analysis and frequency processing of well log curves) could yield promising results, when carefully applied in a multi-disciplinary manner.

1.4 Scope of the study

Given the purpose of the study described in section 1.2, the scope can be defined and restricted in terms of theme, geography and stratigraphy.

Because the most critical petroleum geological factors in the area are reservoir distribution and the occurrence of hydrocarbon traps, the study focuses on these two items. Other factors like the hydrocarbon seal and source rock maturity will not be treated in this study. Especially the question if there can be intra-Carboniferous seals is nevertheless quite important, and will have to be addressed in the future when more well data will be available. Maturity might be an issue locally. This factor would merit a different study, taking into account basin modelling.

Geographically the study is restricted to the area which has been covered by 3D seismic surveys of the 1990's when it comes to the most detailed analyses of the seismic data. The area from which wells have been chosen to be correlated is somewhat larger (13 UK wells, most of them west of the 3D seismic coverage have been added, and Dutch wells just outside the 3D coverage have also been interpreted. In addition the top Carboniferous map is completed with contours from 2D interpretation mainly from blocks E10, E11, E14 and E16.

With respect to stratigraphy we have restricted ourselves to the younger Upper Carboniferous, from Westphalian B to Stephanian, because these rocks are considered to be most prospective. The older Namurian play (E12) has not been taken into account.

achter map & Fig 1.1

2 Sequence and cyclostratigraphic interpretation

2.1 Introduction

At the request of the Netherlands Institute of Applied Geoscience TNO - *National Geological Survey*, ENRES International carried out a sequence and cyclostratigraphic study of the Dutch Cleaverbank High. The objective of this study was to establish a synchronous high-resolution stratigraphic correlation using a frequency analysis of facies-sensitive wireline log data. Subsequently, the results of this study will be integrated with the results of the seismic interpretation which will make the construction of an integrated geological and basin model for the Upper Carboniferous of the Cleaverbank High area possible. Ultimately, the aim is to evaluate the hydrocarbon potential and reserves of the Upper Carboniferous of the Cleaverbank High area.

CycloLog® wireline log analysis tool was used and more specifically the multidimensional frequency curve (INPEFA) was applied in the analysis and correlation of the wells. INPEFA curves were generated for each well. The INPEFA curves were subsequently used in the prediction of the important geological events during the Late Carboniferous in each well. These geological events are characterised by major "knickpoints" in the INPEFA curves which in frequency terms represent important breaks in the frequency continuity. These knickpoints are defined as *Frequency Break Points* (FBP). The sedimentary successions between the FBP surfaces are characterised by a specific suite of tectonic and climatic parameters. These sedimentary successions or packages are defined as *Composite Stratigraphic Packages* (CSP) and can be correlated at a regional scale. The INPEFA curves can be imported into the seismic workstations and were an important tool for interpreting the seismic patterns. For the first time, a close link was established between the stratigraphic zonation and correlation of wells and the seismic expression.

The results of this study therefore represent a state-of-the-art integration between geology and geophysics and show some important differences with the existing concepts of the subsurface Upper Carboniferous.

2.1.1 Scope and objectives

The study includes the largest well database of the Upper Carboniferous as well as the most extensive 3D seismic survey coverage. The well location map (figure 2.1) shows the distribution of the wells in the Cleaverbank High area. Most of the Dutch wells are located within the 3D coverage area. The UK wells were used for comparison purposes as well as for obtaining a better geological overview of the region. Only two of the UK wells are located in the area of available 3D seismic surveys.

Despite the large number of wells, well density is still relatively low. The average distance between the wells are in the range of 5-10 km.

The different stages (see figure 2.2) of the project are :

1. frequency analysis of the wells
2. high-resolution stratigraphic correlation between the wells (in full integration with the seismic interpretation)
3. construction of an integrated geological model
4. a renewed play type definition, focusing on mixed structural-stratigraphic and pure stratigraphic hydrocarbon traps.

2.1.2 Well database

NITG-TNO has provided ENRES International with the digital data of logs in ASCII format. A listing of the supplied logging data is given in figures 2.3 and 2.4

Facies sensitive GR logs were used for evaluating the cyclic pattern of sand-shale in the time-depth domain. Facies sensitive ratio of RHOB and NPHI were used for calibration. The Potassium logs were used for correlation calibration points, related to major changes in climate.

Not all wells were used in the correlations. Wells containing thin and incomplete Carboniferous intervals (such as E10-1, E14-1, E16-1 and E16-2) were not included in the correlation lines.

2.2 Concepts and methods in cyclostratigraphy

2.2.1 Introduction

Sequence stratigraphic concepts are widely applied in hydrocarbon exploration and production for subsurface stratigraphic correlations. Since sequence stratigraphy has evolved from seismic stratigraphy, correlation was initially in agreement with the seismic resolution. With a better understanding of the principles of sea level fluctuations, stratigraphic fill and basin dynamics, sequence stratigraphy became a more geological tool and subseismic resolution became feasible. The latest developments resulting in high-resolution sequence stratigraphy (m-scale) involve the use of e.g. orbital-forcing Milankovitch cycles. Despite the rapid development of the understanding of the sequence stratigraphic concepts, a number of important constraints are still present. Up to now sequence stratigraphic analysis is mostly carried out in a model-driven manner. The recognition of boundaries for example is established with the support of a number of tools (e.g. biostratigraphy, chronostratigraphic charts, seismics, etc.) and the known facies and basin model. For this reason, subsurface correlations are highly subjective and the results may be inaccurate. A more objective recognition of the significance, the lateral correlation and the erosional magnitude of third or higher order boundaries in wells as well as in outcrops is an important but still an elusive aspect of high-resolution sequence stratigraphic analysis. Also standard well-to-well correlations using extensive biostratigraphic data followed by a detailed log pattern correlation (including available core data) still cannot avoid establishing a mixed framework of time and lithostratigraphic correlation lines. This often gives rise to larger or smaller uncertainties in correlation. If a biochronostratigraphic control is missing as in barren sequences, correlation will become very difficult.

A new approach is presented here where the different features of frequencies which are stored in geophysical logs, are used. Frequencies detected in geophysical logs which are sensitive to depositional facies, are related to cycles in the sedimentary rock record. Changes of lithofacies will also cause changes in the cycle or frequency characteristics.

The basic concept of this new approach is to use the frequency variability and characteristics in well zonations and correlations. For this purpose a specially-designed software tool, *CYCLOLOG*®, has been developed.

2.2.2 Working concepts and interpretation of frequencies in logging data

Generally, frequencies in facies-sensitive logging data are related to mainly allocyclic patterns in the sedimentary record. The origin of these cycles is partly related to orbitally-forced Milankovitch cycles. However, more cycles can be distinguished and their origin is still a problem. The basic concept in cyclostratigraphy is that the depositional patterns of sediments are strongly influenced by a suite of climatic parameters and basinal conditions. This means that the cycle characteristics, e.g. the cycle hierarchy and dominance, are strongly related to certain lithofacies variations. These cycle characteristics and their related lithofacies variability are generally developed basin-wide and might be even recognisable at a regional scale. The working concept in subsurface correlations using cyclostratigraphy and frequency analysis of logging data, is linking similar patterns of frequencies or cycles between wells.

CycloLog is a wireline log analysis tool where its frequency analysis sub-routine is an important part of the programme. CycloLog essentially is using the presence and the characteristics of the detected frequencies or cycles in the sedimentary rock record for predicting discontinuities in these cycle successions. Frequency or cycle discontinuities indicate important geological events such as major tectonic disturbances or changes in climate which has its implications in changes of sea level. These discontinuities also characterise the cyclic succession of specific stratigraphic intervals formed during a certain geological period. The following procedures of frequency analysis were followed (see figure 2.5).

A spectral image of the frequencies as detected from the log data shows in a deterministic way the presence and characteristics of the frequencies. The analysis

is using a specially-designed time series analysis programme - Maximum Entropy Spectral Analysis (MESA).
The Prediction Error Filter Analysis (PEFA) detects the presence of breaks in the frequency continuity.
The Integrated Prediction Error Filter Analysis (INPEFA) uses a mathematical filter to construct a frequency-derived curve which shows the Frequency Break Points (FBP) and the cycle pattern between these surfaces.

A very intimate relationship exists between the observed frequencies in geophysical logs and the stratal architecture as observed from outcrops (figure 2.6) However, the cyclic patterns in outcrop are not always clearly seen. The preservation of the cyclic succession is a function of basin accommodation development. Creation of accommodation space, related to a high subsidence rate and a sediment supply less than the accommodation increase, will preserve the cyclic pattern. When the increase of accommodation space is less than the sediment supply, a more close stacking of the different lithofacies will occur and the cyclic pattern can be obscured. In more extreme cases erosion of the different subsequent lithofacies units may occur which leads to the destruction of the cyclic pattern.

2.2.2.1 Maximum Entropy Spectral Analysis (MESA)

Maximum Entropy Spectral Analysis (MESA) of the GR log of well 44/19-3 shows a well defined arrangement of spectrum bands. MESA has been carried out in three different windows, sized - 30, 40 and 50 m. (figure 2.7)

A number of features can be described as follows:

A clear hierarchical pattern of frequencies or cycles can be observed. Low frequencies represent a cyclic stacking of certain lithofacies with a long wavelength. The high frequencies are equivalent to small wavelengths.
The low frequencies seem to have a higher amplitude, indicating the presence of pronounced “long” wavelength cycles. In this case the “long” wavelength is produced by the cyclic stacking of the coal-bearing layers. The breaks in frequency continuity are also clearly shown. The upward or downward position of these breaks in the well can be determined through the different break position in the three windows. It exact depth position is a half-window upwards or downwards (in this case 15 m upwards).

MESA not only shows the consistent presence of cycles, but also the quality or the cyclic development of the sediments.

2.2.2.2 Prediction Error Filter Analysis (PEFA)

The Prediction Error Filter Analysis (PEFA) of logs (figure 2.8) predicts the presence and continuity of frequency characteristics of a set of logging data. Any change of these frequency characteristics will be considered as an “error” and its depth position in a borehole is indicated. Each "error" therefore indicates a break or a discontinuity surface which is related to either missing frequencies or a dramatic change of frequency characteristics. In geology, these discontinuity surfaces are generally interpreted as stratigraphic breaks representing missing time.

PEFA recognises negative as well as positive breaks. Negative breaks are related to a jump from high to low values. The negative breaks in GR log are related to a sudden transition from shale to sand and may represent an erosional surface. The positive breaks are related to a sudden transition from sand to shale and represent flooding surfaces. Generally, the amplitude of the PEFA breaks are related to the magnitudes of stratigraphic breaks. The high negative peaks as displayed in K5-2 are related to important geological events related to a change in sand supply, probably related to a change in basin dynamics. The high positive breaks represent important flooding events or are related to coal layers.

2.2.2.3 Conversion of logging data to the frequency domains of PEFA and INPEFA

Facies-sensitive geophysical logging data are converted into three different frequency domains (figure 2.9). Generally, frequency domains are displayed within a time scale. In this case the three frequency domains are displayed within a time-depth scale, where the frequency periodicity is within the time scale, while the appearances of the frequencies are plotted against the depth scale of the well.
The three conversions into the frequency domain are:
MESA, where the spectrum bands of the frequencies are displayed. Frequency amplitudes, periodicity, breaks and wavelengths are displayed within the time-depth scale.
The conversion from the GR log data to the Prediction Error Filter Analysis (PEFA) breaks shows negative (to the left) as well as positive (to the right) breaks. The **negative breaks** are formed when sediment supply is larger than the increase of basin accommodation. In most cases negative breaks are at the base of a sand-prone interval and also indicate the presence of an erosional surface. Negative breaks within a sand interval indicate the presence of erosional surfaces within the sand succession. **Positive breaks** are formed when sediment supply is lower than the increase of basin accommodation. It mostly initiates the onset of a shale-prone interval.

In sequence stratigraphic terms, negative breaks mostly represent sequence boundaries or any higher-order erosional boundary. It is mostly related to a relative fall of sea or base level.
Positive breaks are related to flooding surfaces. It is related to the beginning of a relative rise of sea or base level.
The INPEFA multidimensional frequency curve is a conversion from PEFA. A succession of predominantly negative breaks will show a negative or "progradational" trend of the INPEFA curve. A succession of positive PEFA

values however, will show a positive or "retrogradational" INPEFA trend. The curve shows multidimensional features:
It shows the cycle hierarchical pattern in terms of sand-shale depositional cycles.
It shows a time-related progradational or retrogradational trend which is related to sediment supply and changes in basin accommodation at well location.
It predicts the occurrences of geological events at well locations.

2.2.3 Sequence and cyclostratigraphy of the Upper Carboniferous

The development of sequence stratigraphy which principles (see figure 2.10) are mainly based on the allocyclic controls of climate, eustacy and basin tectonics, has improved the understanding of the nature of depositional systems of fluvial-delta plain successions such as those of the Upper Carboniferous (see e.g. Flint et al, 1995). Application of sequence stratigraphic concepts in the Upper Carboniferous is making use of the stratigraphic appearances of coal seams or intervals. These coal beds are commonly related to low ash coal deposited in close proximity of siliciclastic sediment inputs and are related to raised mires. These mires are initiated, sustained and preserved in conditions of slowly rising base level or relative sea level.
Thus coal may be correlated with initial flooding surfaces and has an important time-correlative significance (see e.g. Flint et al., 1995, Whately & Spears, 1995).

Application of relative sea or base level fluctuations and the position of the different systems tracts as a function of the rate of accommodation space development (creation and destruction) and sediment preservation are summarised in figure 2.10. Preservation of thick coal accumulations are favoured by high accommodation space. In a mire, accommodation space can be defined as the maximum height to which a peat could build (McCabe 1993). Properties of coal, such as thickness, ash content and maceral type, are controlled by the type of vegetation, humification rates, sediment supply rates and rates of base level change. In turn, these are controlled by the allocyclic processes of eustacy, climate and tectonics which determine the sequence stratigraphy (Flint et al., 1995).

Carboniferous cyclostratigraphy is usually explained by the variation in depositional environments associated with Carboniferous cyclothems. Weedon & Read (1995) have carried out spectral analysis on the Namurian interval of 6 boreholes of west Scotland. Important in their study is the recognition and simplified lithofacies description of these cyclothems. Each cyclothem was described in terms of mean grainsize and ideally shows a succession of coal-claystone-siltstone-sand-siltstone or paleosol.
These cyclic features are precisely the lithofacies variations in the Upper Carboniferous, which are recorded by facies-sensitive logs.

2.2.4 Geological interpretation of the INPEFA multidimensional frequency curve

2.2.4.1 Frequency break points (FBP) and composite stratigraphic packages (CSP) - an example from well 44/19-3

The INPEFA frequency curve of well 44/19-3 (figure 2.11) shows large-scale negative as well as positive trends. Generally, a negative or progradational trend is related to a sand-prone interval, while a positive or retrogradational trend shows a shale-prone interval. An important aspect of the INPEFA curve is the presence of "kinks" indicating a sudden change to a negative or positive trend. These "kinks" are related to frequency breaks which can also be seen in the MESA displays. These *Frequency Break Points* (FBP) represent geologically a change in basin conditions and/or depositional patterns. A hierarchical pattern of FBP's can be observed (red dots in Figure).

The major negative FBP's (at the base of resp. Westphalian A, B and C), i.e. the pronounced change from a positive to a negative INPEFA trend, can mostly be noticed immediately (red dots in Figure). The major positive FBP's are equally easy to recognise and represent the main flooding surfaces or *Transgressive Boundary Surfaces* (TBS). These surfaces indicate the onset of a fine-grained interval, mostly with numerous coal-bearing layers.

The major FBP surfaces represent the boundaries of the *Composite Stratigraphic Packages* (CSP). CSP500 for instance, represent lithostratigraphically the Caister and Maurits Fms. In sequence stratigraphic terms, it represents a complete cycle. The presence of higher resolution cycles can clearly be observed.

2.2.4.2 The relationship between CSP cycles, higher-order cycles and lithofacies development

The hierarchical organisation of the cycles (see figure 2.12) is in agreement with the MESA pattern of the spectral bands. CSP's mostly are build-up by different cycles from different hierarchical orders. The hierarchical pattern and cycle development can be interpreted in terms of climatic changes and related lithofacies variability:

The hierarchical order of cycles can also be seen in the hierarchical development of lithofacies. The CSP cycle consists of a lower sand-prone interval and an upper more shale-prone interval. The higher-order cycle shows the same pattern. Cycle #5 will have more fine-grained sediments or matrix as compared to cycle #4. This is caused by the large-scale climatic trend of the lower order CSP cycle which approaches the stage of a flooding period.

Another important aspect in evaluating the cycles is their Symmetry Pattern (SYP). Cycles can have a full development, i.e. no important truncations occurred during their formation. Formation of these ***complete cycles*** occurred when basin accommodation increase was in balance with the sediment input. Truncated or ***incomplete cycles*** are usually missing their upper part. Low basin accommodation increase and a relatively high sediment input caused a erosional down-cutting of the subsequent depositional cycle.

The SYP gives information whether a cycle is dominated by a lower sand-prone or an upper shale-prone interval. A negative SYP indicates that the period of a slow increase of accommodation during a falling sea or base level was extended and a more extensive sand deposition occurred. A positive SYP indicates that the transgressive stage was extended and a more shale-prone deposition occurred. Forced sediment input may indicate a more proximal or distal point of deposition in the basin.

2.2.4.3 Geological and cyclostratigraphic interpretation of the INPEFA frequency curve - an example from well 44/29-1a

The INPEFA frequency curve of well 44/29-1A shows a well developed cycle hierarchy pattern (figure 2.13) for the Westphalian-B interval. Basin accommodation development and sediment supply patterns allowed the development of distinct depositional trends and the recognition of a relatively clear stratigraphic subdivision.

The main features can be summarised as follows:

1. A main event (EVENT-1) at W500 can clearly be recognised as the onset of a period of major sand deposition in the basin. This boundary can generally be recognised in the whole study area. We believe that this important geological event coincides with the beginning of the sand deposition of the Westphalian B.

2. Two more events (EVENT-2 and EVENT-3) can be observed, indicating the onset of two periods of widespread sand deposition.

3. Each sand interval shows a predicted negative trend. In frequency terms this means that the predicted frequencies are disrupted by low GR values. In geological terms, sedimentation is controlled by an allocyclic sand-prone deposition causing a basinal sand prograding pattern.

4. The cycle hierarchy can easily be observed from the INPEFA curve. The long-term cycles consist of a sand-prone lower part and a shale-prone upper part, separated by a major flooding surface. A similar pattern can be recognised in the higher order cycles.

5. The W400 CSP generally is characterised by a positive trend, indicating an allocyclic control of a shale-prone deposition.

2.3 The Carboniferous - Upper Rotliegend boundary

Although the boundary between the Carboniferous and Permian Upper Rotliegend represents a major stratigraphic hiatus, its identification in the wells has always been a problem. This is partly caused by the absence of biostratigraphic markers and very slight changes in lithofacies. Facies differences between the Upper Carboniferous (e.g. Barren Measures) and the red-beds of the Upper Rotliegend are not very distinct and even in cores it is sometimes difficult to recognise and define the boundary. The boundary is equally difficult to recognise in the seismic pattern when no angular unconformity is present.

Frequency analysis, including MESA, PEFA and INPEFA also did not show conclusive results. In some wells, the MESA frequency patterns show a distinct break. However, this break can not be recognised in a consistent way. Frequency analysis of the available spectral logs also did not show any results.

To define the top Carboniferous or base Upper Rotliegend, a combined approach was used in this study. Available core data and dipmeter data were included in the frequency analysis. Conclusive and clear boundaries established by core and dipmeter data were integrated in the INPEFA frequency pattern. Subsequently, a characteristic INPEFA frequency pattern was defined for the Upper Rotliegend as well as the Upper Carboniferous interval. An example for such an approach was carried out in well K2-2, where good core coverage was available within the relevant interval.

2.3.1 Top Carboniferous / base Upper Rotliegend in well K2-2

The analysis procedures and results (see figure 2.14) can be summarised as follows:

1. The base Upper Rotliegend was defined from core data and was put at the base of a thin conglomeratic interval. The underlying paleosol interval probably represents the major hiatus surface and a subaerial hardground.

2. The INPEFA frequency curve shows a distinct peak representing the conglomeratic interval and a "transition" pattern around the Upper Rotliegend boundary. The Rotliegend as well as the Upper Carboniferous intervals show distinct and different frequency patterns. The Upper Rotliegend frequency pattern generally shows a high-frequency character, while the Upper Carboniferous shows a more blocky low frequency pattern.

3. The "transition" interval in the INPEFA curve is more pronounced when coarse siliciclastic sediments are present at the base of the Upper Rotliegend. These sediments are interpreted as eroded or reworked Upper Carboniferous.

2.3.2 Definition of top Carboniferous from INPEFA frequency characteristics - an example from well K3-1

The INPEFA frequency curve can be used for defining the Carboniferous-Permian Rotliegend boundary after establishing the exact position of this boundary in cores (e.g. in well K2-2). The specific frequency pattern in well K2-2 can then be used for other wells if similar patterns can be recognised.
The adjacent well K3-1 shows a more or less similar frequency pattern. The conglomeratic interval is not present here, but the INPEFA still shows a negative peak indicating the time-correlative position of the conglomeratic interval in well K2-2. The "transition" zone shows a similar INPEFA pattern as in well K2-2, indicating similar depositional conditions. See also figure 2.15.

2.3.3 Major sand development at the Carboniferous-Upper Rotliegend boundary - well 49/5-2.

The top Carboniferous in well 49/5-2 has been established by correlation of the INPEFA frequency curves of adjacent wells. The characteristic frequency pattern for the Rotliegend is well developed above the deepest major sand interval. The Upper Carboniferous INPEFA frequencies can not only be recognised below this sand interval, but also extent until the top of the last sand interval.
Adjacent wells (e.g. J3-2 and K1-3) show similar patterns. However, detailed comparison with the INPEFA patterns of the uppermost Carboniferous sand intervals of other wells shows important differences (see in the correlation panels the INPEFA frequency development of W600 and W700 sands). Based on these observations, the base of the Rotliegend interval was defined at the base of this deepest major sand interval. See also figure 2.16.

2.3.4 Upper Carboniferous-Upper Rotliegend boundary in well 44/19-3

The boundary between the Upper Carboniferous and Upper Rotliegend in well 44/19-3 is characterised by a thin "transition" zone. The typical Upper Rotliegend INPEFA frequency patterns are practically directly above the low frequency INPEFA pattern of the Upper Carboniferous. see also figure 2.17.

2.3.5 Some preliminary conclusions concerning the Carboniferous-Upper Rotliegend boundary

The features characterising the boundary between the Upper Carboniferous and Upper Rotliegend can be summarised as follows:

1. The appearance of the boundary in the study area is not uniform. In some wells a thick "transition" interval is marking the transition from the Upper Carboniferous to the Permian Rotliegend interval. This fact is an important aspect for the difficulty in recognising the Carboniferous-Upper Rotliegend boundary.

2. The occurrence of a "transition" zone in some wells indicates that the basin topography towards the end of the Carboniferous showed more relief in certain

parts of the basin. These features produced local siliciclastic deposition in the adjacent depressions. The “flat” areas of the basin are characterised by thin or no “transition” zones. INPEFA frequency characteristics of the Upper Carboniferous and Upper Rotliegend are then superimposed on each other.

3. The “transition” probably represent local depositional systems, such as scree deposits or small alluvial fans.

4. Frequency analysis as a stand-alone tool for defining the Carboniferous-Upper Rotliegend boundary can not be used. Integration with core data and dipmeter data is essential for defining the exact position of the boundary.

5. A possible additional way for defining this boundary is a frequency analysis of spectral logs and log ratios.

2.4 Cyclostratigraphic patterns and correlations

Correlation of wells was carried out by using the INPEFA curve of the GR logs. GR logs are essentially being used as a “shale log” in siliciclastic sequences for discriminating shales from sand intervals. Low GR values are mostly related to sand intervals, while high GR values are indicators for shale. Consequently, the INPEFA frequency curves show a decreasing trend for sand and an increasing trend for shale. INPEFA frequency curves are therefore useful and support the correlation of sand-shale cycles or important sand intervals. INPEFA frequency curves of GR logs also display depositional trends in relation to accommodation changes. These trends are additional criteria which may be useful in well-to-well correlations

2.4.1 Constraints in INPEFA interpretations and correlations

INPEFA generates a machine-objective frequency analysis. Well-to-well correlations have to be carried out by using at the same time the full integration of other stratigraphic and sedimentological tools and concepts. CycloLog frequency analysis as a stand-alone tool should be used with care and several constraints should be considered. The constraints of CycloLog frequency analysis and specifically INPEFA consist mainly of two aspects:

1. The quality of the original logging data
2. INPEFA anomalies

The quality of the original logging data :

Measurement errors and data gaps will influence the frequency analyses in an important way. Severe distortions of the INPEFA frequency curves may occur and if this is not taken into account, serious wrong interpretations and correlations will take place. In this study, several wells contained errors in the logging data which seriously affected the frequency analyses. Some of the data errors were corrected manually, but interpretation and correlation should be carried out with great care.

INPEFA anomalies :
Anomalies in the INPEFA frequency curve may be caused by the occurrence of specific minerals which generate high GR values (e.g. mica, uranium minerals, etc.). Another aspect is a very high net accumulation rate of sand within a relatively short time span (e.g. turbidites, episodic flood deposits, etc.).
Most of the INPEFA correlations are carried out by correlating the important Frequency Break Points (FBP) and/or maximum floodings. Subsequently, the negative INPEFA trends or progradational patterns are correlated. Each large-scale cyclic CSP in the Upper Carboniferous consists of a progradational interval, followed by a retrogradational succession. For instance, the Westphalian B, C and D all consist of one large-scale CSP cycle. By correlating wells which are separated by a long distance, a wrong correlation may occur by connecting a cycle from for example the Westphalian B with the cycle belonging to Westphalian C. In this case additional stratigraphic data or seismic interpretation data is needed for calibration.
Furthermore, correlation of INPEFA frequency curves still consists of a visual comparison of patterns and may produce errors.

2.4.2 Composite stratigraphic package (CSP) cycles and boundary hierarchy

CycloLog frequency analysis displays the hierarchical pattern of cycles. All the derivatives of the frequency analysis such as PEFA and INPEFA will also show this hierarchical pattern. Each cycle can be differentiated into a lower, more sand-prone interval, and an upper, more shale-prone interval. These two parts are separated by a flooding surface. In sequence stratigraphic terms, these cycles can be subdivided into a lower "lowstand" and an upper "transgressive" part.
The major low order cycles are generally bounded by major FBP or major knickpoints in the INPEFA curve. The higher order cycles on the other hand are bounded by minor FBP's. Each well has been analysed according to this concept and each specific boundary has been defined and allocated to a specific cycle hierarchical dimension. (See figure 2.18)

2.4.3 Cyclostratigraphic boundaries and their relationship to regional geological events

Based on the CSP cycle hierarchical framework discussed earlier, main and secondary boundaries were defined (see figure 2.19). Based on general biostratigraphic data from the earlier Carboniferous study, a tentative relationship was established with the biochronostratigraphy.

The Upper Carboniferous (as far as it has been penetrated by the wells) consists of 4 main CSP cycles in the Netherlands Offshore and 5 main CSP cycles in the UK Offshore. The W400 probably belongs to the Westyphalian A. The W500 has a uncertain biochronostratigraphic position. In frequency or in sequence stratigraphic terms, the W500 boundary mostly shows a distinct break in the INPEFA curve, indicating a major change in sediment supply and basin accommodation. The W500 boundary is the onset of important sand deposition in the Netherlands as well as in the UK Offshore.

Another important boundary is the W520. Important sand deposition occurred especially in the Dutch area.

The W600 and W700 boundaries always coincide with important sand intervals. An interesting feature can be observed in some of the wells in the UK area, where another CSP cycle can be recognised (W800).

Three important flooding events can be recognised. The most important flooding is the W520tbs which coincides with the base of the Maurits Formation.

2.4.4 Summary discussion of the correlations and their implication to sedimentary facies and basin development

Not all available wells were used in the correlations. Some wells were not completely analysed because of their limited penetration of the Upper Carboniferous (wells E14-1, E16-1, and E17-1). One well contained a large section of errors in the logging data and was temporarily excluded (UK well 44/28-3).

Correlation of 44/19-3, 44/24-2, D15-4, E16-3, E17-2 and K2-1 (enclosure 2-1) :

TD POSITION OF THE WELLS

Wells 44/19-3, 44/24-2 and E16-3 show a complete succession with TD in W400 (Westphalian A). The wells D15-4 and E17-2 reached into W514 (Westphalian B), while well K2-1 has the shallowest penetration with TD in W522 (Westphalian B or Maurits Fm).

W400 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

Correlation of W400 of the wells 44/19-3, 44/24-2 and E16-3 is not very obvious. INPEFA patterns are differing in an important way. The most clear criteria used in the correlation are two more or less distinct FU trends in the INPEFA (see 44/24-2). Lithofacies development follows clearly sequence stratigraphic trends, two sand intervals and two transgressive coal-bearing intervals.

W500 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The W500 boundary shows a distinct break in the INPEFA curve, separating the lower FU trend from the upper CU and more sand-prone trend. Well 44/24-2 shows a less distinct FU trend, but a more vertical aggradational trend. Three higher order CSP cycles can be determined, each of them showing a sand-prone lower part and a shale-prone coal-bearing upper part. An increasing number of coal-bearing layers are appearing in W501 and W502.

W510 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The W510 boundary is not very well defined in this correlation. Generally, this boundary indicates the onset of a renewed and larger sand influx, and a more pronounced CU trend (see well 44/19-3). This trend is less clear in well 44/24-2.

Five higher order cycles were defined, of which W513 and W514 are the most important. W513 indicates an important sand development and when accommodation increase was sufficiently high, higher order CSP cycles can be recognised (see well 44/19-3). In well 44/19-3 a decrease in thickness of the sand intervals of the three higher order cycles (W513a, W513b and W513c) can be observed. In addition, sand porosity patterns are also decreasing, indicating an increase of matrix infilling of the pores in W513b and W513c.
If basin accommodation increase is low, a stacking of the W513 and W514 may occur (see wells D15-4 and E17-2).
An important flooding event is the W510tbs surface which is the onset of a transgressive coal-bearing interval. The W510tbs flooding interval is considered as the transgressive systems tract of the CSP W510 cycle.

W520 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The W520 is a sand-prone interval and its boundary is clearly indicated by the important break in the INPEFA curve and the subsequent sand "bulge". A two-fold subdivision into W520 and W521 can be made. Depending on the increase of accommodation, a close or more wide stacking of the two sand-prone intervals may occur.
An important flooding event is indicated by the W520tbs surface. The W520tbs interval is interpreted as the transgressive systems tract of CSP cycle W520 and coincides with the Maurits Fm. The whole interval is subdivided into two higher order cycles (W522 and W523). An interesting feature is the occurrence of the coal layers. Wells 44/19-3, 44/24-2 in the UK and K2-1 in the Dutch area have a low number of coal layers, while wells D15-4, E16-3 and E17-2 have a high number of coal layers. Development of coal is related to the position in the basin in relation to groundwater.

W600 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The W600 boundary is generally marked by a pronounced break in the INPEFA. Only three wells contain the W600 succession (wells 44/19-3, D15-4, E17-2 and K2-1). The most complete development of W600 is in K2-1 where the 4 higher order cycles are present. The W602 and W603 boundaries probably represent important geological events in terms of basin dynamics and sand development. Furthermore, the W603 may develop a thicker transgressive shale-prone interval if basin accommodation allows it.

W700 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

Only the wells E17-2 and K2-1 contain the W700 succession. It is more sand-prone in well K2-1. Another important feature is the pronounced flooding surface (W700tbs) and subsequent transgressive shale-prone interval.

Correlation of wells 44/19-3, D12-4, D12-3, D15-3, D15-2 and D15-4 (enclosure 2-2)

TD POSITION OF THE WELLS

TD of wells 44/19-3, D12-3 and D15-3 is in W400 (Westphalian A). TD of the remaining wells is in W510 (Westphalian B). This correlation line shows the relationship between the adjacent UK area with high subsidence rates and the "high" of the D-Quadrant.

W400 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

Correlation of W400 of the wells 44/19-3, D12-3 and D15-3 has a low reliability. INPEFA patterns are differing in an important way. The two more or less distinct FU trends in the INPEFA are clearly present in wells D12-3 and D15-3. Lithofacies development is similar as discussed earlier (see Enclosure 2-1).

W500 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

A distinct break in the INPEFA curve marks the W500 boundary in well D12-3. In the adjacent well D15-3, this boundary is less clear, but its sand-prone succession is comparable with all the wells in this correlation. Correlation of the three-higher order cycles is supported by the similar frequency patterns.

W510 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The W510 boundary is clearly marked by the INPEFA curves in the wells D12-3, D15-3 and D15-2. Correlation with the W510 boundary in well 44/19-3 is less clear and is probably masked by the high subsidence rate. The correlation of the higher order cycles is also clearly supported by the similar INPEFA frequency patterns. Note that the W510tbs flooding interval wedges out towards the higher parts of the D-Quadrant. This is caused by the onlap towards the D-Quadrant high and the subsequent erosion, enhanced by a low increase of basin accommodation.

W520 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The W520 boundary represents another rejuvenation of the basin and increase of sand input. The break in the INPEFA curve is clearly displayed in all the wells and can be correlated. A problem is the W520 in well D12-4, which show an abnormal thickness. In correlation it is difficult to shift the W520 boundary upwards. Another explanation for this abnormal thickness is probably faulting.

The flooding surface at W520tbs is clearly developed in all wells. However, its exact position is not always easy to determine. In principle the boundary has been drawn at the first main knickpoint of the INPEFA curve. The sequence is generally followed by a shale-prone, coal free succession. Sometimes a thin sand layer may occur within this interval (see well D12-4).

The coal-bearing layers may appear within certain intervals (see well D15-2). This may be controlled by groundwater fluctuations or basin topography changes.

W600 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

See correlation explanation of Enclosure 2-1.

Correlation of 49/5-2, J3-2, K1-3, K1-2, K5-2 and K5-1 (enclosure 2-3)

TD POSITION OF THE WELLS

TD of wells 49/5-2, J3-2 and K1-2 is in W400 (Westphalian A). TD of the wells K1-3 and K5-2 is in W500 (Westphalian B), while well K5-1 penetrated until W522 (Maurits Fm). This correlation line shows the relationship between the adjacent UK area with the J and K Quadrants. The line coincides with the random seismic line displayed as enclosure 3.1

W400 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

No correlation of the W400 was carried out in this correlation line.

W500 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The W500 boundary marks a change in INPEFA patterns in the wells J3-2 and K1-2. It shows very clearly the onset of the more-sand-prone sequence as discussed earlier. The W500 boundary in well K5-2 was probably not reached, while in 49/5-2 it is missing. The missing W500 interval in 49/5-2 was established by correlating the adjacent wells in the UK sector (see explanation of Enclosure 2-8).

W510 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The W510 boundary is clearly seen in the INPEFA curve of K5-2, K1-2 and in a slightly lesser degree in K1-3. It indicates the onset of a renewed sand influx into the basin, probably controlled by basin dynamics and change of climate. The

W510 is very well developed and relatively thick in all the wells within this correlation line. The higher order cycles are especially well developed in K1-2, showing the two-fold subdivision of each cycle pattern. Despite the good preservation of the higher order cycles which was related to a high subsidence rate relative to sediment accumulation, the sand development of W510 is rather low. In J3-2 the W510 was truncated by the Rotliegend unconformity.
The W510tbs flooding interval shows an increase in thickness towards K5-2.

W520 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

Because of the Rotliegend truncation, the W520 is only present in K1-2 and K5-2. The W520 in 49/5-2 is questionable. Well K5-1 did not reach the base of the W520 interval. Sand development was very limited, only K5-2 shows a relatively well developed sand interval. A problem in the correlation of the W520 interval between K1-2 and K5-2 was caused by the similar sand development of W514 in K1-2.
The W520tbs flooding surface is well developed in K1-2 and K5-2.

Correlation of J3-2, K1-2, K2-1, K2-2, K3-1 and K3-2 (enclosure 2-4)

TD POSITION OF THE WELLS

TD of J3-2, K1-2 and K3-2 is in W400 (Westphalian A). TD of K2-2 and K3-1 is in W510 (Westphalian B), while well K2-1 penetrated until W522 (Maurits Fm). This correlation line shows a two-fold division of the basin in the J and K-Quadrants. The J3 and K1 blocks shows the preservation of the W500 sequence, while the K2 and K3 blocks also contains younger Upper Carboniferous, i.e. W600 and W700 successions.

W500 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The wells J3-2 and K1-2 contain the W500 succession. See explanation of Enclosure 2-3.

W510 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

As mentioned before, the W510 boundary is indicating a pronounced change in the INPEFA pattern of J3-2, K1-2 and K3-2. A thinner and more sand-prone development can be observed in K3-2.
The W510tbs flooding interval seems to be laterally consistent in thickness.

W520 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

For the correlation of W520 of J3-2 and K1-2, see explanations to Enclosure 2-3. INPEFA patterns enable the correlation of W520 between K2-2, K3-1 and K3-2.

The separation of W520 from W521 with a shale-prone interval is large in K3-2, indicating a larger increase in basin accommodation

W600 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

As mentioned earlier, the W600 has its most complete development in K2-1. Laterally, it wedges out towards K2-2 and K3-1, where successively younger units are appearing. This is caused by a decrease in basin accommodation which probably produced successive erosional stages during deposition of W602 and W603. Important basinal and climatic events probably controlled the development of W602 and W603.

W700 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

An important INPEFA break is marking the W700 boundary in K2-1. The W700 boundaries in K2-2 and K3-1 were mainly based on the similar frequency patterns as displayed in K2-1.

Correlation of 49/5-2, J3-2, K4-7, K5-A1, K5-D1, and K5-1 (enclosure 2-5)

TD POSITION OF THE WELLS

TD of 49/5-2, J3-2, K5-A1 and K5-D1 is in W400 (Westphalian A). Wells K4-7 and K5-1 penetrated until the W520 (Westphalian B).
This correlation line shows again a two-fold division of the basin in the J-Quadrant and adjacent UK area, and the southern part of the K-Quadrant.

W500 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The correlation of W500 between K5-A1 and K5-D1 based on the INPEFA patterns is difficult. This is caused by the different sand development and basin subsidence patterns of the two wells. The boundary of W500 however, can be recognised relatively easy. It separates the FU trend from the more CU trend in the W500.

W510 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The boundary of W510 in K5-A1 and K5-D1 show a similar break in the INPEFA curve. An aggradational frequency pattern characterises the W510 in both wells and also shows a similar cycle pattern.

W520 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The W520 at the base of K4-7 is uncertain. It has been defined on the basis of the W520tbs surface and the characteristic frequency trend within the subsequent interval.

Correlation of 44/19-3, D12-3, D15-3, E10-2, E17-2, and E18-3 (enclosure 2-6)

TD POSITION OF THE WELLS

TD of 44/19-3, D12-3, D15-3 and E10-2 is in W400 (Westphalian A). Wells E17-2 and E18-3 penetrated until the W510 (Westphalian B).
This correlation line shows the connection between the high subsidence area in the UK, across the D-Quadrant high to the high subsidence area of the E18 blocks.
For the correlations of 44/19-3, D12-3 and D15-3 see explanations to Enclosure 2-2.

W500 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The W500 boundary shows a change of the INPEFA pattern in E10-2. The subsequent subdivision into three higher order cycles is also clearly displayed. However, correlations to the adjacent wells (i.e. D15-3, D12-3 and 44/19-3) pose some problems. This is mainly caused by the different sand development in the wells. By defining the W510 boundary and by closely comparing the frequency patterns, a correlation can be established. Basin subsidence rates of the E10-2, D15-3, and D12-3 are comparable and no big differences are present.

W510 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The W510 boundary in E10-2 can be correlated to the D-Quadrant, indicating a new influx of sand. The W510 in E10-2 is slightly thicker as in the D-Quadrant, indicating a higher subsidence rate. This is also supported by the occurrence of more shale-prone intervals. E17-2 shows again more sand, while E18-3 contains more shale.

W520 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The distinct sand “bulge” displayed in the INPEFA of E10-2, E17-2 and E18-3 can be correlated without any problems. The well developed flooding surface of W520tbs also shows distinct and similar features in all the three wells. The W520tbs interval (including W522 and W523) seems to be slightly thicker in E18-3. This indicates a progressive higher subsidence rate towards the east, i.e. from E10-2 to E17-2 and E18-3.

W600 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

The above-mentioned higher subsidence rate towards the east was probably responsible for the accommodation of W600 and W700 in E17-2 and E18-3. The distinct break in the INPEFA pattern in E17-2 and E18-3 are comparable. Note the extensive flooding interval of W603 in E18-3.

W700 CORRELATION AND INTERPRETED LITHOFACIES DEVELOPMENT

Correlation of the W700 between E17-2 and E18-3 shows a more complete succession in E17-2. A more important boundary (controlled by basin tectonics ?) seems to be the W701. Note the large-scale FU trend, which has its maximum in the W702 flooding interval.

Correlation of E16-3, E17-2, E18-3, K3-1, K2-2, and K5-2 (enclosure 2-7)

Explanations to the correlation of the wells are summarised in the notes for the Enclosure 2-1, Enclosure 2-4 and Enclosure 2-6.

GENERAL EXPLANATIONS TO THE CORRELATIONS

The correlation of the different CSP's show a "layer cake" geometry. Thickness differences are becoming more pronounced in the W600 and W700. It is obvious that the area between E17-2, E18-3, K3-1 and K2-2 had higher subsidence rates during the deposition of W520 and W600. The preservation of W600 and W700 is probably related to the magnitude of the Rotliegend erosion. Considering the similar thickness of W520 in E16-3 as compared to the other wells, it can be assumed that the W600 and probably the W700 was also deposited in E16-3. Later tectonic movements placed this block at a higher position and the subsequent Rotliegend erosion removed the whole sequence.

Correlation of 44/19-3, 44/24-2, 44/29-1A, 49/4-2A, 49/4-3, and 49/5-2 (enclosure 2-8)

The N-S correlation of UK wells in the adjacent area of the Dutch sector was constructed for evaluating the relationship between the stratigraphic basin fill of the two area.

GENERAL EXPLANATIONS TO THE CORRELATIONS

The correlation shows a distinct trend of an area of high subsidence in the north and a "high" in 49/4-3 and 49/5-2. This high is related to a larger structure which includes the J3 block and the area the around K1-3. Despite the differences in subsidence history, the correlations show a "layer cake" geometry. Correlations of the main CSP cycles did not pose any problem. However, linking the higher order cycles posed a number of problems. The determination of the W510 boundary in 49/4-3 and 49/5-2 posed some problems because of the missing frequency character of the W500 in these wells.

achter table 2.6

3 Seismic interpretation and mapping of the area

3.1 Introduction

For interpretation of the 3D data Charisma (version 3.8.3) workstation software of Geoquest-Schlumberger has been used. Gamma Ray, Sonic, and Denisty logcurves as well as deviation trajectories were loaded into Charisma module “Synthetics”, in order to construct an accurate depth-time relation in the wells, and be able to display the logs on the seismic section in time-domain. As the results of the cyclostratigraphic analysis became available, also the INPEFA curves for the Carboniferous sections of the wells within the 3D area have been imported into the database. The stratigraphic interpretation of the geology younger than Carboniferous has been checked and revisited where needed, and subsequently been imported as markers into Charisma’s database too. Seismic interpretations from previous projects were taken as a start where available.

3.2 Database used

A large database consisting of nine 3D seismic surveys, older time-interpretations of 2D seismic lines, and well data from about 50 Dutch wells and 13 UK wells has been used for the study. None of the 3D surveys have been released yet, as they are younger than 10 years. The 2D lines are older than 10 years, and are therefore available for release. Figure 1.1 shows which of the wells which have been used for the intra-Carboniferous correlations are released at this moment (July 1997).

3.2.1 Wells

To aid the seismic interpretation all of the wells present within the area of the 3D seismic coverage have been used. This means more wells than the ones listed in fig 2.3. Also the wells which penetrated no Carboniferous, or just a small section, have been used for correlation of the overburden and for velocity modelling.

3.2.2 Seismic surveys

Nine different time-migrated 3D seismic surveys have been used for the seismic interpretation study. They are listed below. Figure 1.1 shows their coverage, and the operator and year of acquisition. These surveys have all been acquired in the 1990’s, and can at the moment of the study been regarded as the best data available. It should be noted that two older 3D surveys both from 1988 (one across block J6 and the Markham field, and the other across block K6) have not been used. The reasons for this limitation is the lower data-quality within the Carboniferous, and the limited amount of time for this study. Future 3D surveys are announced by different operators covering blocks E10 north, E14 and E16. As the industry is putting more and more effort into exploration of the area, also reprocessing (e.g. Pre-Stack Depth Migration) of the existing surveys in order to achieve more detail, can be expected in the near future.

Operator	*Year*	*Covering blocks*
Elf/Petroland	1990	K4, K5
NAM	1991	D12south, D15, D18north
NAM	1992	J3, K1, K2, K3west
NAM	1993	E16east, E17
Elf/Petroland	1993	J6, K4
FINA(UK)	1994	44/29b
Wintershall	1994	D12north
Wintershall	1994	E13north
Elf/Petroland	1995	E10south

All of these 3D surveys are of good quality, and processed to zero-phase. The nine surveys listed above together cover an area of about 5000 km^2 (the overlaps excluded). At the moment no other company or organisation has access to a similar large compilation of 3D data sets. The Netherlands Institute of Applied Geoscience is in a unique position to produce and analyse regional maps based on 3D data with a high amount of detail.

To complete the important map of top Carboniferous in areas where no 3D surveys exist, but an older interpretation of 2D seismic lines is available, those time interpretations have been used. They have undergone a new time-to-depth conversion using the same regional velocity models as for the 3D data, but they have not been re-interpreted. Data quality within the Carboniferous is not considered high enough to expect reliable correlation of events across faultblocks. Most of these 2D lines are of the large regional GSI non-exclusive survey N86.

For the time consuming intra-Carboniferous seismic interpretation the two southernmost 3D surveys (in blocks K4 and K5) have not been used, partly because of a lack of time, but also because this southern margin of the study area belongs more to the Rotliegend fairway, and Carboniferous reservoirs are only secondary targets.

3.3 Correlation with wells and horizon picking

3.3.1 Overburden

Because of its location on a tectonic platform, the "overburden" (i.e. the sedimentary succession above the zone of interest) of the Carboniferous in the CBH area is characterised by a relatively small amount of structural deformation, and therefore not too difficult to interpret on 3D seismic surveys. This is particularly true for the Mesozoic and Tertiary deposits. The Permian horizons (especially base Zechstein) take some more time to interpret, because of the higher degree of faulting, and also locally because of the lower data quality underneath Zechstein salt-accumulations. Because of their significance as regional seismic velocity contrasts, the following horizons are necessary to interpret throughout the survey in order to perform a layered cake time-to-depth conversion on the Carboniferous horizons :

Base North Sea group	(= base Tertiary)
Base Chalk group	(= base Upper Cretaceous)
Base Rijnland group	(= base Lower Cretaceous)
Base Zechstein Upper Claystone	(= top Zechstein evaporites)
Base Zechstein group	(= top Rotliegend)

The first three horizons and the Base Zechstein horizon are followed throughout the entire area, but the fourth is locally not interpreted, where the Triassic rocks are missing (large part of the K-blocks). In that case the Base Rijnland horizon can be regarded as being the top of the Zechstein evaporites. Correlation of the stratigraphic interpretation of these levels with the seismic reflectors posed no problems. Base North Sea and Base Rijnland are picked in a trough, and the other three events in a peak. All of these five events could be autotracked with the Charisma ASAP autotracker, after sufficient initial manual input.

3.3.2 Carboniferous

At the beginning of the project it was decided not to interpret the top of the Carboniferous as a seismic horizon. Given the fact that this important stratigraphic horizon only locally shows a clear seismic expression (either a good reflector or a significant angular unconformity), and that in large areas the manual interpretation was going to be very time-consuming, the benefits of manual interpretation were expected to be marginal. Instead a regional isopach grid based on the values from 88 wells (figure 3.6) was constructed and added to the depth-grid of the base of the Zechstein. It should be noted that for the purpose of this study, and the construction of maps at a scale of 1 : 100.000 this approach is good enough, but that in case of later field evaluations this approach results in a later shift of the fault traces on the grids and maps which maybe too large.

During RGD's study of 1994-1995, in which the 3D survey across D12,D15 and D18 was used, it was found that the most striking event within the Upper Carboniferous sequence is the base of the Maurits formation. This lithostratigraphic marker coincided with a sequence stratigraphic marker in that study called WB-2. At the time three wells in D15 and well D12-3 were available within the area of the seismic study. The sequence and cyclostratigraphic analysis decribed in chapter 2 of the current study, again identified this level as an important marker. It has now been given the name W520tbs. Tables 2.1 - 2.3 show the final interpretation of this level in all the wells. For the seismic interpretation it was decided to try and follow this marker through as much of the 3D area as possible.

For correlation of this marker, which is defined on the well logs, with the seismic lines across the wells, synthetic seismograms were constructed using Charisma module “Synthetics”. Figures 3.1 and 3.2 show the results for wells D12-3 and D15-3 respectively. The INPEFA curve of the Gamma Ray, which is an important tool for the stratigraphic correlation (chapter 2) has also been imported into the database of the Charisma project. In this way this curve can be plotted on top of the seismic data at each well. This has been done in the profiles of enclosures 3.1 and 3.2. It can be verified that indeed the remarkable knick-point in the INPEFA curve at the position of marker W520tbs (as defined in chapter 2) corresponds to a clear seismic event.

In the northern part of the area (i.e. D-blocks and vicinity) the seismic data contains a very characteristic doublet of two high amplitude troughs (blue in the figures of this report) at the level of W520tbs (see figures 3.1, 3.2, 3.3 and enclosures 3.1 and 3.2). After analysis of the synthetics of many of the wells, we have decided that the lower of these two troughs best fits most of the positions of the W520tbs marker in the wells. In those wells where it does not exactly fit this correlation (like D15-3) the marker usually plots a little higher near the separating red peak. See also figure 3.4, a line across E13-1 and E13-2, where W520tbs seems to be interpreted a little too low compared to the well marker. This misfit usually is small however. In a large portion of the 3D seismic data the W520tbs marker thus defined and interpreted is the lower boundary of the *high frequency / high amplitude / high continuity* seismic facies described in literature (e.g. Tantow, M.S. 1992). This seismic facies is thought to result from the “ringy” behaviour of the seismic signal. The very high acoustic impedance contrasts at the interfaces bounding the thin coalbeds cause short-path multiples, which -because of the small time-delay- interfere positively with the primary reflection.

In the area of D12/D15 the W520tbs is also known to coincide with the top of the Caister-equivalent sandstones of early Westphalian B age (see figure 3.3). Sometimes (as in D15-south and D18) also the top of the *high frequency / high amplitude / high continuity* seismic facies band is a characteristic reflector, which can be followed across a larger area (see enclosure 3.2). It turns out to coincide with the sequence boundary W600 at the wells.

Some of the other markers listed in tables 2.1 - 2.3 have been used locally as guiding reflectors, but for the larger part of the study area the efforts have been focused on accurately mapping the event W520tbs.

It should be noted that further to the south (J and K-blocks) the distinct seismic facies described above is less obvious, and also the characteristic doublet is no longer present. In the J and K-blocks the zone with the specific *high frequency / high amplitude / high continuity* seismic facies seems to be not restricted to just the Lower Westphalian B as in the D-blocks.

The seismic facies of the units younger than W600 can be characterised as very transparent, making seismic interpretation rather difficult. For evaluations of fields with reservoirs in those units, it will probably -for the time being- be inevitable to map either W600 or W520tbs and then subtract an isopach, in order to delineate the younger reservoir units.

3.4 Time-to-depth conversion

It was decided to use a consistent regional “layered cake” velocity model, based on all the available well information, for the whole region. The alternative approach would have been to model the velocities independently in each of the 9 surveys, and possibly achieve smaller depth-errors locally. The advantage of the chosen approach, however, is the higher regional consistency.

Modelling velocities for the Tertiary, Lower Cretaceous and Triassic posed no problems. Linear trends well fitted the well-data.

The Chalk velocities show a much more complex situation. Using the VELIT software a reasonable choice for a k-factor can be made. We have arrived at k=1.33. The V_0 then had to be calculated for each well, and subsequently gridded and contoured. The result is shown in figure 3.5. A further analyses of the stacking velocities of the survey over J3,K1,K2 and K3 has shown that this approach results in depth errors of about 10-20 m (compared to calibrated stacking velocity modelling) over most of the area, with an exception for the large depression in K2. Locally the depth errors over there could become as high as about 100m, because no wells have sampled this area.

For the Zechstein the cumulative thickness method has been chosen, with a Z_{COR} term to correct for the high velocity anhydrite beds.

To summarise, the following velocity model has been used :

Layer	*Function*
Tertairy	$v = 1699 + 0.36\ z$
Chalk	$v = Vo(grid) + 1.33\ z$
Lower Cretaceous	$v = 1541 + 0.78\ z$
Triassic	$v = 2053 + 0.74\ z$
Zechstein	$z = 4458\ t + 18.3$

Because a Rotliegend isopach grid was used, no Rotliegend velocity needed to be modelled to make a top Carboniferous depthmap. In order to handle the deeper intra-Carboniferous grids, however, a base Rotliegend time-grid had to be made, and therefore a velocity model was needed. A constant interval velocity of 4350 m/s was chosen for the Rotliegend.

For the Carboniferous section above W520tbs a constant interval velocity of 4100 m/s has been used.

3.5 Mapping and contouring

All of the 3D surveys have been gridded with all grid-nodes at multiples of 100 m (for both directions) in the UTM3 coordinate system. This made it possible to merge and subtract grids. Subtraction was done to look at the vertical time-shift between surveys in the area of their overlap. After removal of these shifts (maximum 6 ms) regional time grids were made for each horizon. For the horizons higher than base Zechstein the gridcell size was 100 x 100 meters. For the deeper horizons this size was 50 x 50 meters, because of the higher structural complexity.

The time grids are stored in a database, and are available for future studies. Locally more precise time-to-depth conversions can then be made.

Figure 3.7 and enclosure 3.3 show the resulting depthmap of the top Carboniferous. It should be noted that the relief, especially in the north, of the structures is relatively low. This means that a small error in depth can make a big difference regarding the closure of structures. In enclosure 3.3 the closing contours of the high structures, or the gas-water-contact contours in known fields, have been plotted as black lines on top of the colour-coded contourmap. The same outlines of the structures have been plotted in figure 5.1.

Figure 3.8 and enclosure 3.4 show the depthmap of W520tbs. There are some areas where data-quality was too poor to make a reliable interpretation.

Enclosure 3.5 shows the colour-coded contours of the two-way-traveltime difference between the grids of the W520tbs and base Rotliegend. This gives a so called "preserved thickness" map, showing how much Carboniferous section younger than W520tbs has been preserved by the erosion at the end of the Carboniferous. The contour interval is 25 ms. The first four pink/purple contours represent the subcrop of the W5 (or Maurits fm.), assuming that its thickness is about 100 ms. The yellow/orange means the subcrop of W600 (Westphalian C) and green and darker represents even younger sediments.

achter pag: Fig. 3.9.

4 Results

4.1 Structural geology

Careful examination of the vertical profiles, depth-maps and thickness-maps is very useful for at least two reasons. First of all structurally high features can act as traps for hydrocarbons, and secondly the structures existing at the time of deposition of the relevant Carboniferous sediments bare relevance to the thickness and distribution of potential reservoir sands. The deformation of the Carboniferous sediments is complex, and is the result of a long geologic history in which different tectonic phases affected the sediments.

4.1.1 Observations

In the Cleaverbank High area a first striking observation is the large wavelength (approximately 20 km) folding of the Westphalian sequence. The folded sedimentary sequence is faulted by straight, rather high angle fault-planes. The separation between fault-planes with a throw significantly above the seismic resolution is generally between 2 and 10 km. Four main fault trends can be recognised throughout the CBH area. (see figure 4.1)

1. NW-SE to NNW-SSE faults.
2. E-W faults
3. NE-SW faults
4. WNW-ESE faults

Throughout the region the faults seem to be quite uniformly distributed. However, looking at the distribution of the different fault-orientations, there are some differences noticeable in the area.

Comparing the intra-Carboniferous map (enclosure 3.4) with the base Rotliegend map (enclosure 3.3), the NE-SW faults are far more abundant on the intra-Carboniferous map, whereas the NW-SE faults are generally the same faults on both maps. The E-W faults are present on both maps but do generally have a larger throw at intra-Carboniferous level than at base Zechstein level. These observations are better illustrated in enclosure 3.5, which shows the “thickness” (in two-way-traveltime) between W520tbs and base Rotliegend. The thickness differences are mainly the result of the erosion by the base Permian unconformity. Apart from some erroneous thickness values close to the faults zones as a result of dipping of the fault-planes, jumps in colour, straddling a fault zone between two tectonic blocks, indicate a pre-Rotliegend fault movement.

The *NE-SW faults* are more pronounced in the northern K-blocks and southern part of E17 than in the northern part of the study area. These faults most often, but not always, have their downthrown block to the SE. The throw observed at

Westphalian B level is similar to that at lower Westphalian C level, which place their time of movement after the Early Westphalian C. For the larger part of the area, the NE-SW faults were generally only active in Westphalian to early Permian times with only locally (e.g. K5b and the western part of K3) post-Permian reactivation of some of these faults.

One of the NE-SW faults can be traced through a large part of the study area (figure 3.9). The preserved thickness of post-W520tbs Westphalian sediments varies considerably along the strike of the fault. Therefore it can be concluded that the Pre-Permian structuration continued after the activity of this NE-SW fault trend. Another indication is that the NE-SW fault trend is sometimes horizontally offset by (younger) NW-SE faults or has a slight change in strike crossing a NW-SE fault.

The *E-W faults* in the north show a normal throw to the south. From differences in vertical throw caused by changes in strike of the E-W faults can be deduced that at least some of these faults experienced a sinistral strike-slip component. (RGD study 1995). In the western part of the D-blocks the straight E-W faults, which have a significant normal throw at Westphalian levels, show a small amount of reversed throw at base Zechstein level (just above the limit of vertical seismic resolution).

The *NW-SE to NNW-SSE faults* are very complex. The length of these faults is very high compared to the throw which is the result of repeated fault reactivation with locally short N-S and E-W link-ups to accommodate oblique-slip (Oudmayer and de Jager 1993). As far as the throw on intra-Westphalian level is concerned only parts of these fault zones show a throw larger than the seismic resolution. This confirms the suggestion that in Westphalian times these faults were not as continuous as observed today. Generally these faults have a normal throw at intra-Westphalian level. Along several segments of the faults sub-Hercynian or Laramian reverse throw has exceeded the intra-Westphalian throw which results in an intra-Westphalian reverse throw. Only at very few locations there are indications for very subtle intra-Westphalian reverse faulting along NW-SE faults.

The *WNW-SSE faults* do generally not have an intra-Westphalian throw that is significantly different from the throw at Base Zechstein level. These faults are abundant in E17 and the western part of K1. At base Zechstein level these faults show a reverse throw which can be accounted to the late Cretaceous compressional phase.

There are three remarkable deep intra-Westphalian depressions in the area (Figure 3.9 green/brown colours), with an infill of a thick sequence of Westphalian C and D (and probably Stephanian) sediments.

The smallest of the three depressions (Depression 1) lies in E13 and has a rather asymmetric, half-graben like shape. Figure 4.2 shows a seismic section across this feature. The Westphalian sequence is dipping strongly in a NW direction towards a NE-SW to ENE-WSW trending normal fault . This fault terminates against a long E-W fault zone. The depression is thought to be the result of NW-SE extension along the E-W zone, resulting in a sinistral strike-slip creating a 'pull-apart' half graben along the NE-SW normal fault.

The largest and deepest of the three depressions (Depression 2) covers a large part of K2 and the southern fringe of E17. It is shown in figure 4.3. The depression has two structural axes : one running SW-NE to WSW-ENE and the other running NW-SE to NNW-SSE. The northern side of the depression is disrupted by intra-Westphalian faults. The blocks are downthrown along the NE-SW striking faults. The southern fringe is more cut by post-Permian faults. The western and the eastern side of the depression are cut by normal faults with a NW-SE to NNW-SSE strike. Because the internal reflectivity of post-Maurits Westphalian sediments is low, the timing of the faults can only roughly be put to Mid Westphalian C to Late Westphalian D or even Stephanian times.

The depression in D18 (Depression 3) has a different geometry. It consists of two lows from which the northern one is only cut by NNW-SSE striking faults. The south-eastern low is bounded to the north by a major intra-Westphalian fault.

Some tectonic elements can be identified on the map of figure 3.8 (the preserved thickness from W520tbs to Base Rotliegend). A thin preserved thickness can be recognised (pink colours). In the north the structural axis of High 1A and 1B cannot be defined , because their extension beyond the borders of the study area is not defined. There are two intra-Westphalian highs with a NW-SE structural axis (High 2 and 3). One structural high zone is trending NE-SW and is transsected by a NE-SW fault zone (High 4). This is the only NE-SW zone that has been reactivated after the Permian.

4.1.2 Westphalian to Stephanian deformation

From the observations described above some conclusions can be drawn about the deformation history. It seems that during Westphalian A to the early Westphalian C times, tectonic activity was very mild. Only at a regional scale differences in subsidence resulted in thickness changes of the low order stratigraphic sequences of the Westphalian A to C sediments.

During the late Westphalian C to Westphalian D tectonic activity increased and the region was subjected to an extensional stress regime. The normal faulting across NE-SW striking faults, which are most abundant in the southern part of the study area (J and K blocks), is a clear indication of a NW-SE extensional stress field. In the north (D12, D15, E10 and E13) also some of these faults are observed, but more often this stress was probably released by oblique slip along the older existing E-W trending faults. The oblique slip consisted of a sinistral horizontal component and a normal component which caused downthrowing of southern blocks. Locally some small half grabens were formed along the E-W zones amongst which the depression in E13 is the largest.

According to Quirk (1993) the maximum crustal stretching in the southern North Sea is believed to be oriented NNE-SSW (perpendicular to the strike of the southern Permian basin) during the late Stephanian. The observed normal intra-Westphalian throw on the dominant NW-SE faults in the area may be accounted to this later extensional phase.

Uplift, folding and erosion (resulting in the Saalian unconformity), took place before the deposition of Rotliegend sediments. Because of the rather large time hiatus it is not clear when exactly this compression and erosion occurred

The thickness distribution of preserved Westphalian (and possibly Stephanian) sediments, is an indication of high and low features at the end of the Carboniferous. The observed faulting does not fully explain this distribution. For example Depression 2 for example seems too deep to be only explained by the observed faulting. It is possible that 'hidden' strike slip zones (not penetrating the Westphalian sediments but affecting the Westphalian overburden) define the distribution of these highs and lows to a large extent. These deeper faults would not be visible on seismic sections, because the seismic data quality at those depths is not sufficient. To unravel the mechanisms behind the large scale distribution of highs and lows a larger area should be studied. Seismic data with a better data quality in the deeper time window (3500-6000 ms) could give the opportunity to look at deeper faults which would improve the structural model of the Carboniferous considerably.

4.1.3 Post-Carboniferous deformation

Deformation after the Carboniferous is very important for the prospective structures, but a detailed account of the structural history since Permian times is out of the scope of this study. The tectonic history can be very briefly summarised as follows.

Middle Jurassic - Early Cretaceous

The Kimmerian erosional events related to large scale rifting produced a marked unconformity, which over parts of the Cleaverbank High cuts down into the Zechstein. The normal faulting took place along NW-SE to N-S trending faults. In same cases reactivation of Late Carboniferous NW-SE faults occurred.

Late Cretaceous

Tectonic inversion took place accompanied by reversed faulting along E-W, WNW-ESE and NW-SE existing faults. Locally oblique slip resulted in narrow in pop-up structures mainly along the NW-SE faults. The inversion was not intense enough in the area to prevent the accumulation and preservation of a generally thick Chalk sequence.

Tertiary

During the Tertiary halokinesis became dominant. At the crest of salt-structures small scale faulting occurred. Because of the decoupling by the Zechstein evaporites, this deformation did not effect the carboniferous sequence very much.

4.2 Stratigraphic basin fill patterns

It is difficult to draw straightforward conclusions from the observed thicknesses of the main Composite Stratigraphic Packages (CSP) as found by the wells. Table 2.4 shows these thicknesses. First of all the thickness distribution and patterns do not reflect the true stratigraphic basin fill because of the following aspects:

- The wells were mostly drilled on structural highs and are therefore not reflecting the complete basin fill successions.
- Some of the CSP's are truncated by the base Rotliegend unconformity and these sequences will not show the true thickness development.
- Since the CSP's were deposited on the structural higher parts of the basin, subsequent erosion by the alluvial-fluvial systems will be more numerous. Hence, incomplete CSP's will be more common.

From the tectonic observations made in section 4.1 it is concluded that there is evidence for only minor synsedimentary movements during the Westphalian A and B, while there is more reason to assume such movements during the Westphalian C and D. It can not be completely ruled out, however, that a large part of the faulting which is observed in the Upper Carboniferous section and is absent at younger levels, has its origin after the deposition of most or all of the Westphalian sediments (but of course before deposition of the Upper Rotliegend). If this would be true, one has to assume more or less uniform original thicknesses of the Westphalian C and D all over the area, and folding and faulting at the end of the Carboniferous, which caused depressions like Depression 2 (figure 3.9) where the younger sediments have been preserved by the erosional events.

The alternative interpretation, in which the depressions already existed at the time of deposition of the younger Westphalian sediments is a very interesting option to investigate. To study the relationships between the thicknesses of the CSP's in the wells and the locations of the depressions at the time of the Saalian erosion (as defined by the time-difference map of figure 3.9 and enclosure 3.5), the main Composite Stratigraphic Packages (CSP) were plotted on the top Carboniferous subcrop map (see figures 4.2.1 - 4.2.7).

The main CSP's can probably be compared with third-order sequences. Three main CSP's (W500, W510 and W520) can be recognised in the Westphalian B, while W600 probably is related to Westphalian C. CSP W700 can be related to Westphalian D and the appearance of very young Upper Carboniferous in some UK wells (W800) may probably represent Late Westphalian D to Stephanian.

Two important flooding periods can be recognised - the W510tbs and the W520tbs. Both intervals contain numerous coal intervals. The Maurits Fm is related to the W520tbs interval.

If one would value the observed thickness variations, the following tentative observations can be made :

Thickness development of CSP W500 (Figure 4.2.1) :
W500 shows thick successions in the UK wells and intermediate thicknesses in the K-Quadrant and probably also in the E16 blocks. Relatively thin successions are in the D-Quadrant and the E10, E13 and J3 blocks.

Thickness development of CSP W510 (Figure 4.2.2) :
A similar trend can be observed during the deposition of W510. Slightly higher subsidence rates may have occurred in the E10 and J3 blocks, indicating the onset of the fragmentation of the platform area. High subsidence rates seem to have persisted in the adjacent UK area.

Thickness development of CSP W510tbs flooding (Figure 4.2.3) :
The W510tbs flooding is the transgressive systems tract of W510. It is well developed in those parts of the basin with a sufficient sediment accommodation such as the adjacent UK area. It shows a thin, probably with an onlap pattern, development of the highs or platform areas. This is the case in the D-Quadrant, E10, E16 and J3 blocks. An interesting feature is the relatively high subsidence pattern in the southern K-Quadrant.

Thickness development of CSP W520 (Figure 4.2.4) :
The W520 is more or less equivalent with the Caister equivalent sandstones. Here again it shows a similar pattern as we have observed during the deposition of W500 and W510. Rapid subsidence occurred in the adjacent UK area and around the main possible depositional centres (green). A reduced section, probably reflecting low subsidence rates, is prevailing in the D-Quadrant.

Thickness development of CSP W520tbs flooding (Figure 4.2.5) :
The W520tbs flooding is related to the Maurits Fm and is the transgressive systems tract of W520. Generally, it has a pronounced development through the whole study area. True thicknesses are not always possible to estimate, since it has been truncated by the Rotliegend unconformity in many wells. More or less complete successions are in E17-2, E18-2, E18-3, K2-1 and K3-1. In these wells thick W520tbs successions are present, indicating a high subsidence rate during deposition.

Thickness development of CSP W600 (Figure 4.2.6) :
The W600 is present only in a limited number of wells. Most significant is the presence in the eastern and north-eastern part of a potential main depositional centre (green), i.e. the wells E17-2, K2-1, K2-2, K3-1 and K3-2. The E18 blocks are probably part of another area with high subsidence. It seems that a relationship exists between the depositional centres as shown in the top Carboniferous subcrop map and the presence of W600 successions.

Thickness development of CSP W700 (Figure 4.2.7) :
A similar trend can be observed with the thickness development of W700. The same wells containing W600 successions also have W700. All the W700 successions were truncated by the Upper Rotliegend unconformity and therefore do not display true thickness development.

One exception is the UK well 49/4-1 which shows a relatively complete W700 succession. This well also has a very young Upper Carboniferous succession above the W700. Several other wells west of this field also contain a very young sand interval above the W700, indicating a consistent subsidence pattern during the Late Carboniferous.

4.3 Conclusions on the prospectivity of the area

The two most important critical petroleum geological factors in the area are the occurrence of trap and the reservoir distribution. In section 4.1 the structural geology has been discussed, and some understanding is given of the generation of structures. The structures are often low in relief, and thus sensitive to depth errors. Nevertheless many of the structures now defined are clearly present.

No field has been found in the Dutch sector where the capacity of an intra-Carboniferous seal has been proven. Therefore the operating companies so far take the approach of only regarding structural closure at top Carboniferous level. It may very well be possible that in a later stage an intra-Carboniferous seal will be found, and more structures can be defined than just those at top Carboniferous level. Until such moment a realistic overview of the prospectivity of the area has to be restrited to the structures described.

Another matter is the occurrence of stratigraphic or mixed structural/stratigraphic traps. More or less isolated sand-prone units could be laterally sealed. Also this concept has, however, not been proven.

This study has given much more insight in the distribution of the different Upper Carboniferous sequences. Given the experience and knowledge (which is growing with each new well) of the reservoir potential of each of those units in particular areas, a distribution map of the sequences such as enclosure 3.5 predicts where the sandy units are present. Most potential is with the youngest Carboniferous sediments.

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5 Carboniferous prospectivity per block

Taking the most conservative approach of constraining the prospectivity of the Upper Carboniferous to the structural traps defined at top Carboniferous level, a minimum amount of prospects can be deduced from the structures shown in enclosure 3.2 (top Carboniferous depthmap), also shown in figure 5.1, where the subcrop below the Saalian unconformity is colour-coded as in enclosure 3.5. Because of areas of poor seismic data quality, the subcropping Carboniferous units are not known everywhere.

In case of known fields the structures on this map have been defined by the gas-water-contact. In case of prospects a closing contour has been followed.

It should be noted that in addition to these structural traps, there is scope for stratigraphic traps too.

Block D9
The southernmost part of block D9 in included in the area of 3D seismic coverage. A rather large high area in block D12, part of which has been tested recently by well D12-5, runs into block D9. If a later appraisal of the structure in the north of D12 would find gas, it is very likely that the field crosses the license boundary into block D9, and also into the UK sector.

Block D12
A rather large high area in the north of block D12, part of which has been tested recently by well D12-5, is prospective for most probably the Caister equivalent sandstones of Early Westphalian B age. It is believed that both D12-4 and D12-5 may have been drilled not high enough on the structures. In the centre of the block there is a smaller elongated structure underneath a salt-structure, which is difficult to image with the seismic method. In the south of the block there is the known Andalusite (or D15-FA) field.

Block D15
The Andalusite (Wintershall terminology) or D15-FA (NAM's name for the same field) is known to contain gas in the Early Westphalian B Caister equivalent sandstones. There is the possibility that the reserves of this field are larger than proven so far, because the W600 (Early Westphalian C) sandstones above the Maurits formation could also contain gas. An appraisal would have to confirm this idea.

The southern lobe of the D15-FA field (in which D15-2 has been drilled) most probably runs into block E13.

The field discovered by Hamilton with 44/24-4 crosses the border into the western part of D15.
The structure on which D18-01 has recently been drilled also runs into (the south of) D15.

Block D18
Recently well D18-01 has found gas in a high structure connected to the Orca field on the UK side of border (discovered by 44/29-4). Well D18-01 has not been used in this study. There are indications however that the gas-water-contacts found in the two wells are different. In the area of D18a and around the Orca field, the Upper Carboniferous sandstones immediately beneath the Saalian unconformity are younger than the rocks found in other Dutch wells.

Block E10
In E10 there are 3 clearly defined structures. One of these has been tested by E10-2 which had gas-shows. The other two still offer scope for being small fields. In most of the block the units younger than the Maurits fm are absent because of erosion. The prospectivity would therefore be restricted to the Westphalian B (and possibly older) sandstones.

Block E13
Apart from the known Epidote field (Wintershall terminology) found by E13-1, there only remain two smaller structures in the block. Their reserves would only be marginal.

Block E16
Only part of E16 has been covered by 3D seismics. The high feature on which E16-1 and E16-3 have been drilled could still contain gas. E16-01 has only drilled a few meters of Carboniferous.

Block E17
Recently E17-02 found gas on an extension of the structure of E16. It is very well possible that further to the south of this well, where the very young Carboniferous sequences should be present, gas is trapped in a stratigraphic trap. This can only be confirmed by a well which is off-structure compared to E17-02. If such a concept would prove to be valid the size of a field could be quite large compared to the marginal structurally defined prospects in the area.

Block J3
The structures on the west side of the small block J3 can not be identified very well because we have no access to the seismic data on the UK side of the border. The other structures have all been tested.

Block K1

In block K1 two earlier defined structures (one drilled by K1-2 and the other by K1-3) turn out to be somewhat bigger than previously mapped. The high feature on which K1-2 was drilled can be regarded as an extension of the fields in K5. More to the north a smaller structure on the same trend has not been tested yet.

Block K2

Together with block E17, block K2 offers most scope for stratigraphic traps. These would be situated in a rim around the deep Depression 2, described in chapter 4. For block K2 this means that both the SW and the NE corners of the block are most prospective. There is one small undrilled structure in the south of K2/K3.

Block K3

Only the westernmost part of K3 has been mapped. The only structure is the known K2/K3 field. In the northern part of this structure very young Upper Carboniferous deposits are within closure (green colours in figure 5.1).

Blocks K4 and K5

In these two blocks many structures have been drilled already. They are primarily prospective for the Rotliegend Slochteren sandstones. As explained before, we have not interpreted the intra-Carboniferous in these two blocks.

achter fig. 5.1

6 References

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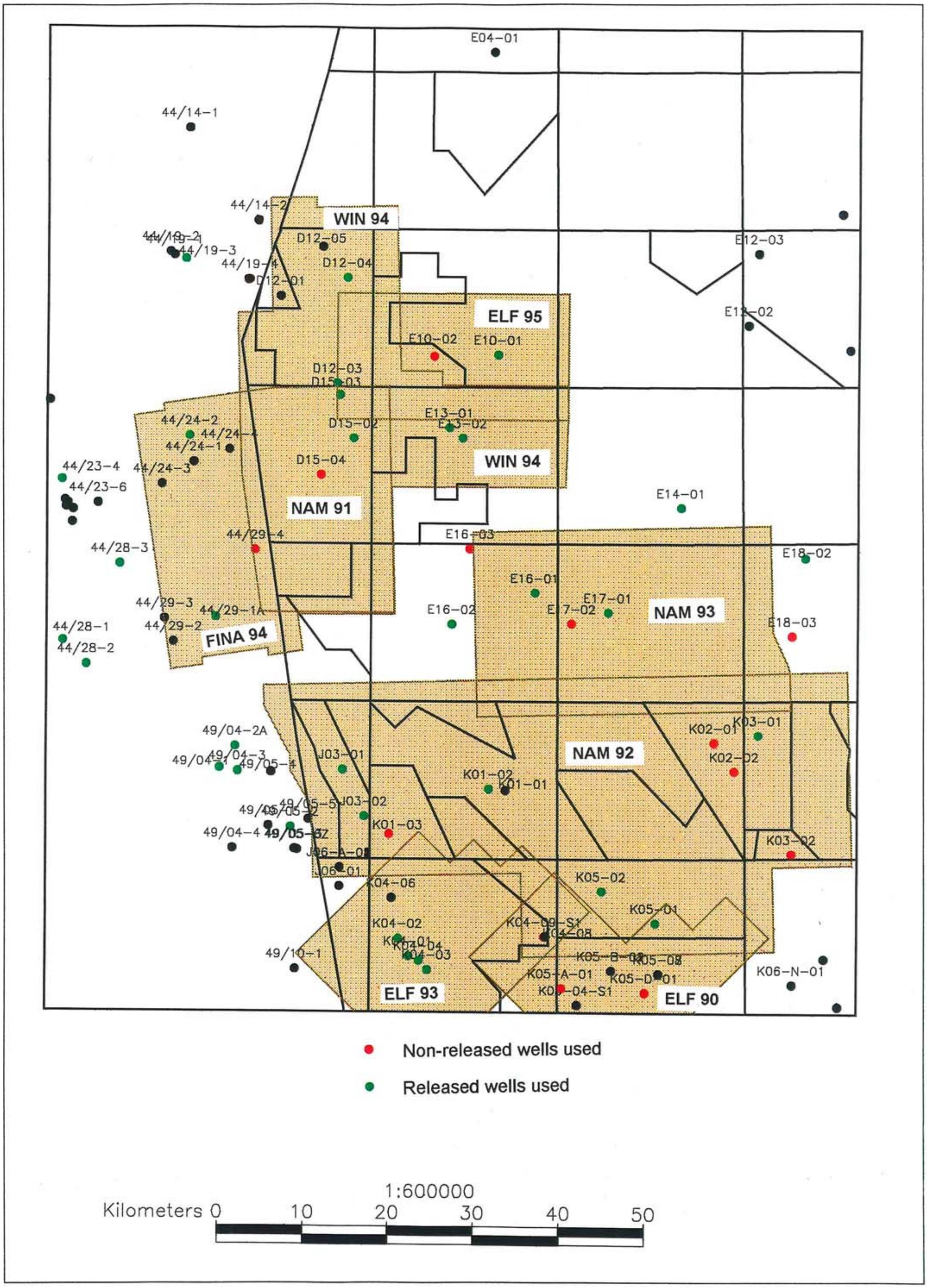
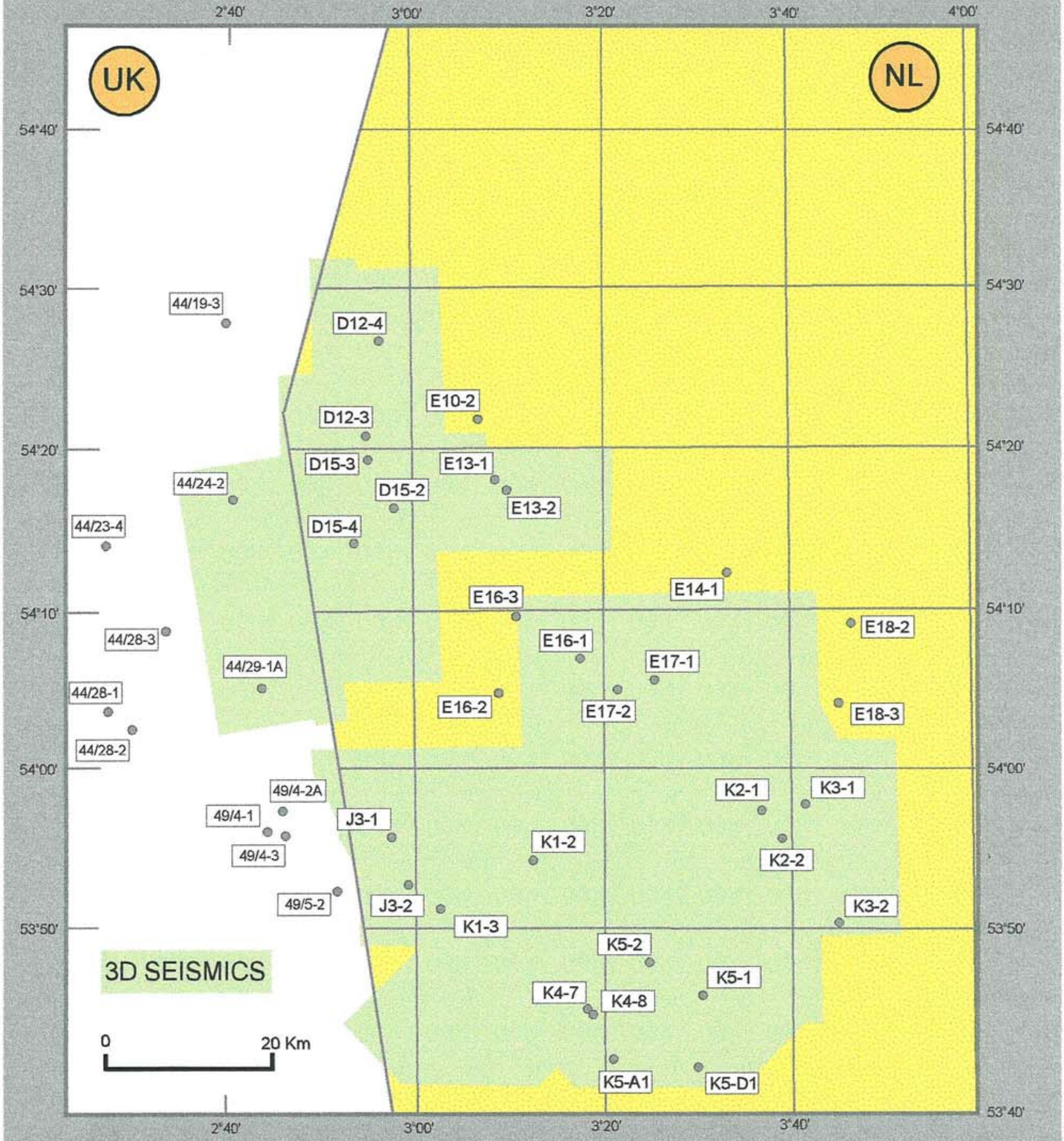


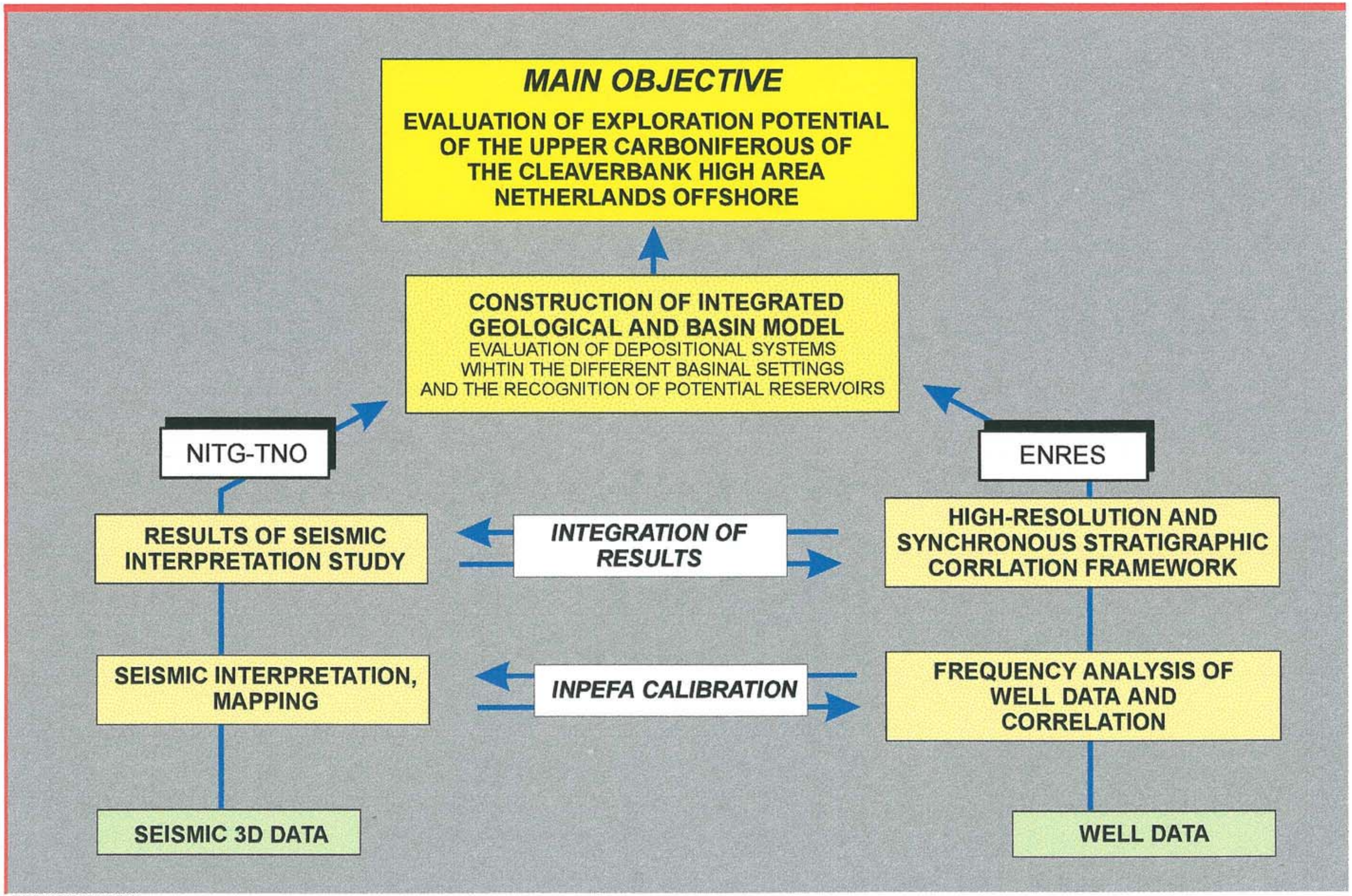
Figure 1.1 : Area of the study

OVERVIEW AND LOCATION OF WELLS USED IN THIS STUDY



ENRES/GRAD/97.235-FG02
235FG02.CDR/DN

OVERVIEW OF OBJECTIVES AND STAGES OF WORK



MAIN OBJECTIVE

EVALUATION OF EXPLORATION POTENTIAL OF THE UPPER CARBONIFEROUS OF THE CLEAVERBANK HIGH AREA NETHERLANDS OFFSHORE

CONSTRUCTION OF INTEGRATED GEOLOGICAL AND BASIN MODEL
EVALUATION OF DEPOSITIONAL SYSTEMS WHTIN THE DIFFERENT BASINAL SETTINGS AND THE RECOGNITION OF POTENTIAL RESERVOIRS

NITG-TNO

ENRES

RESULTS OF SEISMIC INTERPRETATION STUDY

INTEGRATION OF RESULTS

HIGH-RESOLUTION AND SYNCHRONOUS STRATIGRAPHIC CORRLATION FRAMEWORK

SEISMIC INTERPRETATION, MAPPING

INPEFA CALIBRATION

FREQUENCY ANALYSIS OF WELL DATA AND CORRELATION

SEISMIC 3D DATA

WELL DATA

ENRES/GRAD/97.235-FG03
235FG032.CDR/DN

FIGURE 2.2

WELL DATABASE AND AVAILABLE LOGGING DATA NETHERLANDS

WELLS LOGS	GR	DT	RHOB	NPHI	URAN	THOR	POTAS	CALI
D12-3	✓	✓	✓	✓	✓	✓	✓	✓
D12-4	✓	✓	✓	✓	✓	✓	✓	✓
D15-2	✓	✓	✓	✓	✓	✓	✓	✓
D15-3	✓	✓	✓	✓	✓	✓	✓	✓
D15-4	✓	✓	✓	✓				✓
E10-2	✓	✓	✓	✓	✓	✓	✓	✓
E13-1	✓	✓	✓	✓	✓	✓	✓	✓
E13-2	✓	✓	✓	✓	✓	✓	✓	✓
E14-1	✓	✓	✓	✓				✓
E16-1	✓	✓						✓
E16-2	✓	✓	✓	✓				✓
E16-3	✓	✓	✓	✓	✓	✓	✓	✓
E17-1	✓	✓						✓
E17-2	✓	✓	✓	✓	✓	✓	✓	✓
E18-2	✓	✓	✓	✓				✓
E18-3 (tvd)	✓	✓	✓	✓				✓
J03-1	✓	✓	✓	✓				✓
J03-2	✓	✓	✓	✓				✓
K01-2	✓	✓	✓	✓				✓
K02-1	✓	✓	✓	✓				✓
K02-2	✓	✓	✓	✓	✓	✓	✓	✓
K03-1	✓	✓	✓	✓				✓
K03-2	✓	✓	✓	✓	✓	✓	✓	✓
K04-7	✓	✓	✓	✓				✓
K04-8	✓	✓	✓	✓	✓	✓	✓	✓
K05-1	✓	✓	✓	✓				✓
K05-2	✓	✓	✓	✓	✓	✓	✓	✓
K05-A-1	✓	✓	✓	✓				✓
K05-D-1	✓	✓	✓	✓	✓	✓	✓	✓
K01-3	✓	✓	✓	✓	✓	✓	✓	✓

🟩 FACIES-SENSITIVE LOGGING DATA USED FOR FREQUENCY ANALYSIS AND WELL CORRELATIONS

ENRES/GRAD/97 235-F004
235FG04.CDR/DN

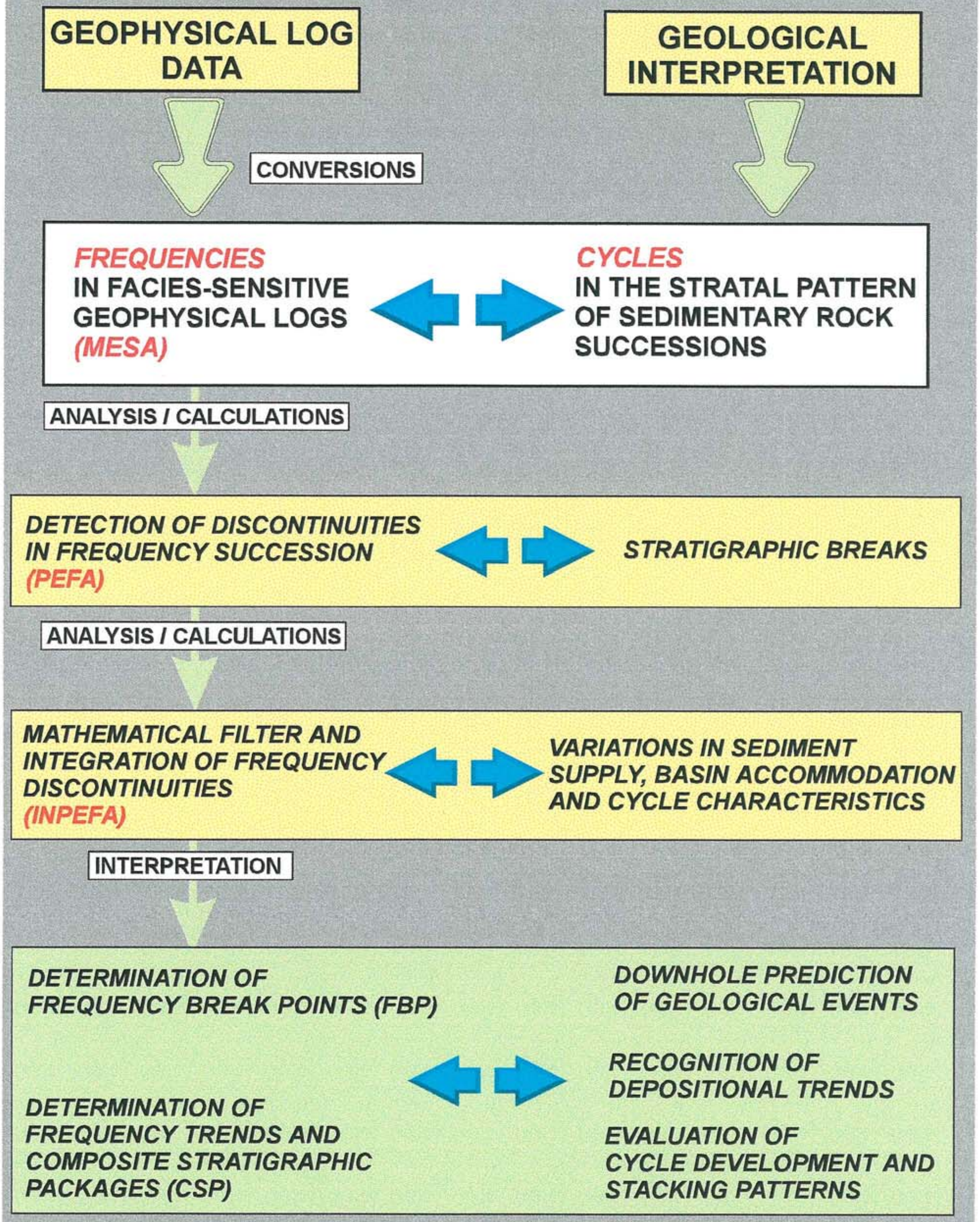
WELL DATABASE AND AVAILABLE LOGGING DATA UNITED KINGDOM

WELLS LOGS	GR	DT	RHOB	NPHI	URAN	THOR	POTAS	CALI
44/19-3	✓	✓	✓	✓	✓	✓	✓	✓
44/23-4	✓	✓	✓	✓	✓	✓	✓	✓
44/24-2	✓	✓	✓	✓	✓	✓	✓	✓
44/27-1	✓	✓	✓	✓	✓	✓	✓	✓
44/28-1	✓	✓	✓	✓				✓
44/28-2	✓	✓	✓	✓	✓	✓	✓	✓
44/28-3	✓	✓	✓	✓	✓	✓	✓	✓
44/28-4	✓	✓	✓	✓	✓	✓	✓	✓
44/291A	✓	✓	✓	✓	✓	✓	✓	✓
49/4-1	✓	✓	✓	✓	✓	✓	✓	✓
49/4-2A	✓	✓	✓	✓	✓	✓	✓	✓
49/4-3	✓	✓	✓	✓			✓	✓
49/5-2	✓	✓	✓	✓				✓

🟩	FACIES-SENSITIVE LOGGING DATA USED FOR FREQUENCY ANALYSIS AND WELL CORRELATIONS

ENRES/GRAD/97.235-F005
235F045.CDR/DN

RELATIONSHIP BETWEEN LOG FREQUENCIES, STRATAL CYCLES AND GEOLOGICAL INTERPRETATIONS



GEOPHYSICAL LOG DATA

GEOLOGICAL INTERPRETATION

CONVERSIONS

FREQUENCIES
IN FACIES-SENSITIVE GEOPHYSICAL LOGS
(MESA)

CYCLES
IN THE STRATAL PATTERN OF SEDIMENTARY ROCK SUCCESSIONS

ANALYSIS / CALCULATIONS

DETECTION OF DISCONTINUITIES IN FREQUENCY SUCCESSION
(PEFA)

STRATIGRAPHIC BREAKS

ANALYSIS / CALCULATIONS

MATHEMATICAL FILTER AND INTEGRATION OF FREQUENCY DISCONTINUITIES
(INPEFA)

VARIATIONS IN SEDIMENT SUPPLY, BASIN ACCOMMODATION AND CYCLE CHARACTERISTICS

INTERPRETATION

DETERMINATION OF FREQUENCY BREAK POINTS (FBP)

DETERMINATION OF FREQUENCY TRENDS AND COMPOSITE STRATIGRAPHIC PACKAGES (CSP)

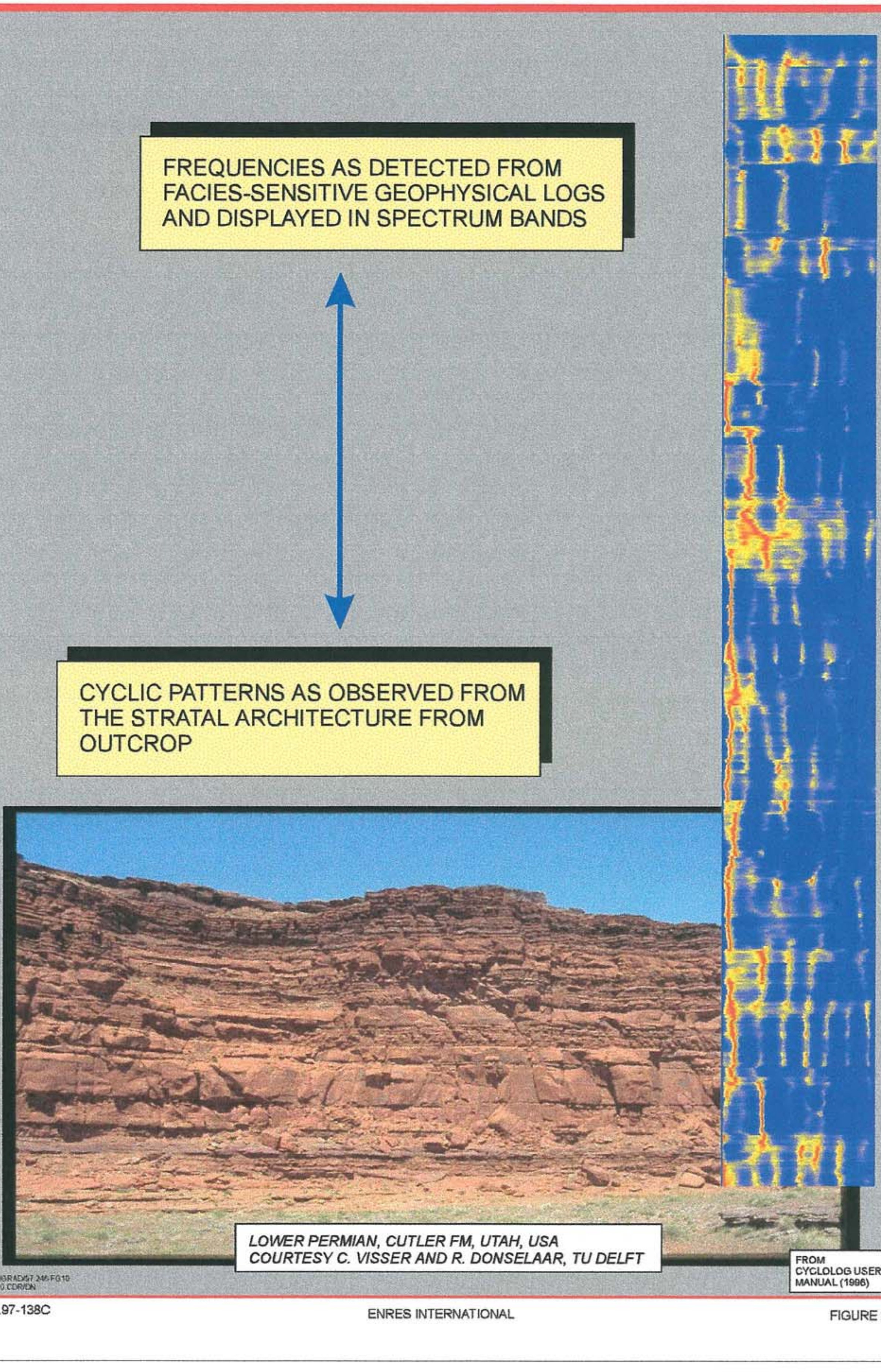
DOWNHOLE PREDICTION OF GEOLOGICAL EVENTS

RECOGNITION OF DEPOSITIONAL TRENDS

EVALUATION OF CYCLE DEVELOPMENT AND STACKING PATTERNS

ENRES/GRAD/97.235-F006
235F006.CDR/DN

RELATIONSHIP BETWEEN GEOPHYSICAL LOG FREQUENCIES AND CYCLIC STRATAL ARCHITECTURE IN OUTCROP



FREQUENCIES AS DETECTED FROM FACIES-SENSITIVE GEOPHYSICAL LOGS AND DISPLAYED IN SPECTRUM BANDS

CYCLIC PATTERNS AS OBSERVED FROM THE STRATAL ARCHITECTURE FROM OUTCROP

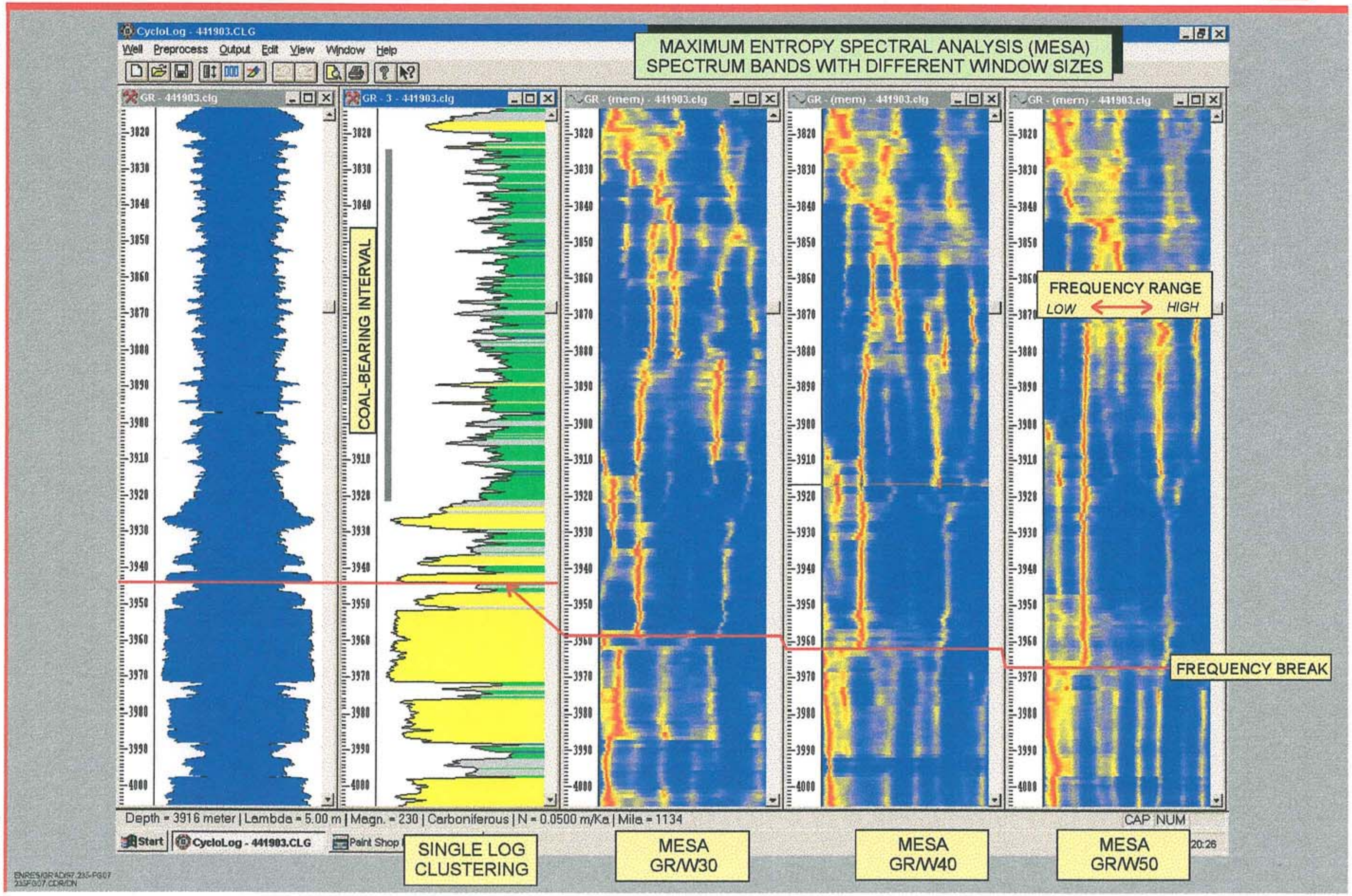
LOWER PERMIAN, CUTLER FM, UTAH, USA
COURTESY C. VISSER AND R. DONSELAAR, TU DELFT

FROM
CYCLOLOG USER
MANUAL (1996)

ENRES/GRAD/97 246 FG10
246FG10.CDR/DN

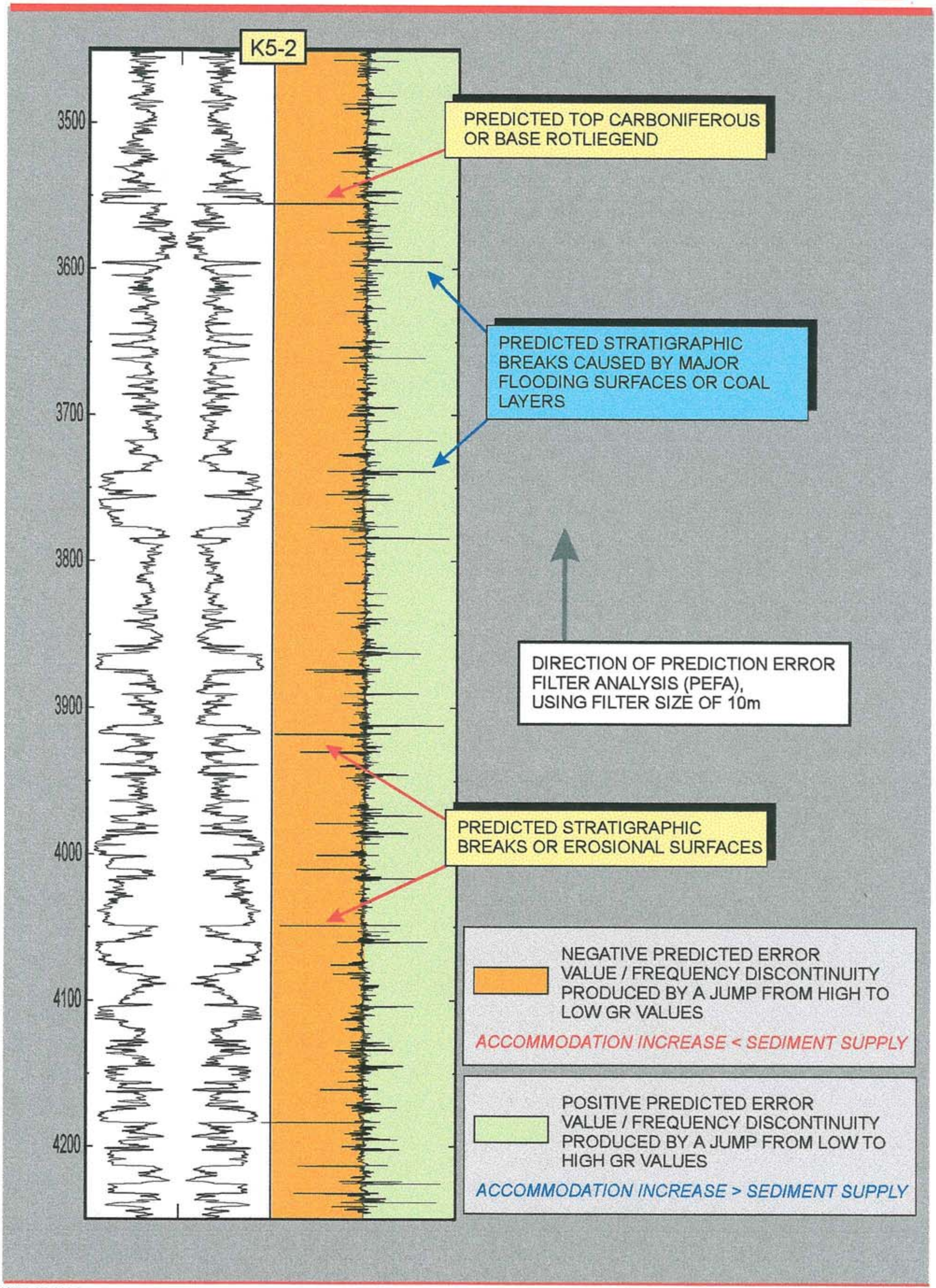
RELATIONSHIP BETWEEN GR-LOG FREQUENCIES AND LITHOFACIES CYCLES

WELL 44/19-3



Depth = 3916 meter | Lambda = 5.00 m | Magn. = 230 | Carboniferous | N = 0.0500 m/Ka | Mila = 1134

PREDICTION ERROR FILTER ANALYSIS (PEFA) AND GEOLOGICAL INTERPRETATION



PREDICTED TOP CARBONIFEROUS OR BASE ROTLIEGEND

PREDICTED STRATIGRAPHIC BREAKS CAUSED BY MAJOR FLOODING SURFACES OR COAL LAYERS

DIRECTION OF PREDICTION ERROR FILTER ANALYSIS (PEFA), USING FILTER SIZE OF 10m

PREDICTED STRATIGRAPHIC BREAKS OR EROSIONAL SURFACES

🟧 NEGATIVE PREDICTED ERROR VALUE / FREQUENCY DISCONTINUITY PRODUCED BY A JUMP FROM HIGH TO LOW GR VALUES

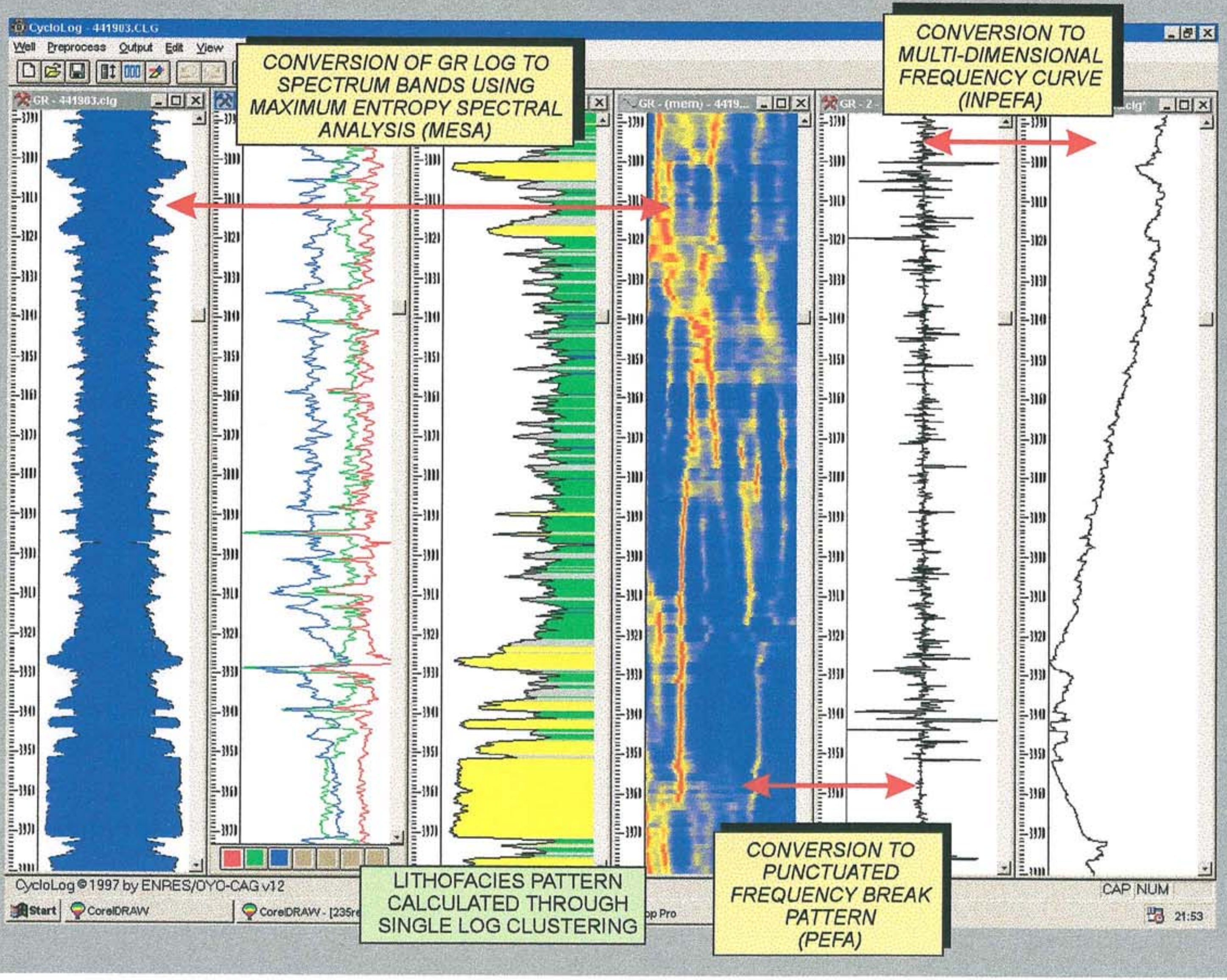
ACCOMMODATION INCREASE < SEDIMENT SUPPLY

🟩 POSITIVE PREDICTED ERROR VALUE / FREQUENCY DISCONTINUITY PRODUCED BY A JUMP FROM LOW TO HIGH GR VALUES

ACCOMMODATION INCREASE > SEDIMENT SUPPLY

FIGURE 2.8

CONVERSION OF FACIES-SENSITIVE GR LOG TO THE DIFFERENT FREQUENCY DOMAINS - WELL 44/19-3



CONVERSION OF GR LOG TO SPECTRUM BANDS USING MAXIMUM ENTROPY SPECTRAL ANALYSIS (MESA)

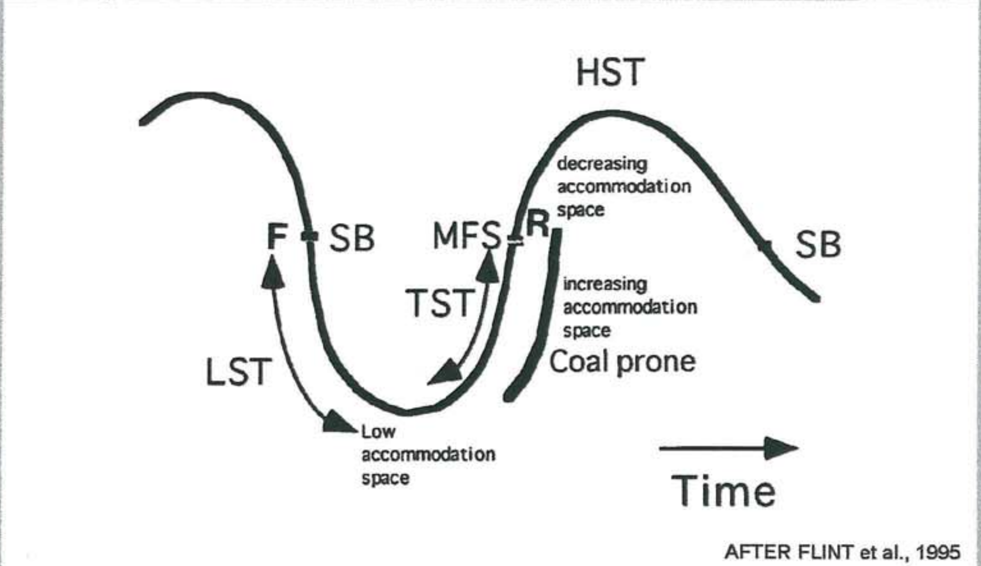
CONVERSION TO MULTI-DIMENSIONAL FREQUENCY CURVE (INPEFA)

LITHOFACIES PATTERN CALCULATED THROUGH SINGLE LOG CLUSTERING

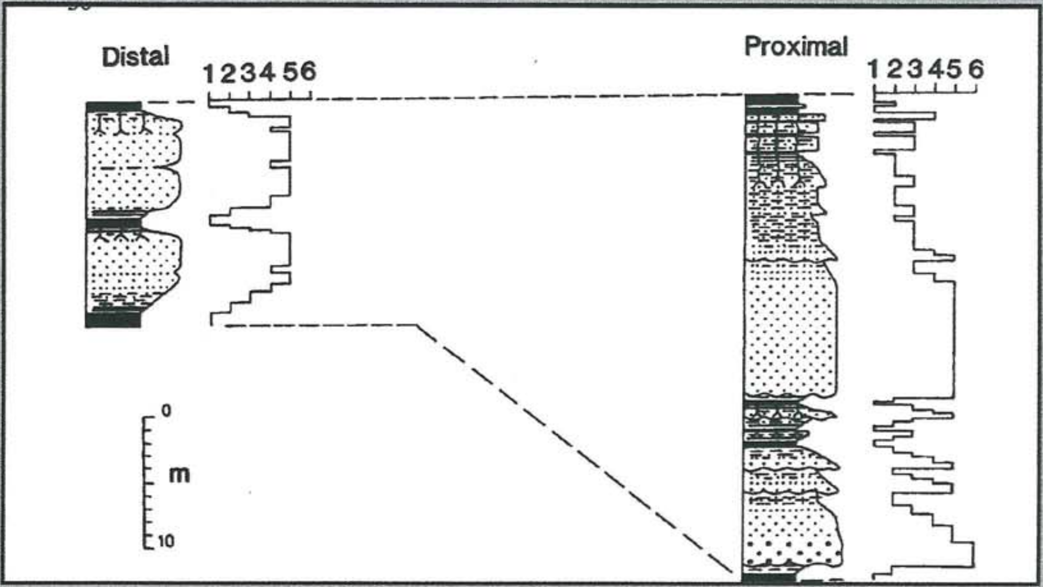
CONVERSION TO PUNCTUATED FREQUENCY BREAK PATTERN (PEFA)

ENRES/GRAD/97-233-FG08
233FG08.CDR/DN

SEQUENCE STRATIGRAPHY AND CYCLOSTRATIGRAPHY APPLICATIONS IN THE UPPER CARBONIFEROUS



AFTER FLINT et al., 1995

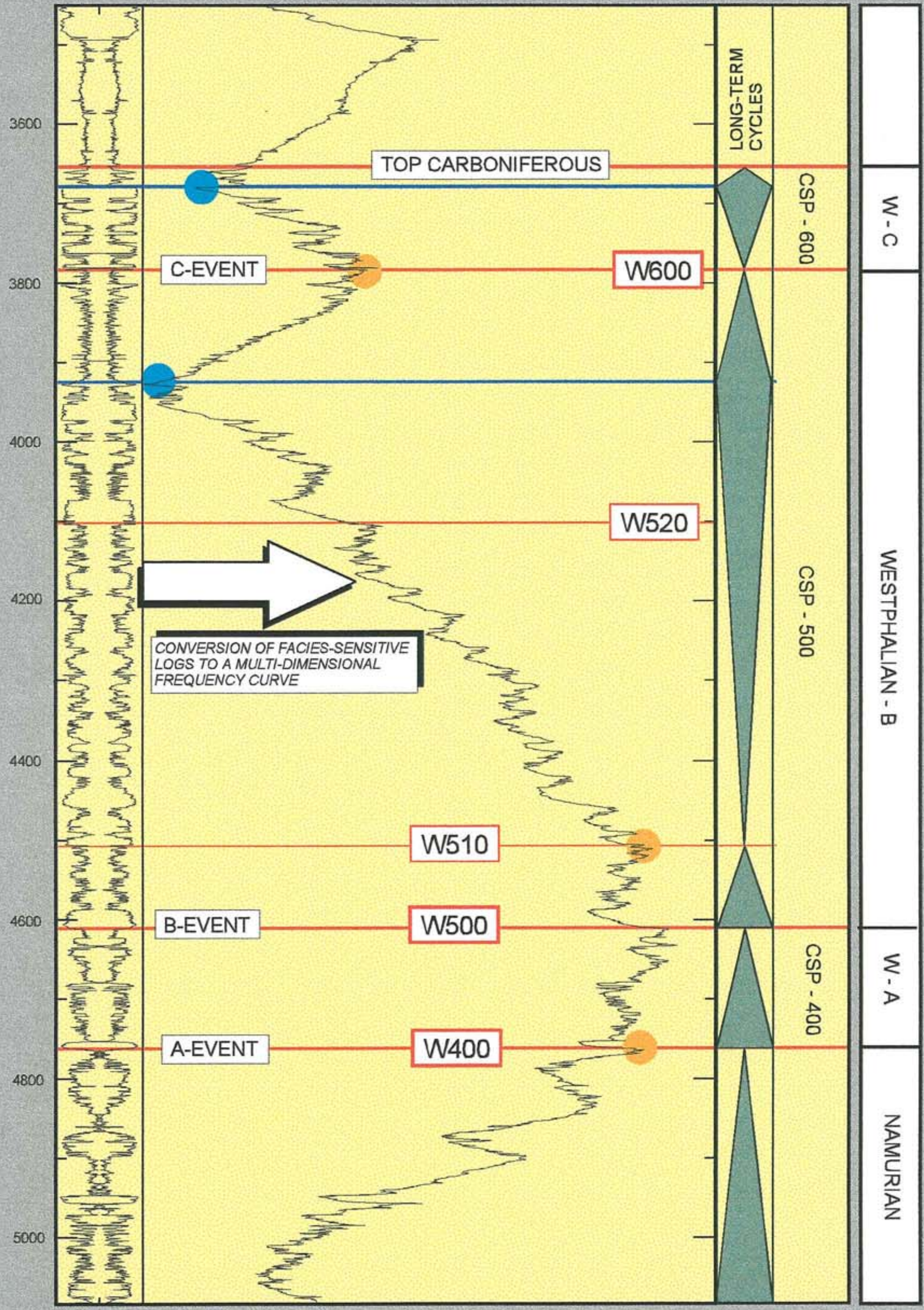


1=coal
2=claystone
3=siltstone
4=fine sands
5=medium sands
6=coarse sands

NOTE MORE REGULAR GRAINSIZE VARIATIONS IN THE DISTAL SETTINGS AND MORE IRREGULAR VARIATIONS IN PROXIMAL SETTINGS

AFTER WEEDON & READ, 1995

INTERPRETATION OF GEOLOGICAL EVENTS AND DEPOSITIONAL TRENDS FROM THE INPEFA FREQUENCY CURVE - 44/19-3



ENRES/GRAD/97.235-FG09
235FG09.CDR/DN

CYCLE HIERARCHY PATTERN AND LITHOFACIES VARIABILITY

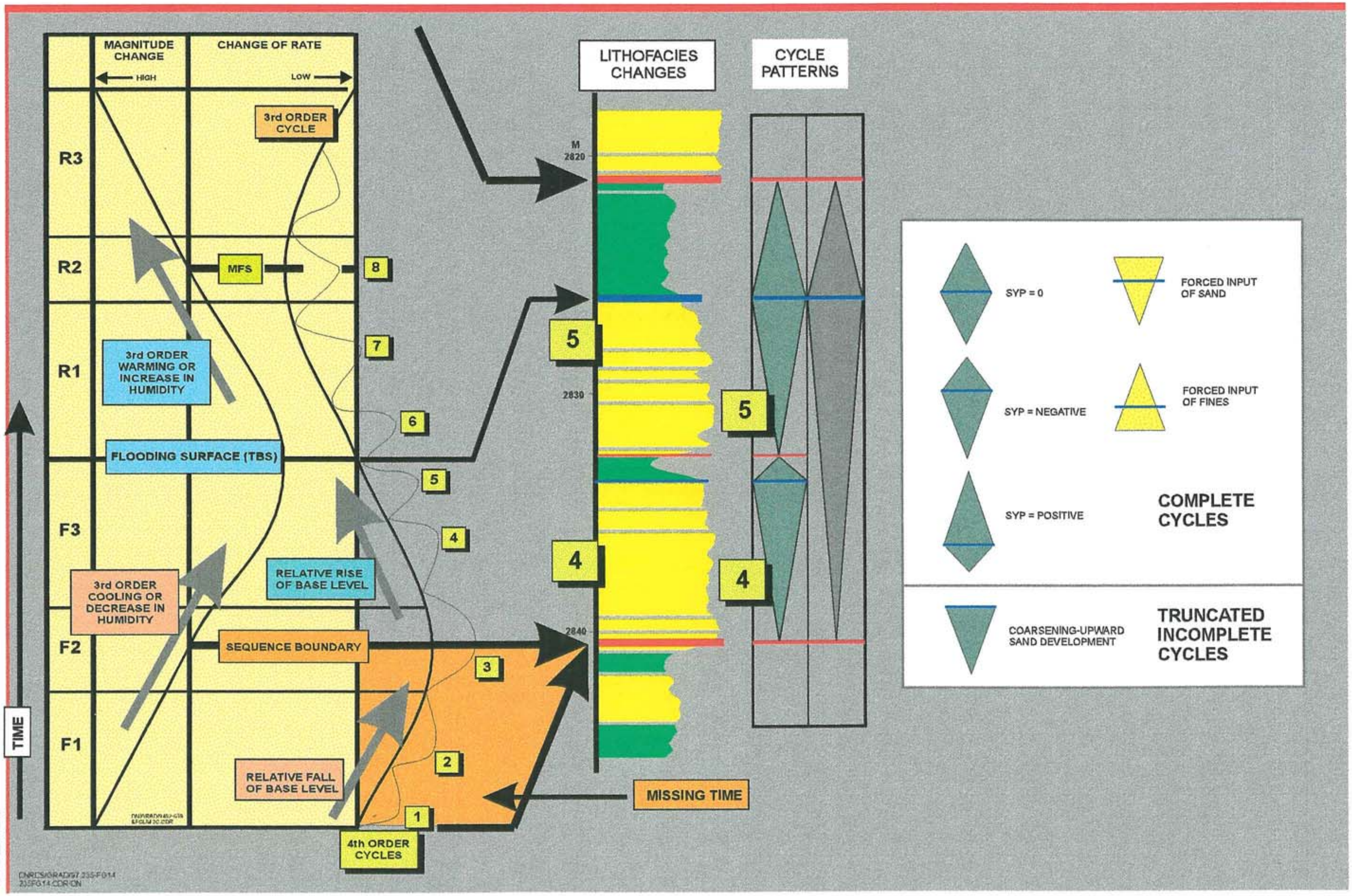
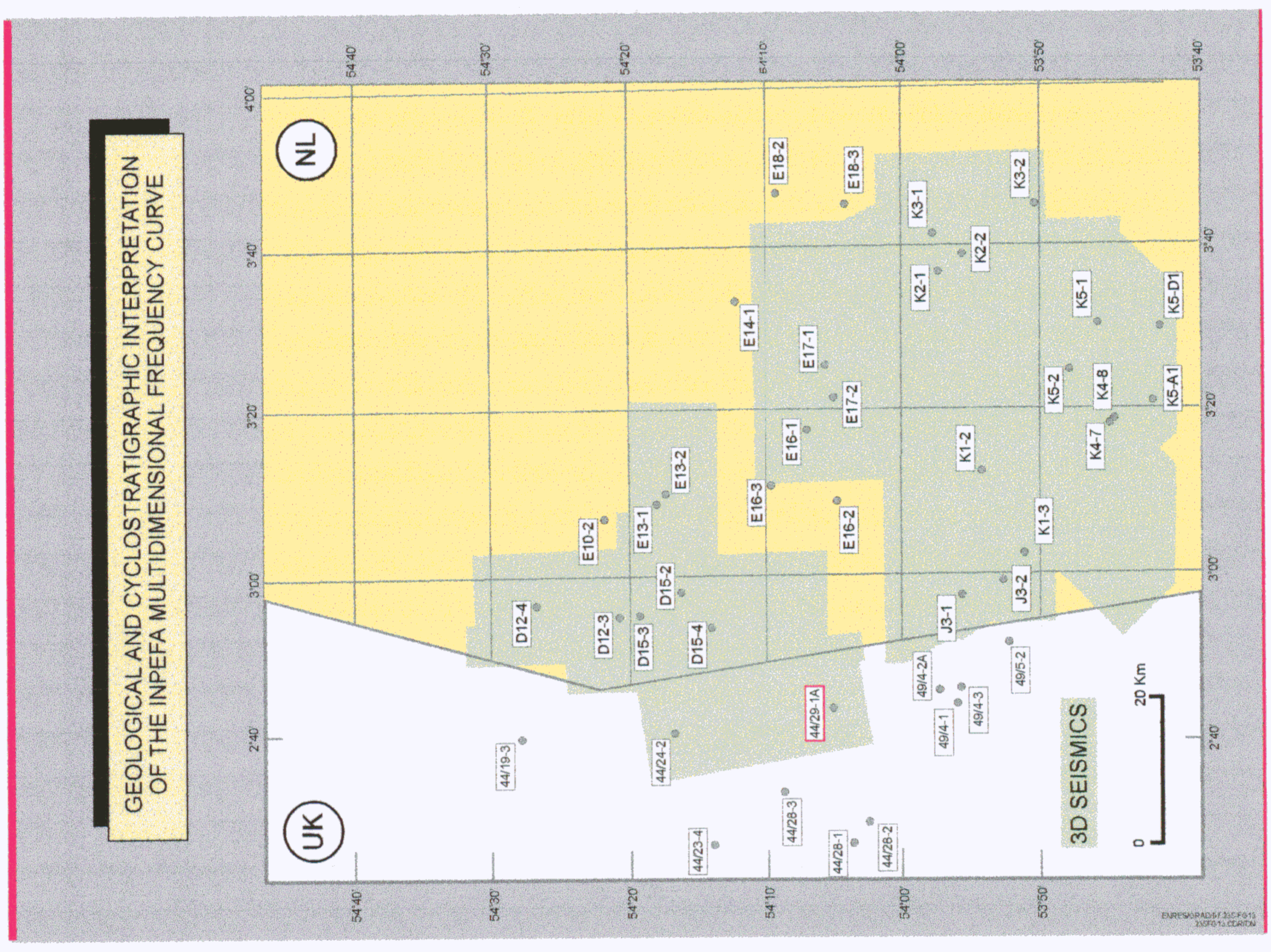


FIGURE 2.12

SEQUENCE AND CYCLOSTRATIGRAPHIC STUDY OF THE UPPER CARBONIFEROUS OF THE
CLEAVERBANK HIGH AREA, NETHERLANDS OFFSHORE

CYCLOLOG COMPOSITE WELL CHART

GEOLOGICAL AND CYCLOSTRATIGRAPHIC INTERPRETATION OF THE INPEFA MULTIDIMENSIONAL FREQUENCY CURVE

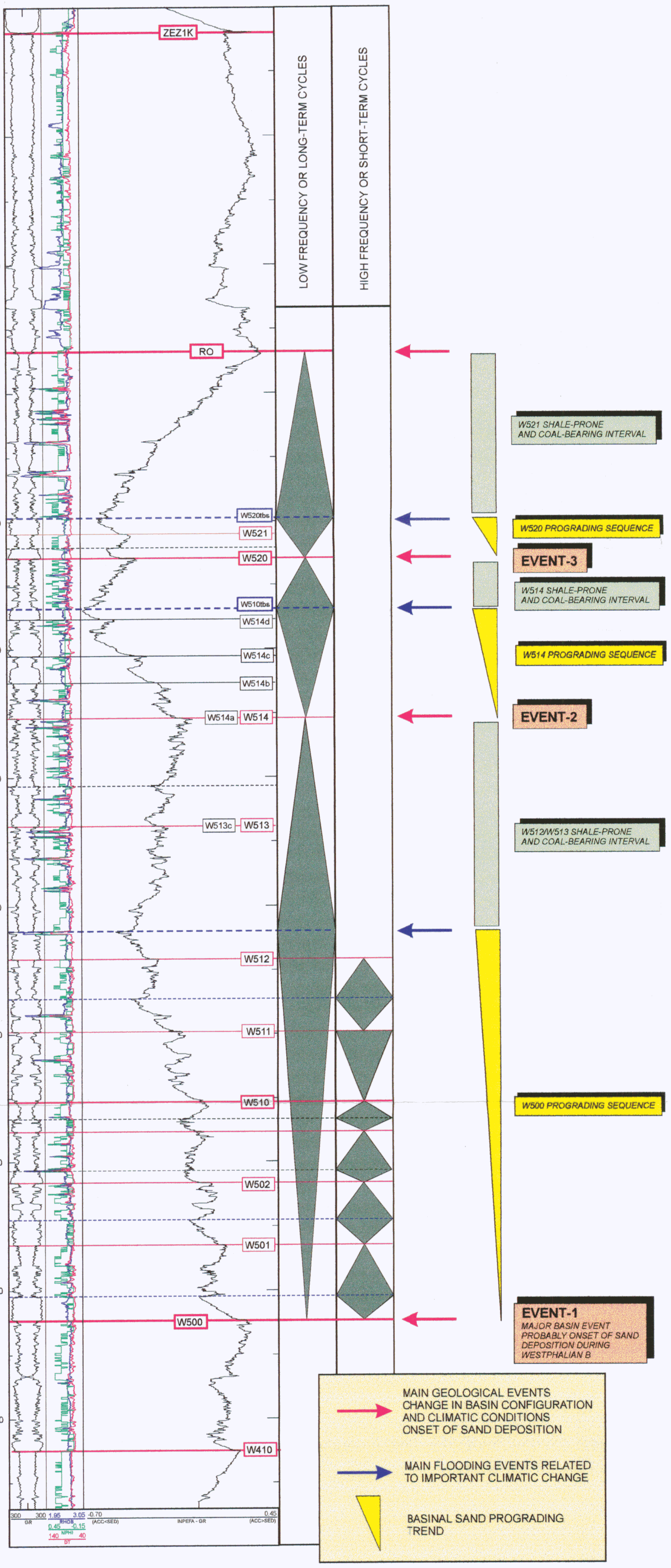


ENRES INTERNATIONAL

NITG.97-138C

FIGURE 2.13

44/29-1A



W521 SHALE-PRONE AND COAL-BEARING INTERVAL

W520 PROGRADING SEQUENCE

EVENT-3

W514 SHALE-PRONE AND COAL-BEARING INTERVAL

W514 PROGRADING SEQUENCE

EVENT-2

W512/W513 SHALE-PRONE AND COAL-BEARING INTERVAL

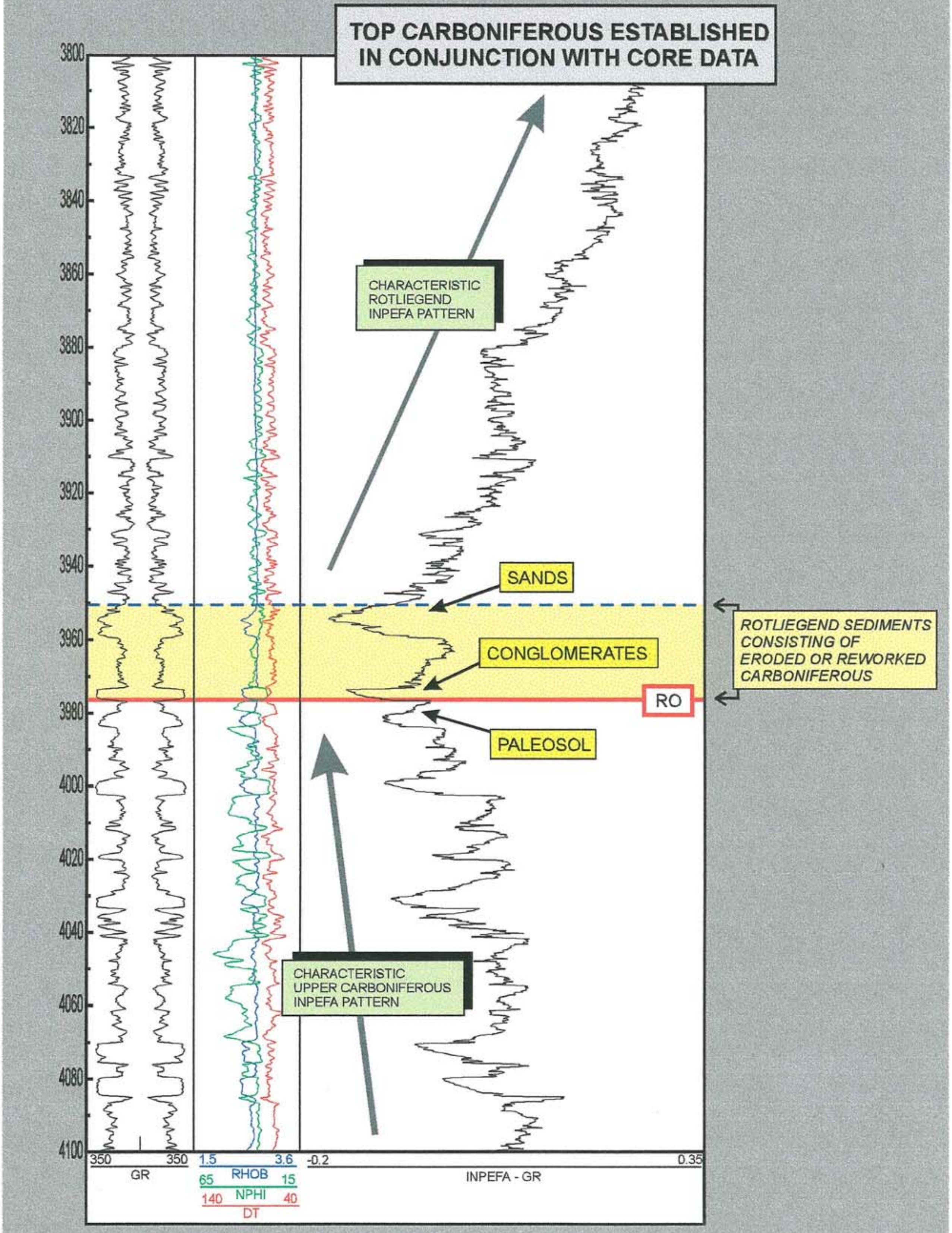
W500 PROGRADING SEQUENCE

EVENT-1
MAJOR BASIN EVENT PROBABLY ONSET OF SAND DEPOSITION DURING WESTPHALIAN B

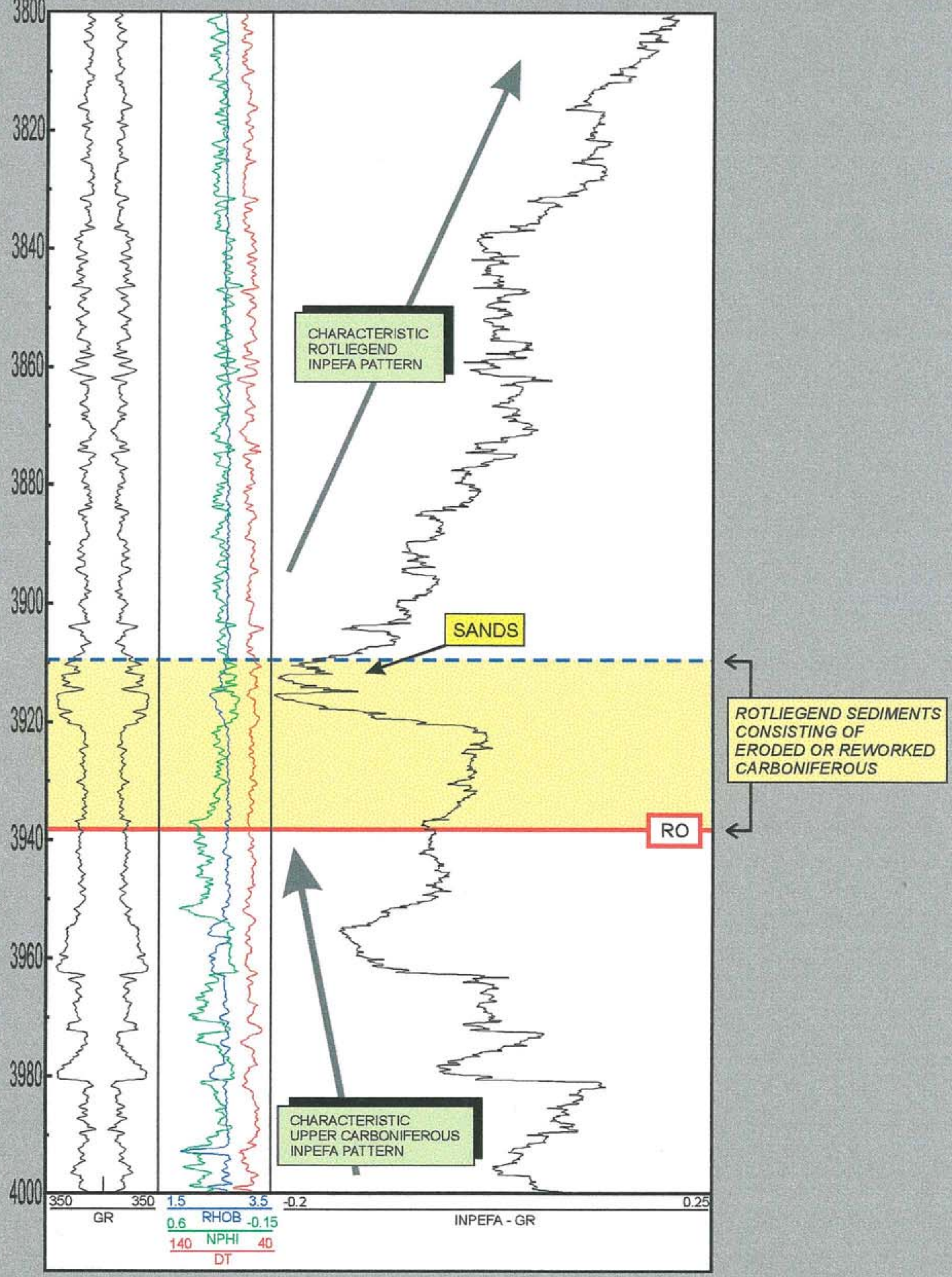
→	MAIN GEOLOGICAL EVENTS CHANGE IN BASIN CONFIGURATION AND CLIMATIC CONDITIONS ONSET OF SAND DEPOSITION
→	MAIN FLOODING EVENTS RELATED TO IMPORTANT CLIMATIC CHANGE
◤	BASINAL SAND PROGRADING TREND

97-138C

DETERMINATION OF TOP CARBONIFEROUS / BASE ROTLIEGEND WELL K2-2

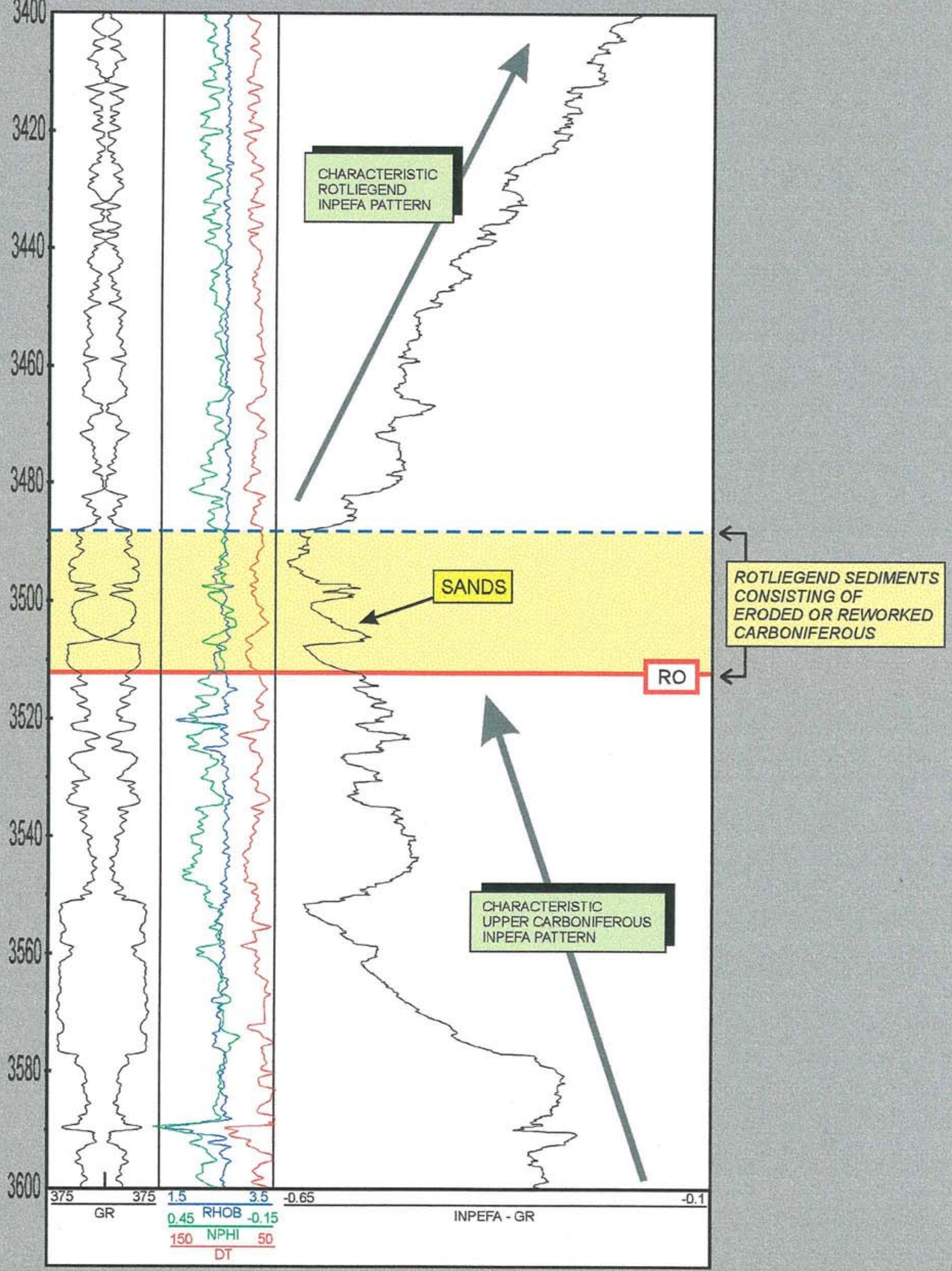


DETERMINATION OF TOP CARBONIFEROUS / BASE ROTLIEGEND WELL K3-1



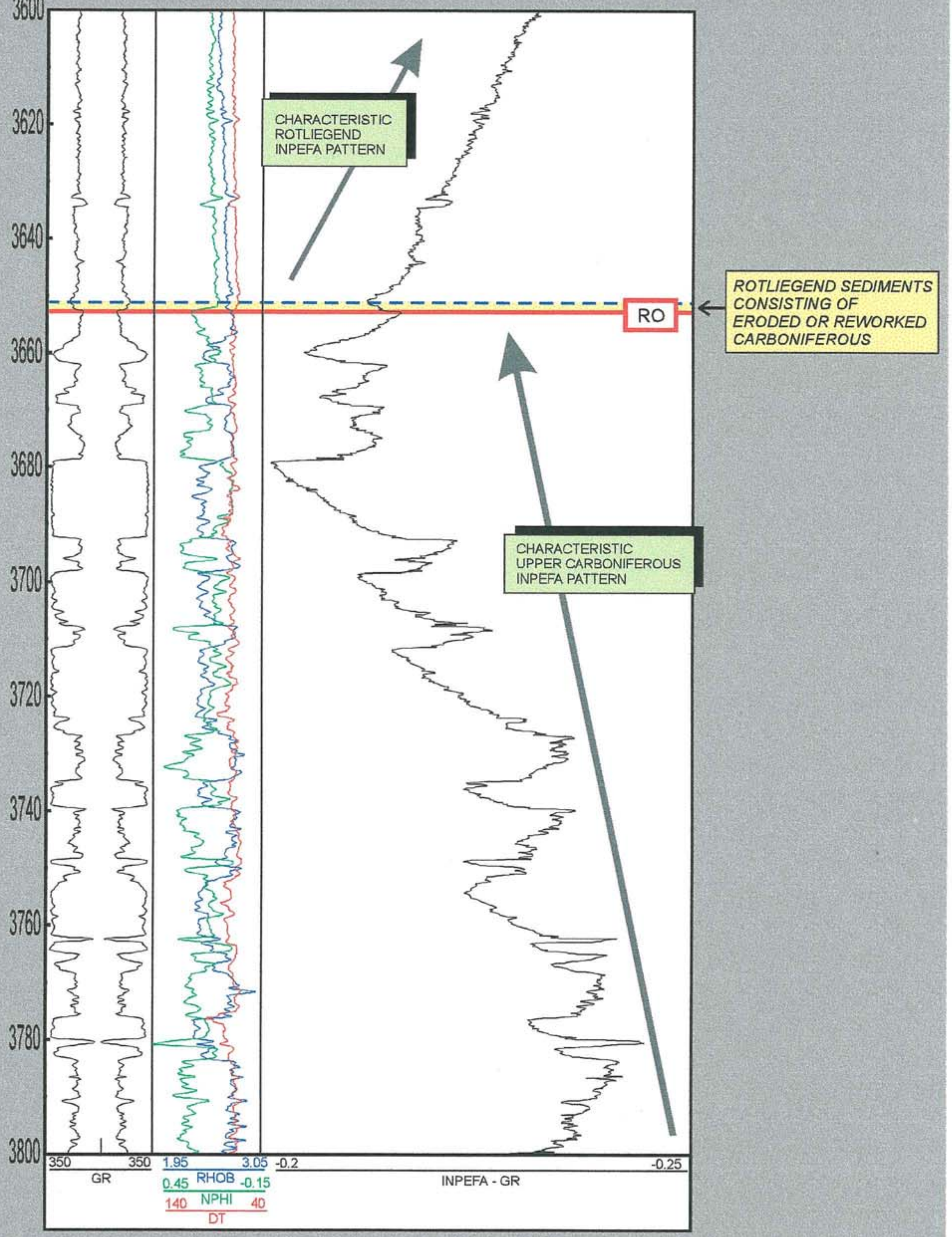
ENRES/GRAD/97.230-FG17
230FG17 CDR/DN

DETERMINATION OF TOP CARBONIFEROUS / BASE ROTLIEGEND
WELL 49/5-2



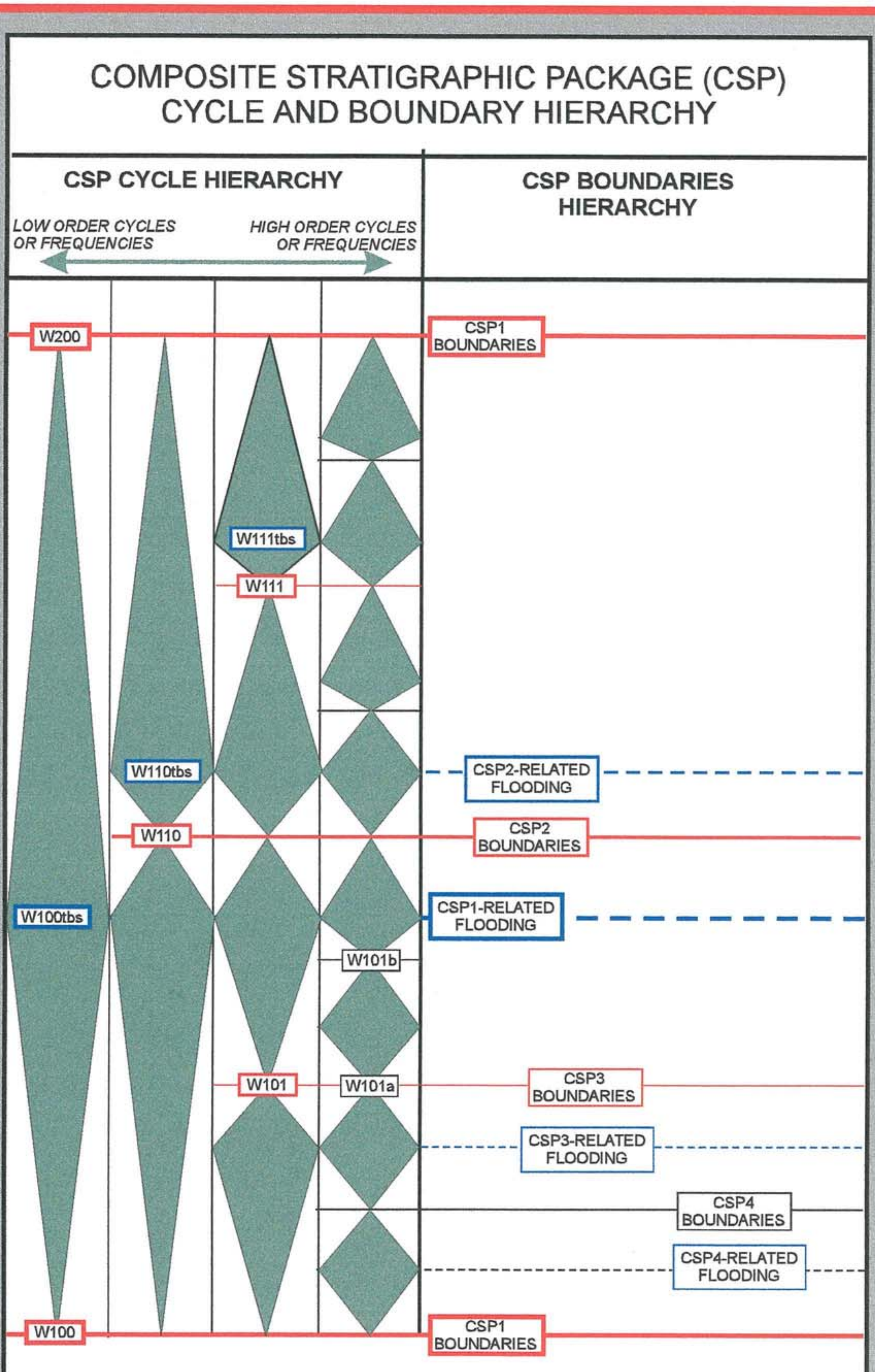
ENRES/GRAD/97 236-FG18
236FG18 CDR/DN

DETERMINATION OF TOP CARBONIFEROUS / BASE ROTLIEGEND
WELL 44/19-3



ENRES/GRAD/97.235-FG19
235FG19.CDR/DN

SEQUENCE AND CYCLOSTRATIGRAPHIC BOUNDARY NOMENCLATURE



COMPOSITE STRATIGRAPHIC PACKAGE (CSP)
CYCLE AND BOUNDARY HIERARCHY

ENRES/GRAD/97.235-FG20
335FG20.CDR/DN

FIGURE 2.18

D AND E QUADRANTS

TABLE 2-1

COMPOSITE STRATIGRAPHIC PACKAGES (CSP) DEPTHS / D AND E QUADRANTS / Version July 1997

WELL		D12-3	D12-4	D15-2	D15-3	D15-4	E10-2tvd	E13-1	E13-2	E16-3	E17-2	E18-2	E18-3
ZEZ1K		**3229.60**	**3193.18**	**3234.79**	**3250.34**	**3422.72**	**3318.76**	**3286.45**	**3318.45**	**3311.28**	**3569.68**	**3475.78**	**3583.86**
RO		**3487.18**	**3520.59**	**3507.61**	**3516.00**	**3696.46**	**3560.17**	**3558.66**	**3648.77**	**3650.90**	**3939.04**	**3984.37**	**4047.01**
W800		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
W702		▨	▨	▨	▨	▨	▨	▨	▨	▨	3981.43	4040.34	4098.55
W700tbs		▨	▨	▨	▨	▨	▨	▨	▨	▨	4003.24	4057.72	4118.53
W701		▨	▨	▨	▨	▨	▨	▨	▨	▨	4012.85	4079.68	4122.95
W700		▨	▨	▨	▨	▨	▨	**3598.77**	▨	▨	4039.08	▨	▨
W603		▨	▨	▨	▨	▨	▨	3651.07	▨	▨	4091.84	4149.68	4204.08
W602		▨	▨	▨	▨	▨	▨	3666.48	▨	▨	4139.27	4240.72	4291.92
W601		▨	▨	▨	▨	▨	▨	3692.10	▨	▨	▨	▨	▨
W600		▨	▨	▨	▨	**3753.04**	▨	**3736.17**	▨	▨	▨	▨	▨
W523		▨	▨	3534.76	▨	▨	▨	3784.21	▨	3724.86	4187.31	4267.26	4346.21
W522		▨	▨	3618.18	▨	3800.77	3580.29	3825.38	▨	3791.51	4245.26	4329.02	4429.63
W520tbs		3545.43	3626.43	3670.02	3588.28	3880.68	3618.73	3882.72	3762.53	3874.31	4290.55	4398.10	4529.82
W521		3559.92	3679.96	3693.66	3596.98	3929.94	3650.14	3886.69	3772.60	3891.55	4305.50	4412.59	4552.24
W520		**3582.64**	**3791.74**	**3705.56**	**3605.06**	**3966.54**	**3681.40**	**3903.92**	**3783.27**	**3927.39**	**4342.55**	**4420.83**	**4579.84**
W510tbs		3587.37	3836.12				3689.94	3925.88	3797.91	3944.62	4350.79	4433.33	4602.56
W514		3599.88	3860.52	3713.64	3636.93	3977.52	3714.80	3933.35	3812.71	3972.68	4398.83	4461.39	4628.95
W513		3607.04		3721.26	3648.06	3986.21	3730.97	3964.16	3831.31	3995.86			
W512		3625.34		3742.77	3657.67		3761.47	3990.84	3844.88	4026.81			
W511		3648.98		3763.05	3671.70		3795.78	4017.69	3853.88	4065.55			
W510		**3678.11**		**3783.03**	**3698.39**		**3822.01**	**4032.78**	**3866.54**	**4087.05**			
W502		3701.29		3824.97	3744.29		3870.35	4060.69	3909.24	4138.29			
W501		3729.65		3836.55	3771.44		3893.38	4102.63	3921.74	4199.75			
W500		3750.70		**3853.33**	**3807.43**		**3922.51**	**4128.25**	**3940.65**	**4266.39**			
W410		3802.70			3876.21		3960.17	4169.42	3979.39	▨			
W400		3842.96			3929.27			4216.09	4017.21	4308.64			
W300		3895.73			3966.03								
🟩	W800 CSP												
🟥	W700 CSP												
🟫	W600 CSP												
🟩	W520tbs												
🟨	W520 CSP												
🟦	W510tbs												
🟨	W510 CSP												
🟨	W500 CSP		▨	not present									

TABLE 2-1

TABLE 2-2

COMPOSITE STRATIGRAPHIC PACKAGES (CSP) DEPTHS / J AND K QUADRANTS / Version July 1997

WELL		**J3-1**	**J3-2**	**K1-2**	**K1-3**	**K2-1**	**K2-2**	**K3-1**	**K3-2**	**K4-7**	**K5-1**	**K5-A-1**	**K5-2**	**K5-D-1**
ZEZ1K		**3500.32**	**3276.72**	**3424.25**	3350.02	**3626.99**	**3639.98**	**3585.23**	**3611.75**	**3314.96**	**3391.96**	**3396.96**	**3288.89**	**3536.29**
RO		**3745.70**	**3542.83**	**3669.47**	**3620.86**	**3969.97**	**3976.24**	**3937.81**	**3941.61**	**3546.76**	**3624.06**	**3625.10**	**3555.30**	**3770.84**
W800	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
W702		▒	▒	▒	▒	3984.30	4002.16	3962.51	▒	▒	▒	▒	▒	▒
W700tbs		▒	▒	▒	▒	3999.25	▒	▒	▒	▒	▒	▒	▒	▒
W701		▒	▒	▒	▒	4032.19	▒	▒	▒	▒	▒	▒	▒	▒
W700		▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
W603		▒	▒	▒	▒	4108.13	4041.66	4023.67	▒	3568.87	▒	▒	▒	▒
W602		▒	▒	▒	▒	4196.27	4084.82	▒	▒	3653.96	▒	▒	▒	▒
W601		▒	▒	▒	▒	4267.80	4120.81	▒	▒	3676.07	▒	▒	▒	▒
W600		▒	▒	▒	▒	**4304.55**	▒	▒	▒	▒	▒	▒	▒	▒
W523		▒	▒	▒	▒	4348.93	4143.53	4109.98	▒	3734.33	3716.17	▒	3596.94	▒
W522		▒	▒	3741.60	▒	4402.15	4198.73	4147.04	3993.31	3803.72	3781.90	▒	3653.67	▒
W520tbs		▒	▒	3811.90	▒		4408.27	4241.74	4029.15	3854.80		3752.74	3717.11	▒
W521		▒	▒	3822.73	▒		4439.08	4262.79	4079.77	3859.07		3797.58	3755.08	▒
W520		▒	▒	**3832.79**	▒		**4455.09**	**4269.19**	**4103.41**			**3825.94**	**3776.74**	**3810.79**
W510tbs		▒	▒	3869.70	3635.96		4502.97	4303.35	4121.41			3856.90	3863.05	3858.83
W514		▒	▒	3909.35	3673.17		4529.66	4324.09	4124.31			3873.06	3873.57	3879.27
W513		3870.44	3675.97	3985.75	3709.92		4547.35	4344.68	4140.77			3906.01	3917.95	3952.16
W512		3893.17	3712.41	4062.31	3726.70		▒	4385.85	4158.01			3915.61	4000.76	3981.44
W511		3929.61	3756.18	4114.92	3777.78		4631.53		4183.17			3927.05	4048.95	4007.22
W510		**4003.88**	**3816.42**	**4144.66**	**3809.66**				**4221.90**			**3950.53**	**4081.58**	**4022.77**
W502		4072.35	3837.01	4194.68	3861.20				4288.55			3992.32	4154.78	4045.34
W501		4113.68	3854.85	4224.26	3881.94				4315.69			4050.42	4183.30	4076.15
W500			**3890.99**	**4297.46**	**3910.00**				**4380.96**			**4088.55**		**4100.54**
W410				4423.73								4115.08		4142.94
W400														
W300														

🟩	W800 CSP		
🟥	W700 CSP		
🟫	W600 CSP		
🟩	W520tbs		
🟨	W520 CSP		
🟦	W510tbs		
🟨	W510 CSP		
🟨	W500 CSP	▒	not present

TABLE 2-2

TABLE 2-3

COMPOSITE STRATIGRAPHIC PACKAGES (CSP) DEPTHS / 44 AND 49 UK QUADRANTS / Version July 1997

WELL		**44/19-3**	**44/23-4**	**44/24-2**	**44/27-1**	**44/28-1**	**44/28-2**	**44/29-1A**	**49/4-1**	**49/4-2A**	**49/4-3**	**49/5-2**
ZEZ1K		**3493.61**	**3197.58**	**3487.06**	**3822.02**	**3575.16**	**3417.39**	**3420.28**		**3192.08**	**3112.82**	**3251.09**
RO		**3652.52**	**3501.21**	**3729.53**	**4038.88**	**3795.52**	**3677.70**	**3668.86**	**3347.42**	**3421.90**	**3342.33**	**3511.41**
W800					**4114.52**	**3842.04**	**3688.53**		**3394.08**			
W702					4179.17	3890.53	3758.07		3469.72			
W700tbs												
W701					4188.78		3765.24		3490.92			
W700					**4223.71**				**3519.59**			
W603		3692.63			4272.50	4007.50	3878.24		3587.00			
W602		3768.27			4310.78	4036.93	3907.98		3601.94			
W601					4345.55	4091.38	3944.27		3615.36			
W600					**4397.86**	**4157.41**	**3986.82**		**3661.87**			
W523			3545.43		4438.88	4210.48	4059.72		3724.70			
W522		3819.51	3586.61		4840.57	4260.96	4208.86		3772.44			
W520tbs		3921.07	3637.24	3809.14	4892.11		4299.75	3797.26	3798.67	3459.26		
W521		3971.25	3642.57	3832.17	4910.41		4317.90	3809.77	3822.61	3481.07		
W520		**4027.67**	**3701.44**	**3904.15**	**4987.58**		**4362.89**	**3829.44**	**3878.27**	**3497.23**	**3365.21**	**3535.04**
W510tbs		4072.05	3824.51	3960.57			4481.07	3867.41	3971.14	3515.53	3392.51	3550.90
W514		4103.31	3834.57	4002.81			4483.67	3953.88	3979.68	3582.63	3411.26	3576.83
W513		4216.62	3918.45	4130.91			4531.40	4037.76	4051.36	3639.67	3476.23	3666.04
W512		4303.39	4112.89	4243.15				4141.46	4092.38		3521.06	3753.57
W511		4370.19	4161.99	4294.39				4184.46	4138.13	3671.24	3556.14	3797.95
W510		**4458.33**	**4207.89**	**4345.79**				**4250.80**	**4169.70**	**3702.04**	**3598.53**	**3821.74**
W502		4505.00		4384.37				4316.52		3750.53		
W501		4546.93		4429.96				4364.56		3834.10		
W500		**4611.75**		**4496.00**				**4423.12**		**3891.45**		
W410		4709.50		4604.58				4525.60	4225.36	3987.22	3690.19	3878.47
W400		**4761.81**		**4689.98**					**4261.20**		**3762.32**	
W300												
▨	W800 CSP											
▨	W700 CSP											
▨	W600 CSP											
▨	W520tbs											
▨	W520 CSP											
▨	W510tbs											
▨	W510 CSP											
▨	W500 CSP		▨	not present								

TABLE 2-3

CSP THICKNESSES

TABLE 2-4

CSP THICKNESSES / D AND E QUADRANTS / Version July 1997

WELL	D12-3	D12-4	D15-2	D15-3	D15-4	E10-2tvd	E13-1	E13-2	E16-3	E17-2	E18-2	E18-3
W800-RO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
W700-W800	0.00	0.00	0.00	0.00	0.00	0.00	40.11	0.00	0.00	100.04	95.31	75.94
W600-W700	0.00	0.00	0.00	0.00	56.58	0.00	137.40	0.00	0.00	100.19	161.04	168.97
W520tbs-W600	58.25	105.84	162.41	72.28	127.64	58.56	146.55	113.76	223.41	151.28	157.38	237.90
W520-W520tbs	37.21	165.31	35.54	16.78	85.86	62.67	21.20	20.74	53.08	52.00	22.73	50.02
W510tbs-W520	4.73	44.38	0.00	0.00	0.00	8.54	21.96	14.64	17.23	8.24	12.50	22.72
W510-W510tbs	90.74	0.00	77.47	93.33	0.00	132.07	106.90	68.63	142.43	0.00	0.00	0.00
W500-W510	72.59	0.00	70.30	109.04	0.00	100.50	95.47	74.11	179.34	0.00	0.00	0.00

CSP THICKNESSES / J AND K QUADRANTS / Version July 1997

WELL	J3-1	J3-2	K1-2	K1-3	K2-1	K2-2	K3-1	K3-2	K4-7	K5-1	K5-A-1	K5-2	K5-D-1
W800-RO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00
W700-W800	0.00	0.00	0.00	0.00	62.22	25.92	24.70	0.00	0.00		0.00	0.00	0.00
W600-W700	0.00	0.00	0.00	0.00	272.36	118.65	61.16	0.00	129.31		0.00	0.00	0.00
W520tbs-W600	0.00	0.00	142.43	0.00		287.46	218.07	87.54	178.73		127.64	161.81	0.00
W520-W520tbs	0.00	0.00	20.89	0.00		46.82	27.45	74.26			73.20	59.63	39.95
W510tbs-W520	0.00	0.00	36.91	15.10		47.88	34.16	18.00			30.96	86.31	48.04
W510-W510tbs	258.18	273.59	274.96	173.70				100.49			93.63	218.53	163.94
W500-W510		74.57	152.80	100.34				159.06			138.02		77.77

CSP THICKNESSES / J AND K QUADRANTS / Version July 1997

WELL	44/19-3	44/23-4	44/24-2	44/27-1	44/28-1	44/28-2	44/29-1A	49/4-1	49/4-2A	49/4-3	49/5-2
W800-RO	0.00	0.00	0.00	75.64	46.52	10.83	0.00	46.66	0.00	0.00	0.00
W700-W800	0.00	0.00	0.00	109.19	48.49	76.71	0.00	125.51	0.00	0.00	0.00
W600-W700	115.75	0.00	0.00	174.15	266.88	221.58	0.00	142.28	0.00	0.00	0.00
W520tbs-W600	152.80	136.03	79.61	494.25		312.93	128.40	136.80	37.36	0.00	0.00
W520-W520tbs	106.60	64.20	95.01	95.47		63.14	32.18	79.60	37.97	22.88	23.63
W510tbs-W520	44.38	123.07	56.42			118.18	37.97	92.87	18.30	27.30	15.86
W510-W510tbs	386.28	383.38	385.22				383.39	198.56	186.51	206.02	270.84
W500-W510	153.42		150.21				172.32		189.41		

115.75 TRUNCATED BY RO

TABLE 2-5

RELIABILITY RATING OF BOUNDARIES IN THE CORRELATED WELLS

WELL	D12-3	D12-4	D15-2	D15-3	D15-4	E10-2	E16-3	E17-2	E18-3	J3-2	K1-2	K1-3	K2-1	K2-2	K3-1	K3-2	K4-7	K5-1	K5-A-1	K5-2	K5-D-1	44/19-3	44/24-2	44/29-1A	49/4-2A	49/4-3	49/5-2
RO	2	2	2	2	2	3	2	1	2	2	3	2	1	1	1	2	3	2	3	1	2	2	2	2	2	2	2
W800	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
W702	NP	NP	NP	NP	NP	NP	NP	2	1	NP	NP	NP	3	2	1	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
W700tbs	NP	NP	NP	NP	NP	NP	NP	1	1	NP	NP	NP	1	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
W701	NP	NP	NP	NP	NP	NP	NP	1	1	NP	NP	NP	1	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
W700	NP	NP	NP	NP	NP	NP	NP	1	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
W603	NP	NP	NP	NP	3	NP	NP	1	1	NP	NP	NP	1	1	1	NP	3	NP	NP	NP	NP	1	NP	NP	NP	NP	NP
W602	NP	NP	NP	NP	NP	NP	NP	1	1	NP	NP	NP	1	1	NP	NP	3	NP	NP	NP	NP	1	NP	NP	NP	NP	NP
W601	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	1	1	NP	NP	1	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
W600	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	1	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP
W523	NP	NP	2	NP	NP	NP	2	1	1	NP	NP	NP	2	1	1	NP	1	2	2	2	NP	NP	NP	NP	NP	NP	NP
W522	NP	2	2	NP	1	NP	2	1	1	NP	3	NP	2	1	1	2	1	2	2	2	NP	2	NP	NP	NP	NP	NP
W520tbs	1	1	1	1	1	1	1	1	1	NP	1	NP	NP	1	1	1	2	NP	1	1	NP	1	1	1	1	NP	NP
W521	1	1	2	1	1	1	1	1	1	NP	1	NP	NP	1	1	2	3	NP	2	1	NP	1	1	1	2	NP	NP
W520	1	3	2	1	1	1	1	1	1	NP	1	NP	NP	1	1	1	NP	NP	1	1	2	1	1	1	2	3	3
W510tbs	2	1	NP	NP	2	1	2	2	1	NP	1	2	NP	1	1	1	NP	NP	2	1	1	1	1	1	1	1	1
W514	2	3	2	2	2	1	2	2	2	NP	1	2	NP	1	2	2	NP	NP	2	1	1	1	1	1	1	1	1
W513	2	NP	2	2	NP	1	2	NP		2	2	2	NP	2	2	2	NP	NP	2	2	2	2	2	2	2	2	1
W512	2	NP	2	2	NP	1	2	NP	NP	2	2	2	NP	NP	3	2	NP	NP	2	2	2	2	2	2	3	2	2
W511	2	NP	2	2	NP	1	2	NP	NP	2	2	2	NP	3	NP	2	NP	NP	2	2	2	2	2	2	3	2	2
W510	1	NP	1	1	NP	1	2	NP	NP	1	1	1	NP	NP	NP	1	NP	NP	2	1	1	1	1	1	1	2	2
W502	1	NP	2	1	NP	1	1	NP	NP	1	1	2	NP	NP	NP	2	NP	NP	2	2	2	1	1	1	1	NP	NP
W501	1	NP	2	1	NP	1	1	NP	NP	1	1	2	NP	NP	NP	2	NP	NP	2	2	2	1	1	1	1	NP	NP
W500	1	NP	3	1	NP	1	1	NP	NP	1	1	2	NP	NP	NP	3	NP	NP	1	NP	1	1	1	1	1	NP	NP
W410	3	NP	NP	3	NP	3	1	NP	NP	NP	3	NP	NP	NP	NP	NP	NP	NP	3	NP	3	2	2	2	2	2	3
W400	NP	NP	NP	3	NP	3	3	NP	NP	NP	3	NP	NP	NP	NP	NP	NP	NP	3	NP	3	2	1	2	2	2	3
W300	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	NP	2	NP	NP	NP	NP	NP

1 HIGH RELIABILITY
2 MEDIUM RELIABILITY / BASED ON ADJACENT WELL CORRELATIONS / BOUNDARIES SUBJECTED TO CHANGE
3 LOW RELIABILITY / BOUNDARIES UNCERTAIN
NP NOT PRESENT

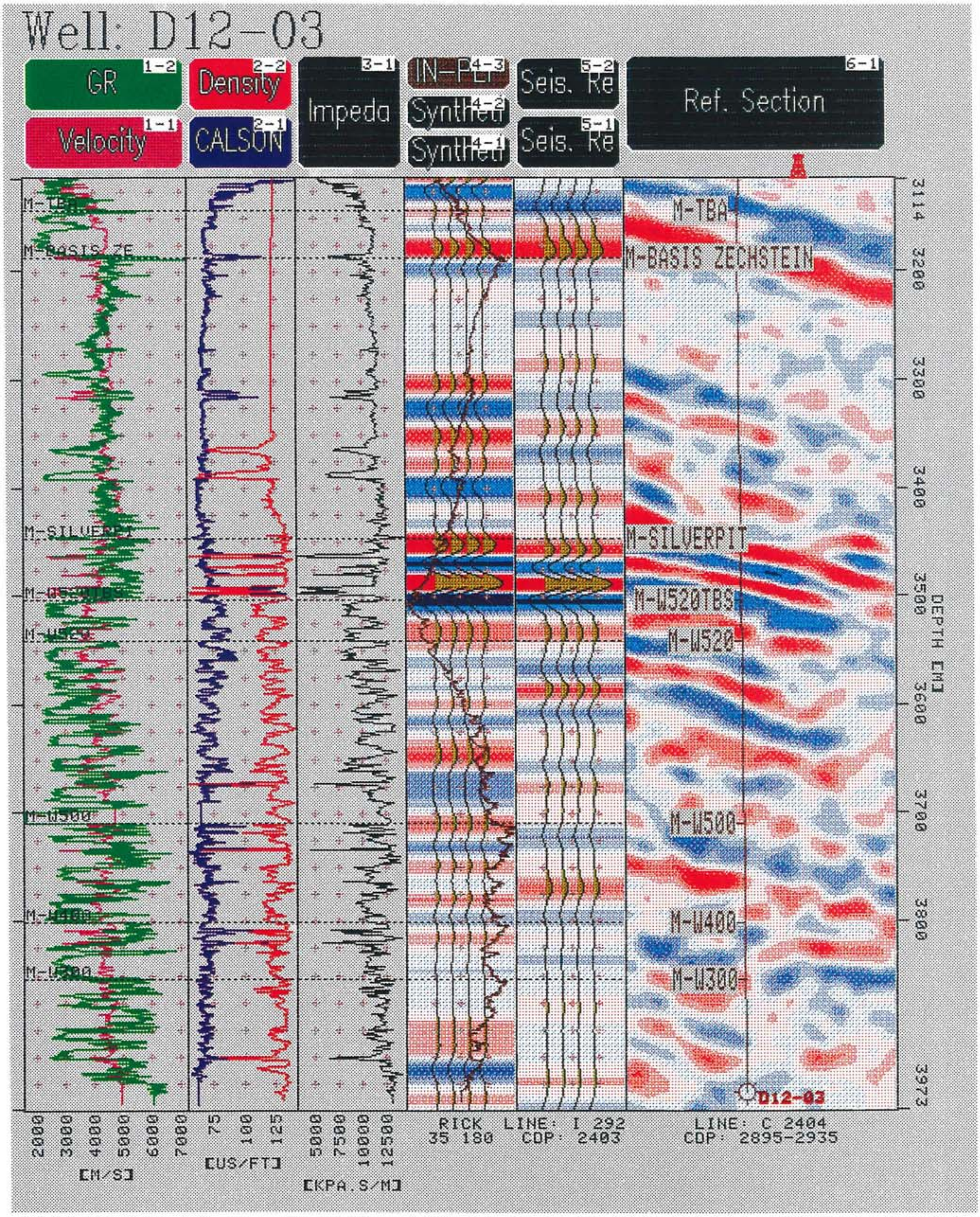


Figure 3.1 : Synthetic seismogram of well D12-03

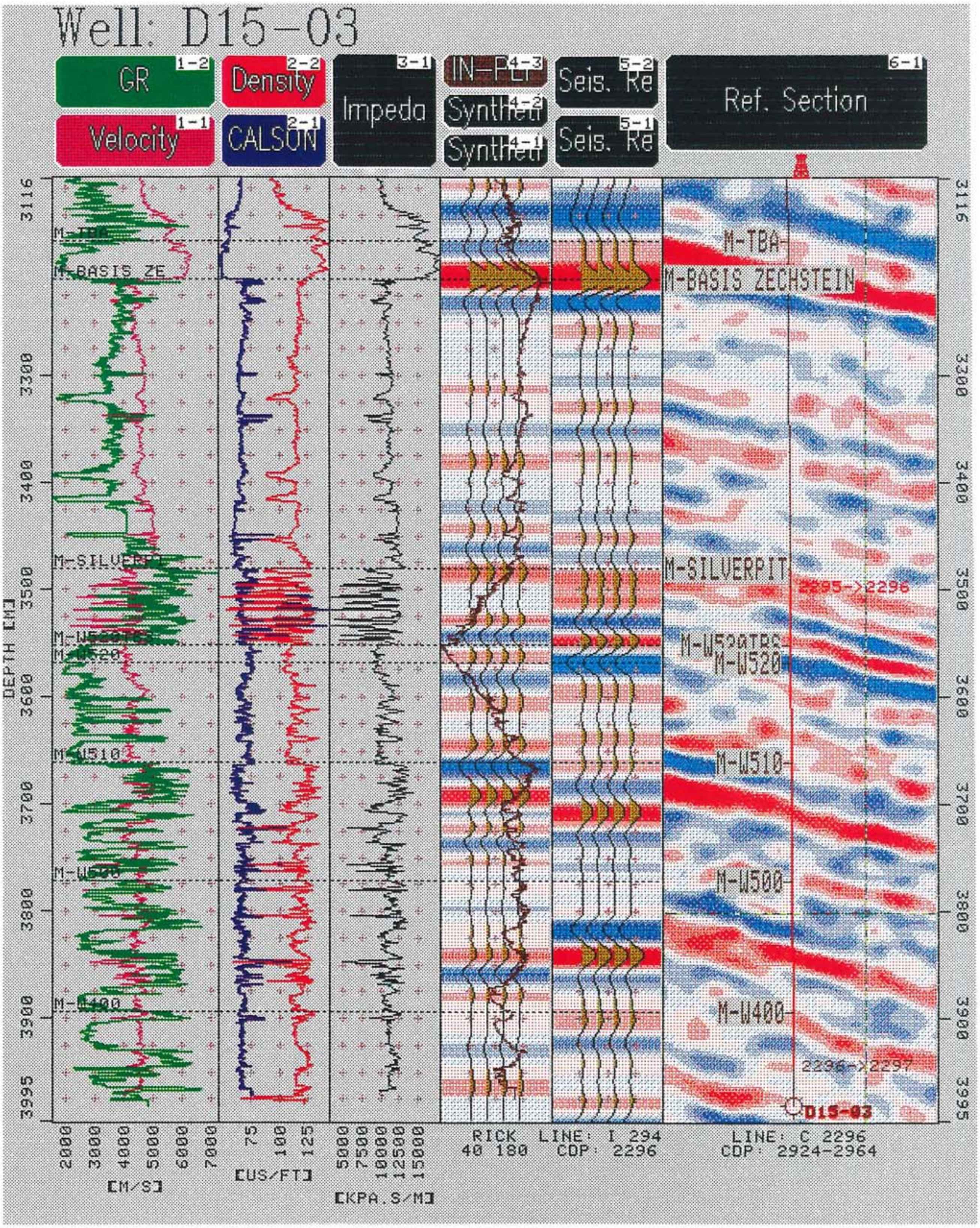
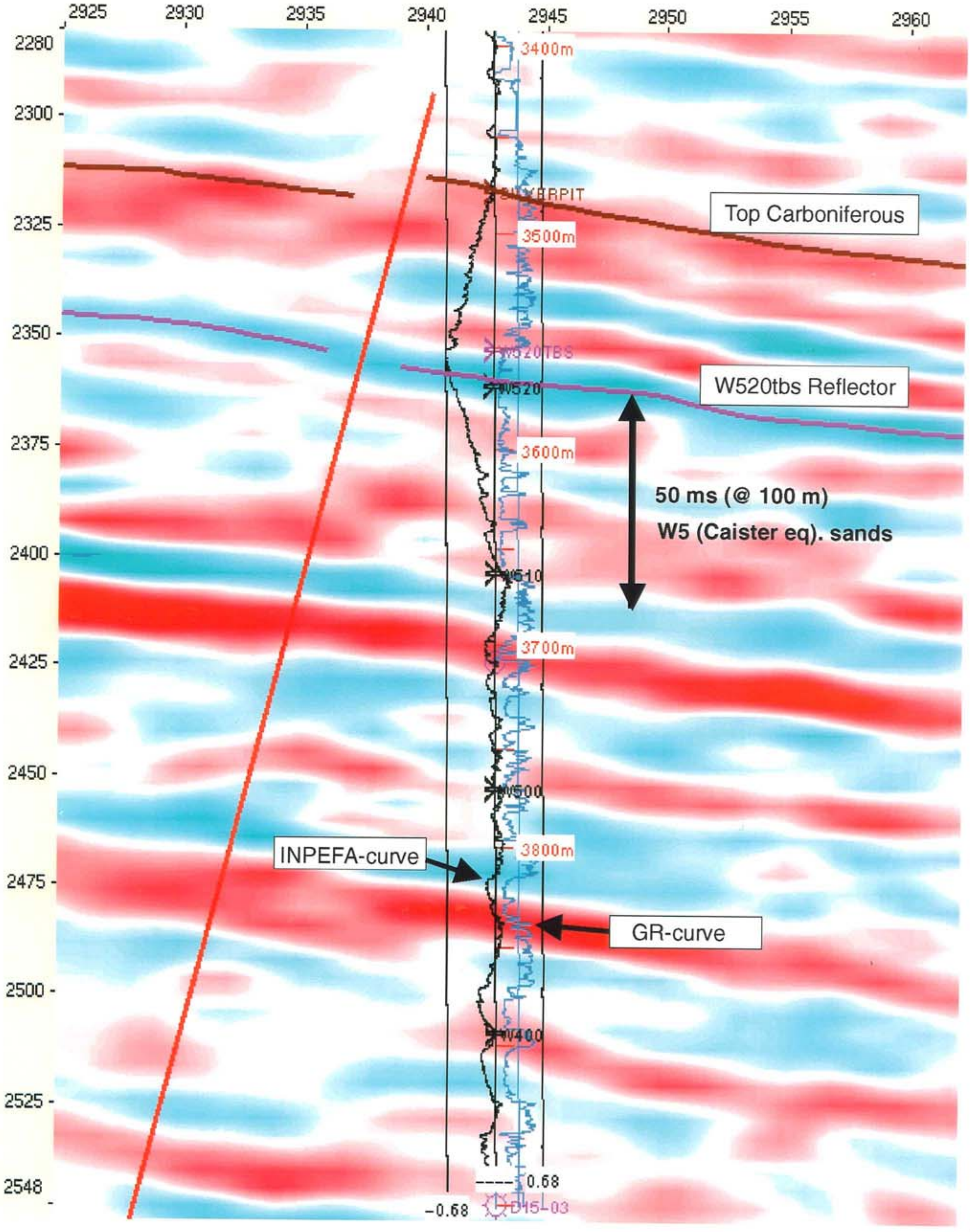


Figure 3.2 : Synthetic seismogram of well D15-03



Exploration Well D15-03

Figure 3.3 : 3D Seismic line at D15-03

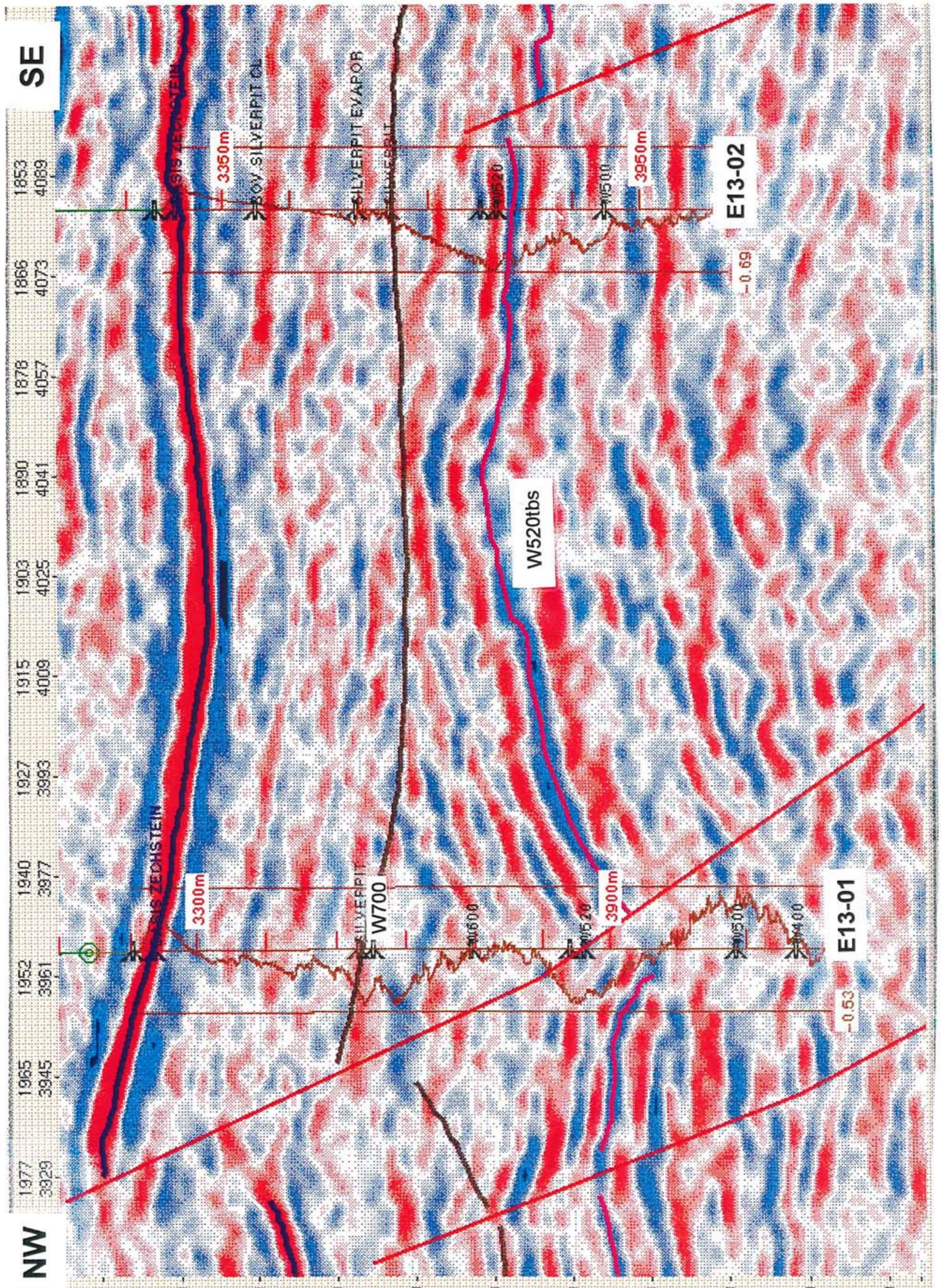


Figure 3.4 : Random seismic line across wells E13-01 and E13-02

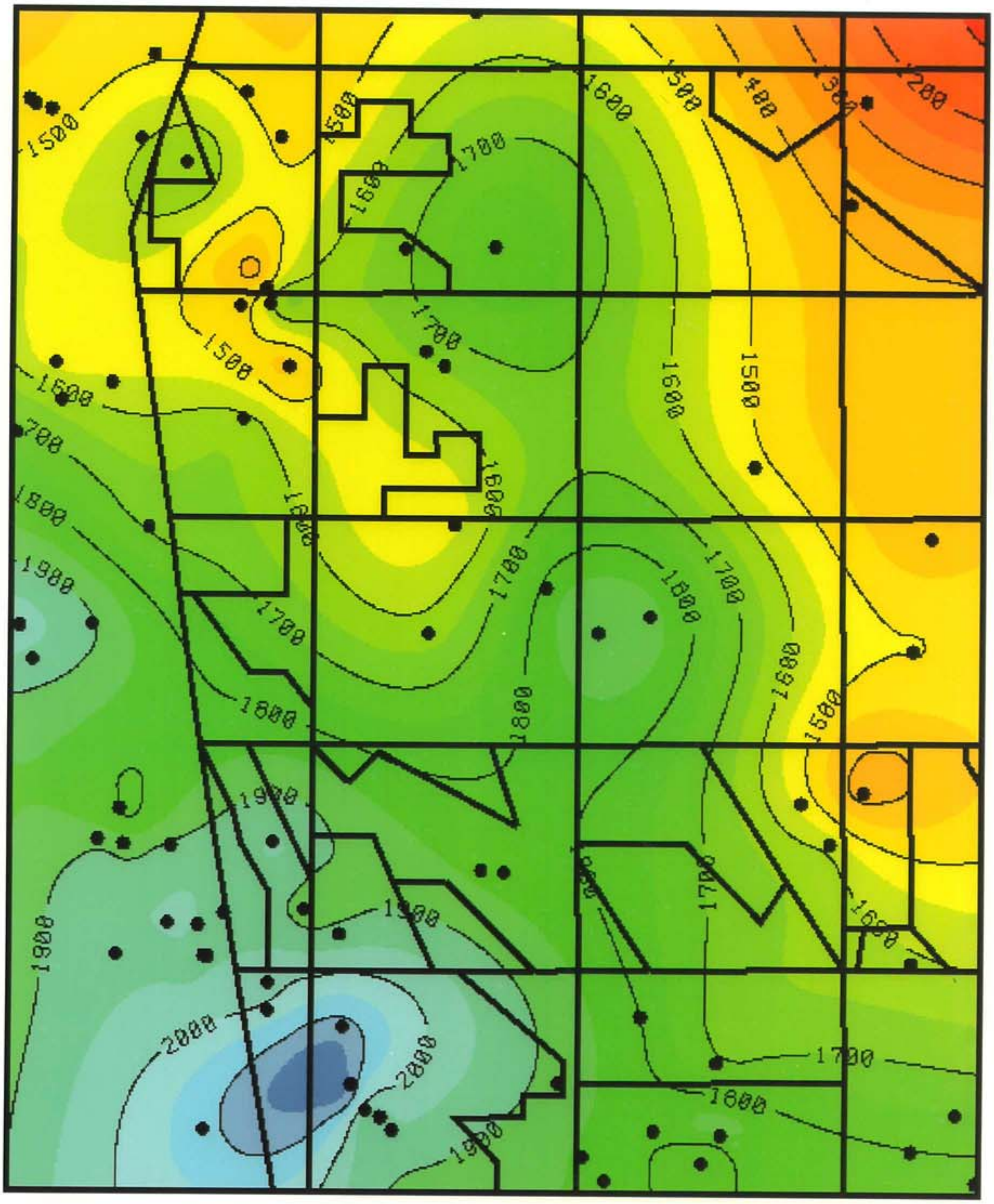
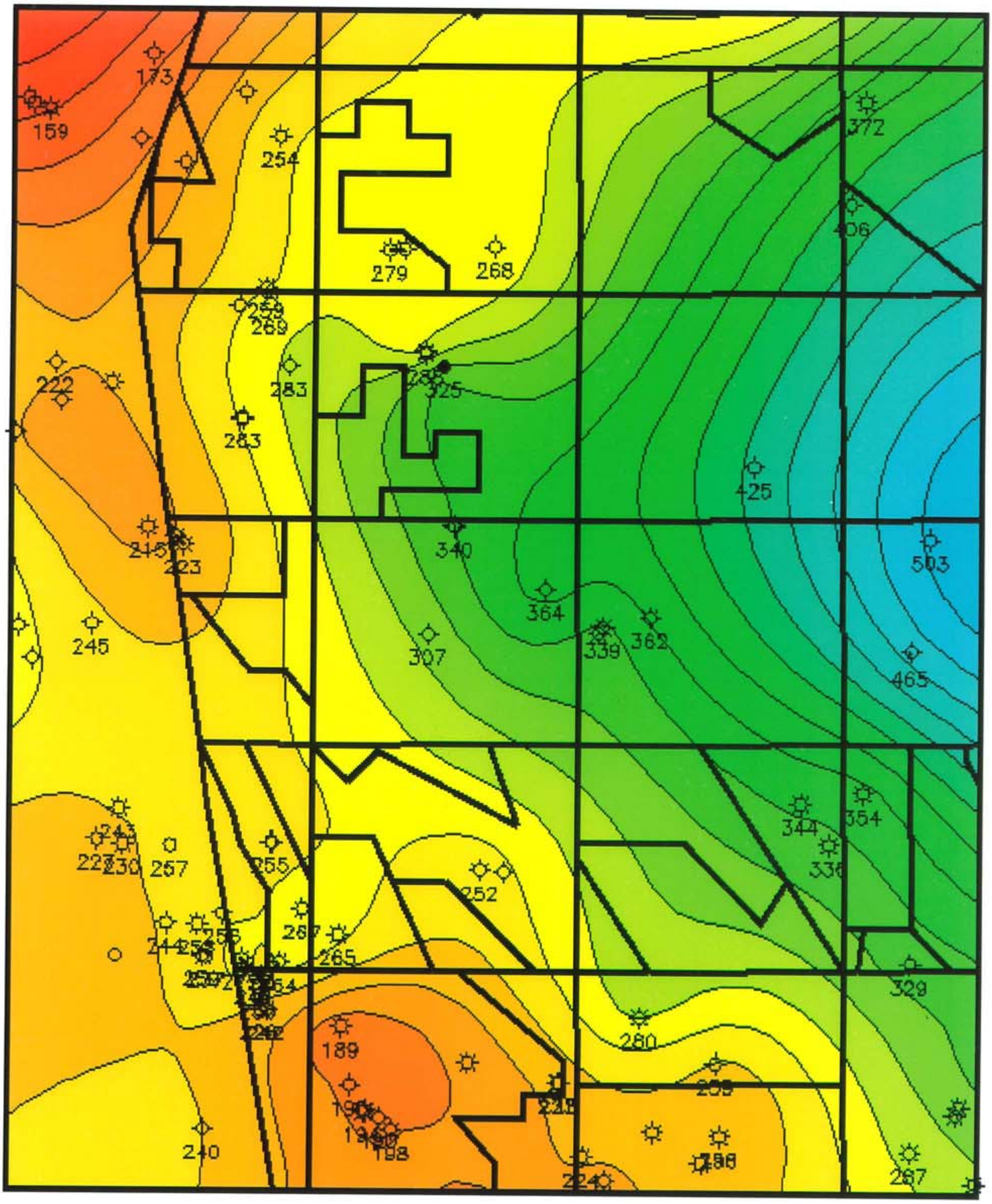


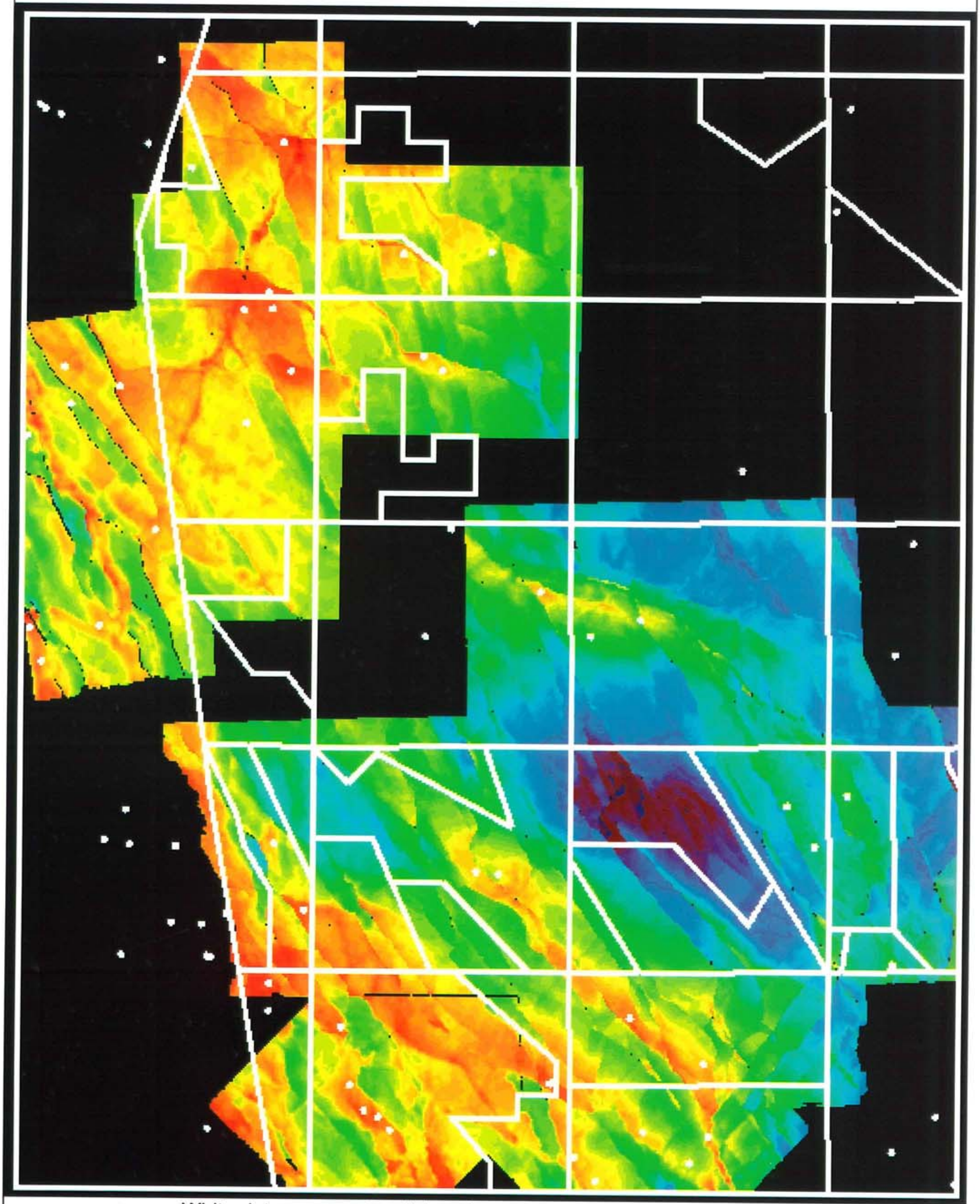
Figure 3.5 : Contoured Vo values for k=1.33, Chalk group



Contourmap of Rotliegend isopach used for construction of the top Carboniferous depthmap.

Contourinterval 20 m.

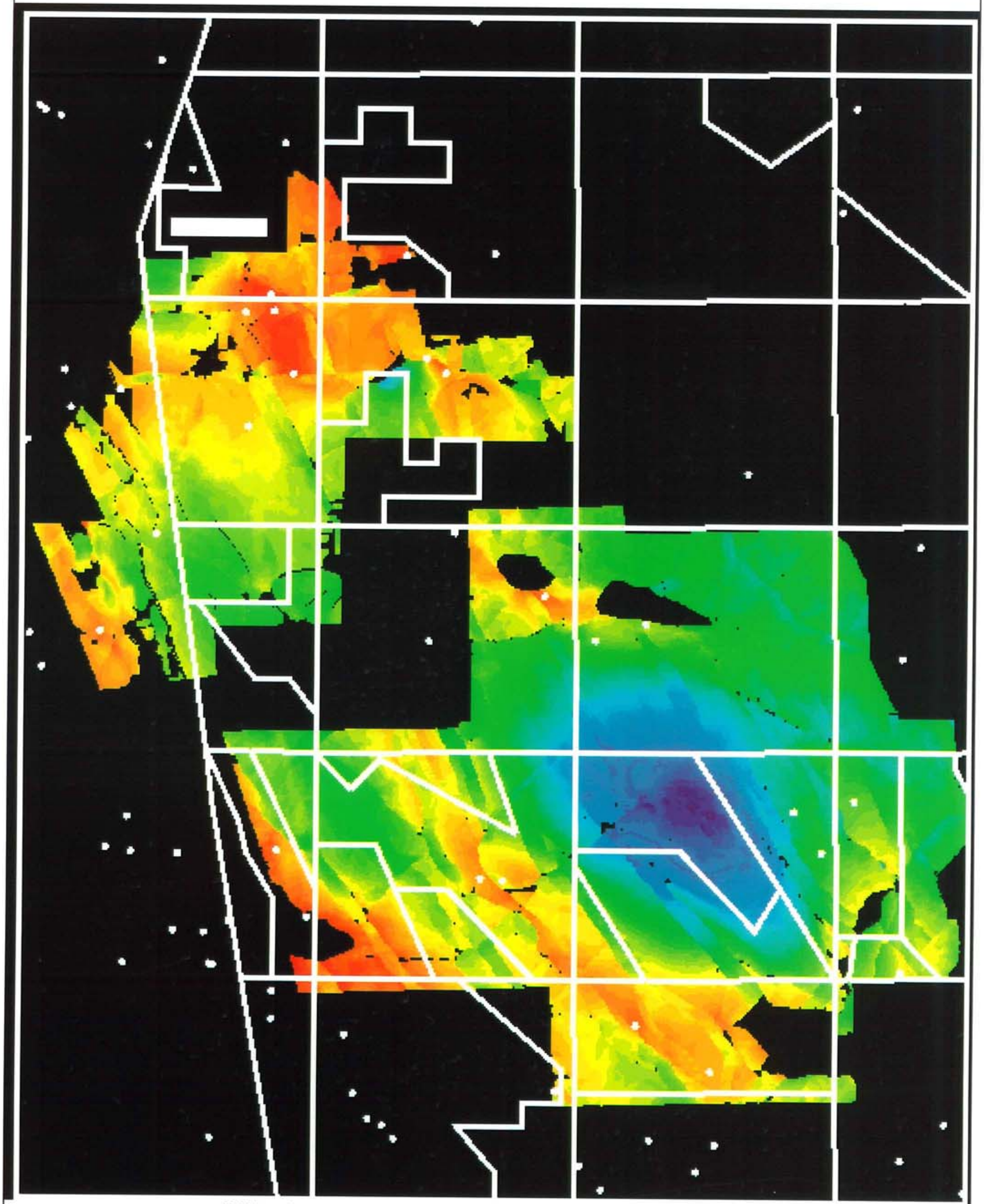
Figure 3.6 : Rotliegend Isopach (in meters) from 88 wells



White dots represent well locations

Depth range : Highest (red) 3100m to Low (purple) 4700m

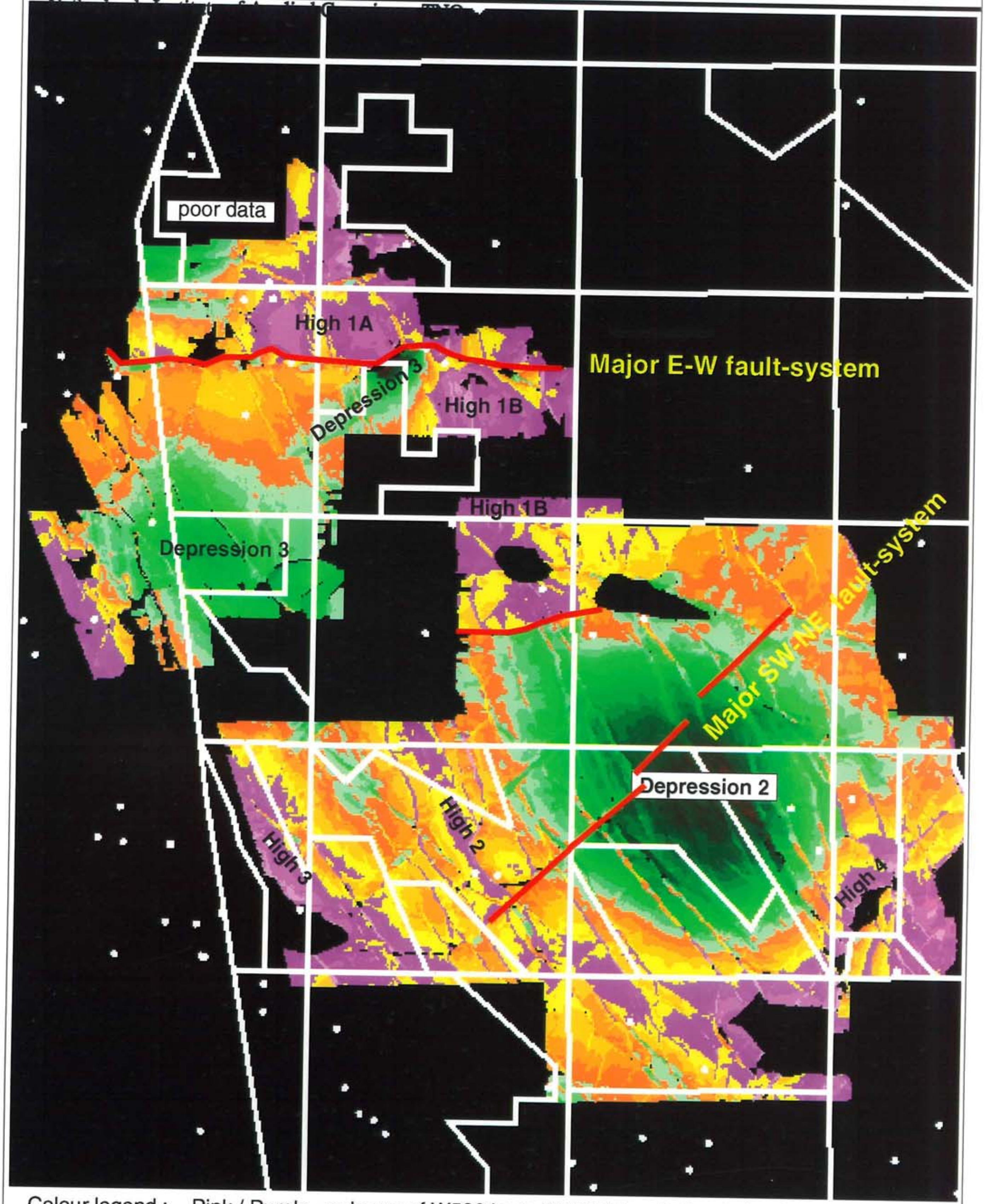
Figure 3.7 : Top Carboniferous depth map of 3D area



White dots represent well locations

Depth range : Highest (red) 3200m to Low (purple) 6000m

Figure 3.8 : Intra-Carboniferous horizon W520tbs depthmap



Colour legend : Pink / Purple - subcrop of W520tbs to W600 (Maurits fm shales & coals)
Yellow / Orange : subcrop of W600 to W700 (Westphalian C sand-prone units))
Green : subcrop of Westphalian D to Stephanian

Figure 3.9 : Preserved time-thickness of interval W520tbs - Base Rotliegend

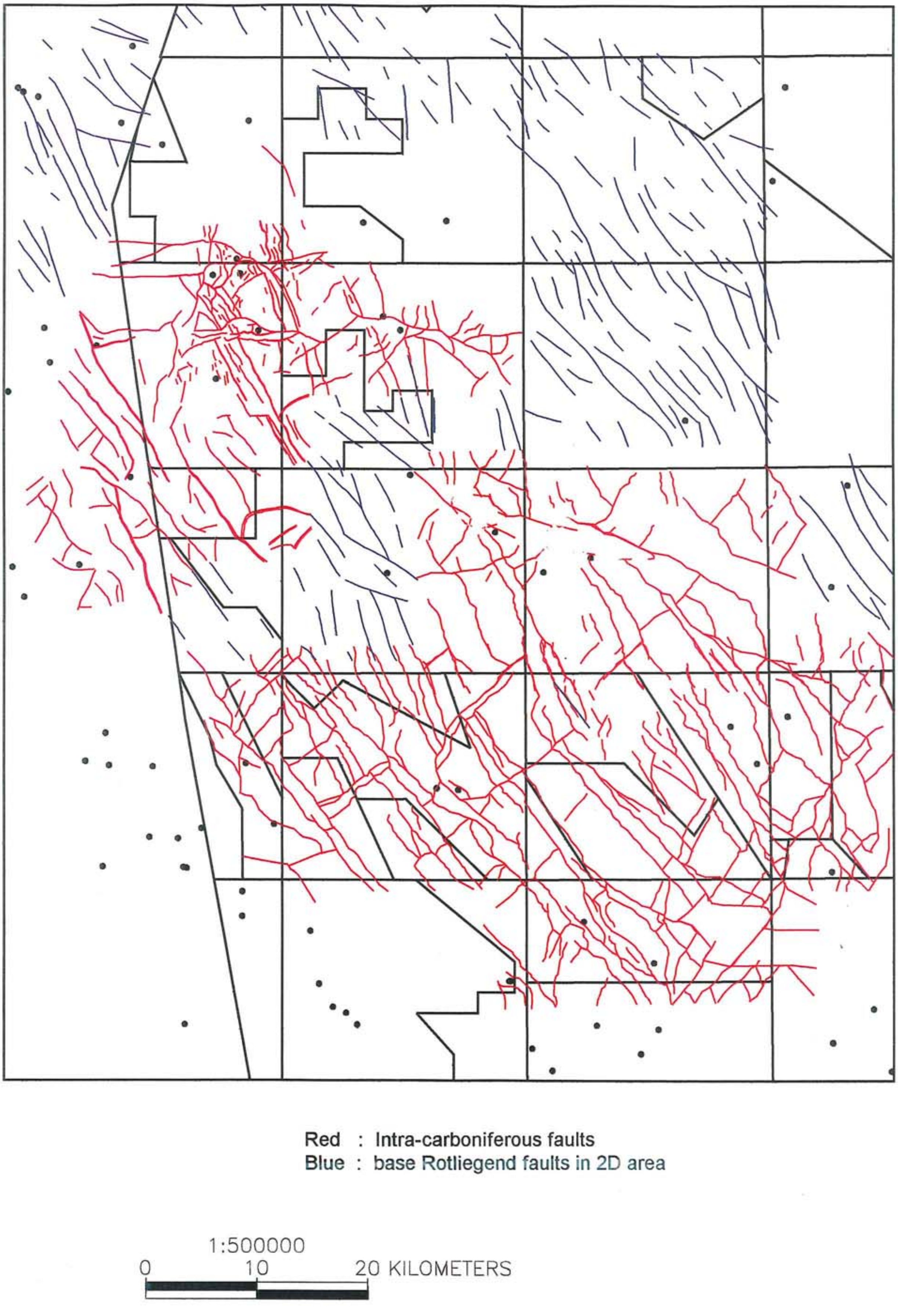


Figure 4.1 : Faultmap at intra-Carboniferous level W520tbs

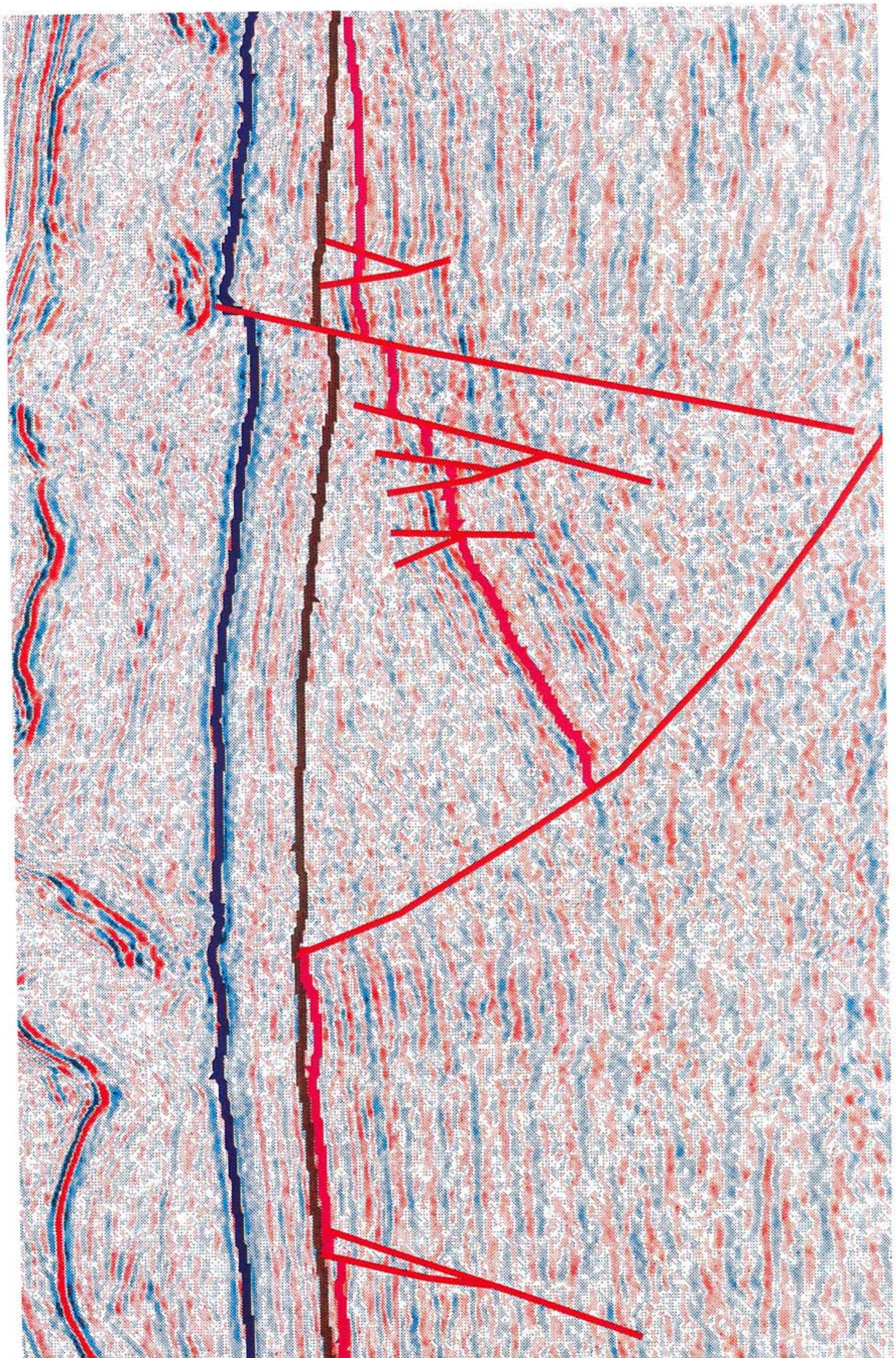


Figure 4.2 : Seismic line across depression 1 in block E13

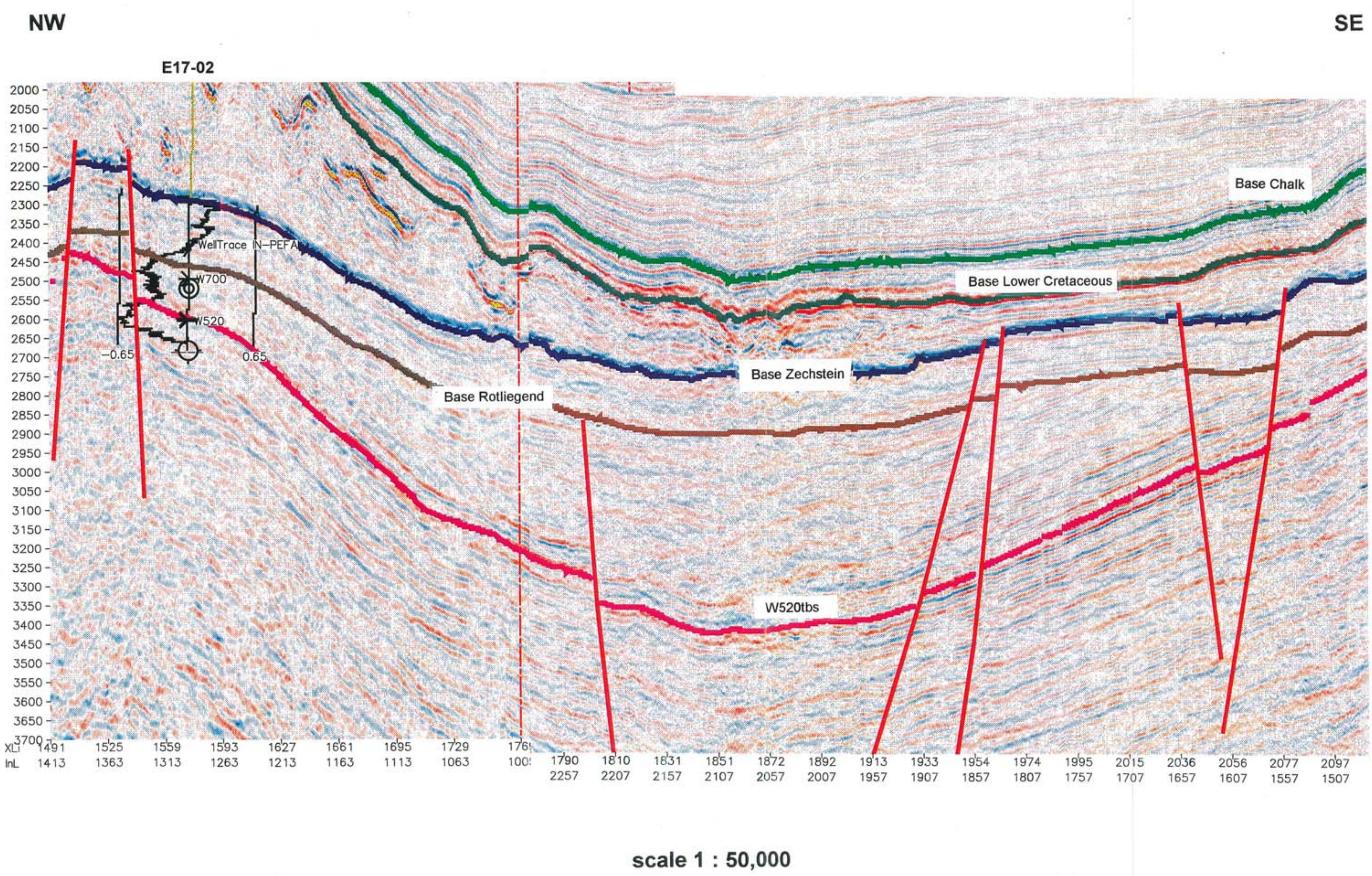
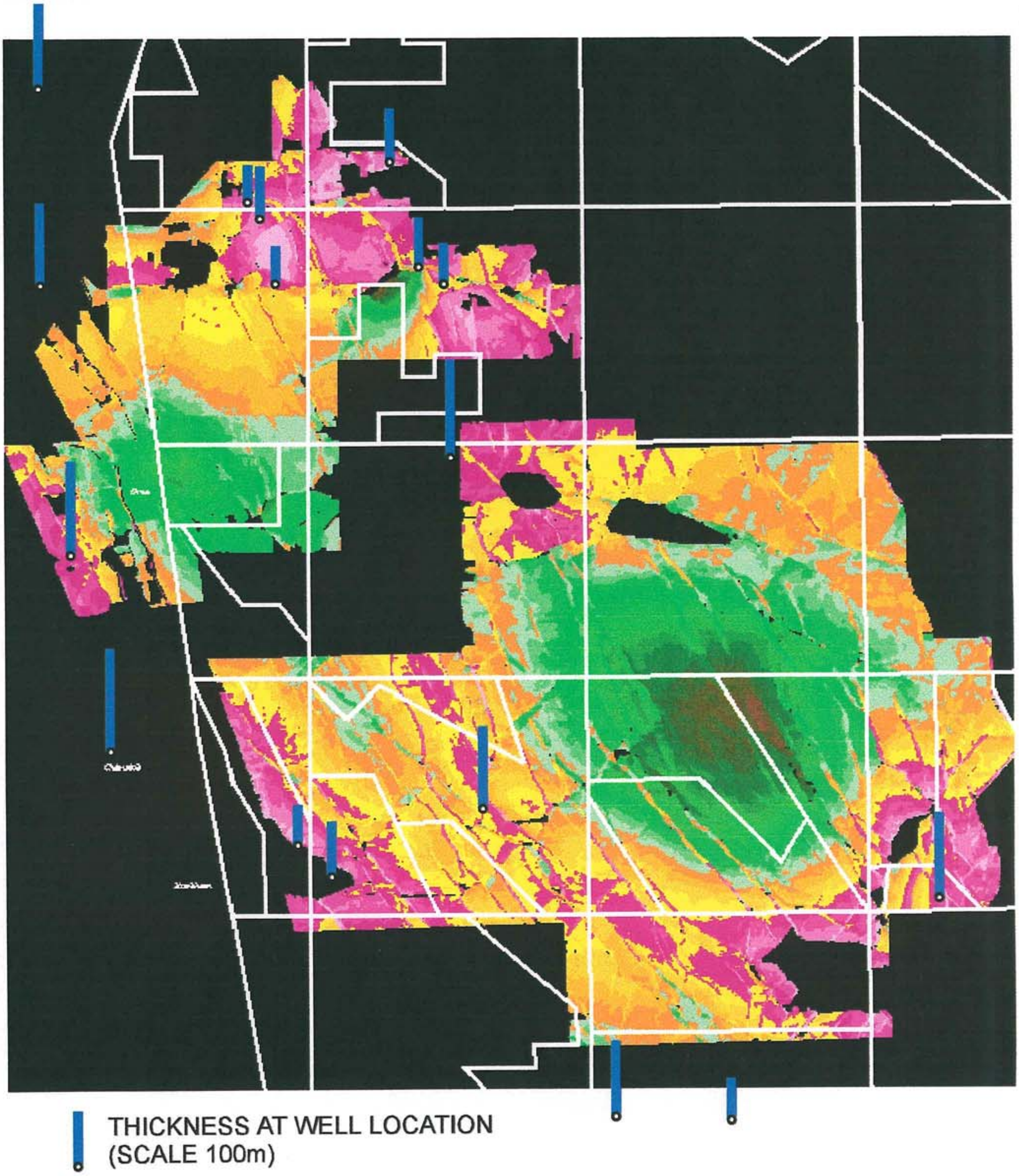
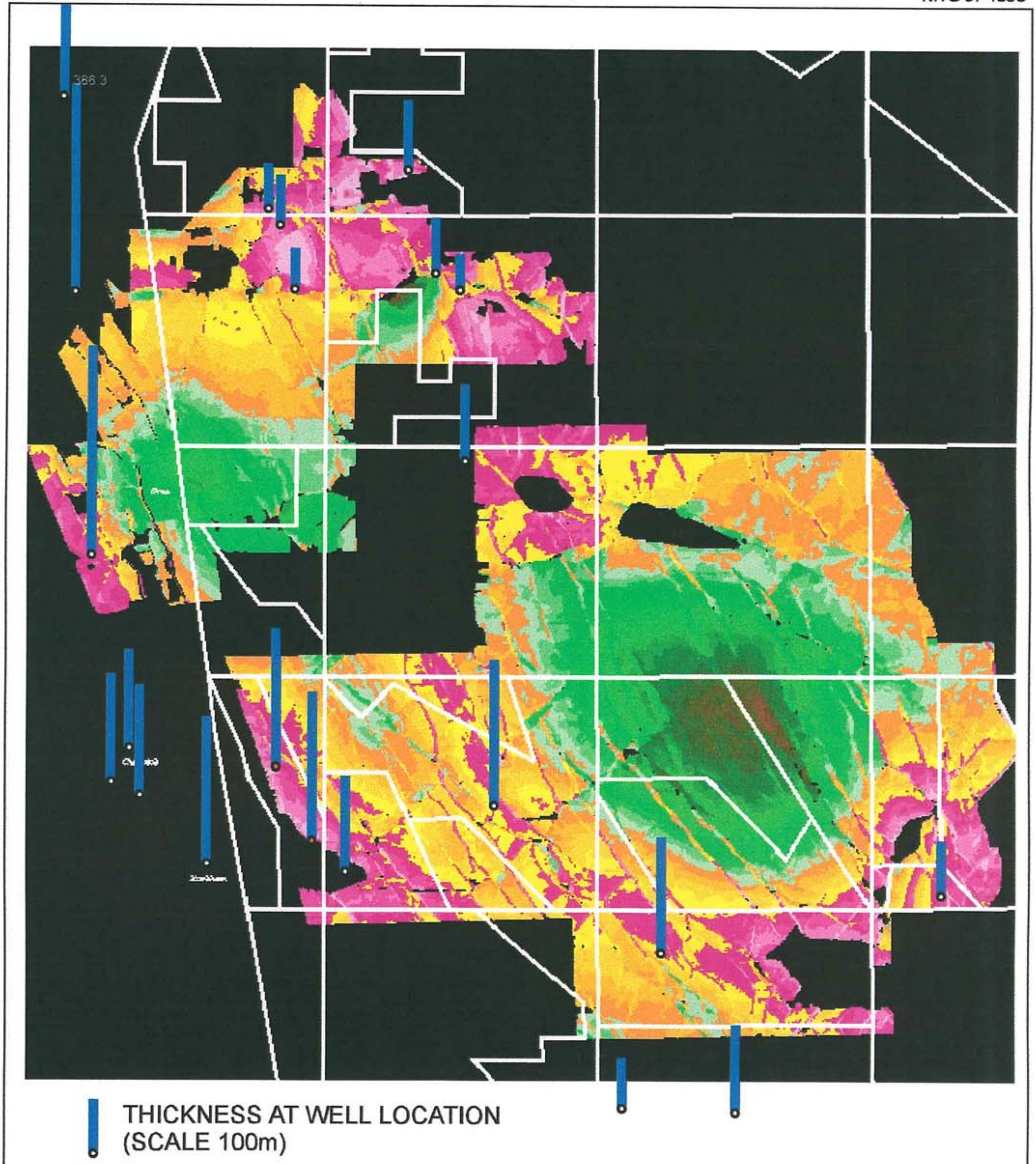


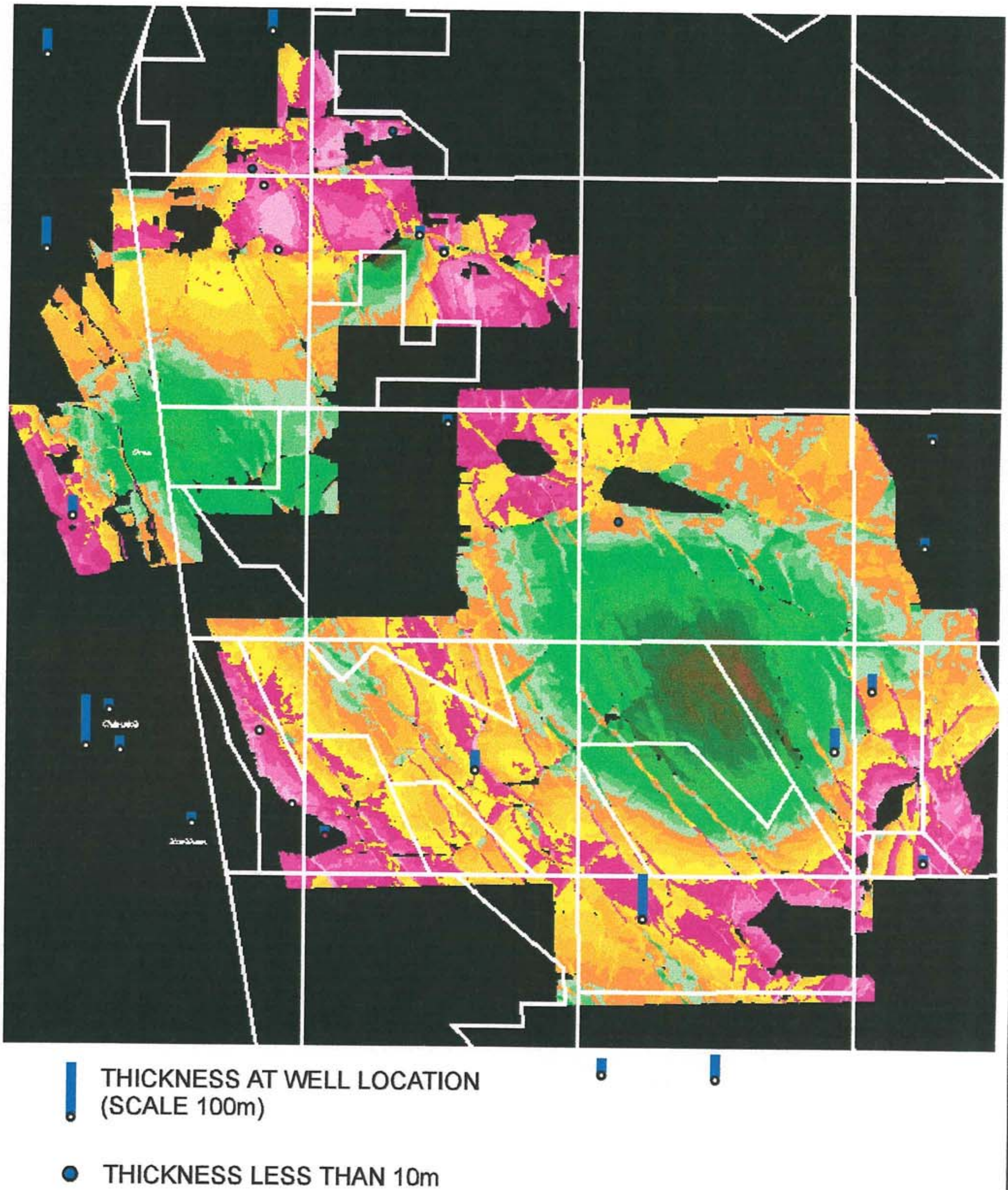
Figure 4.3 : Seismic line across Depression 2 in block K2



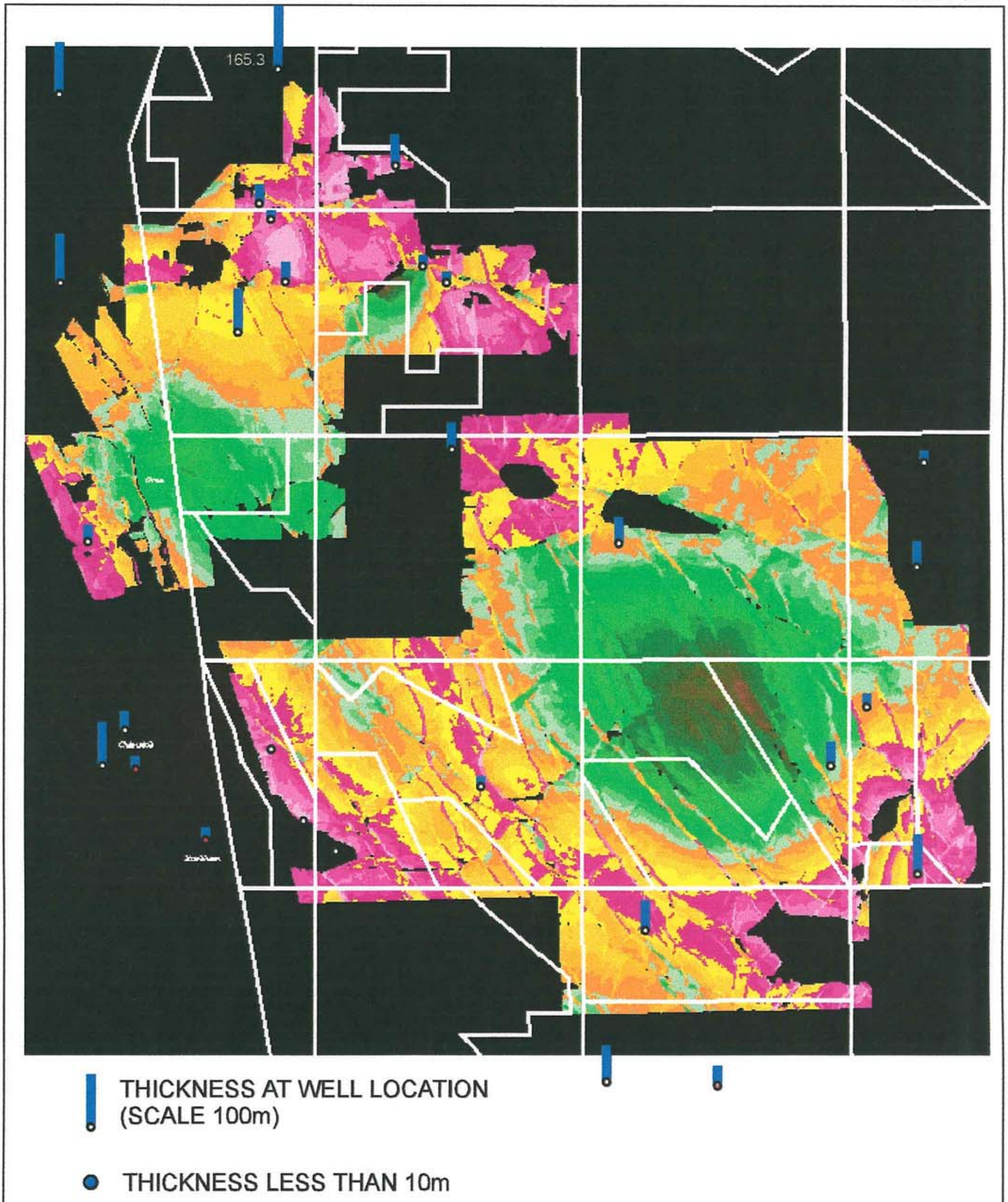
THICKNESS DEVELOPMENT OF CSP W500
PROJECTED ON TOP CARBONIFEROUS SUBCROP MAP



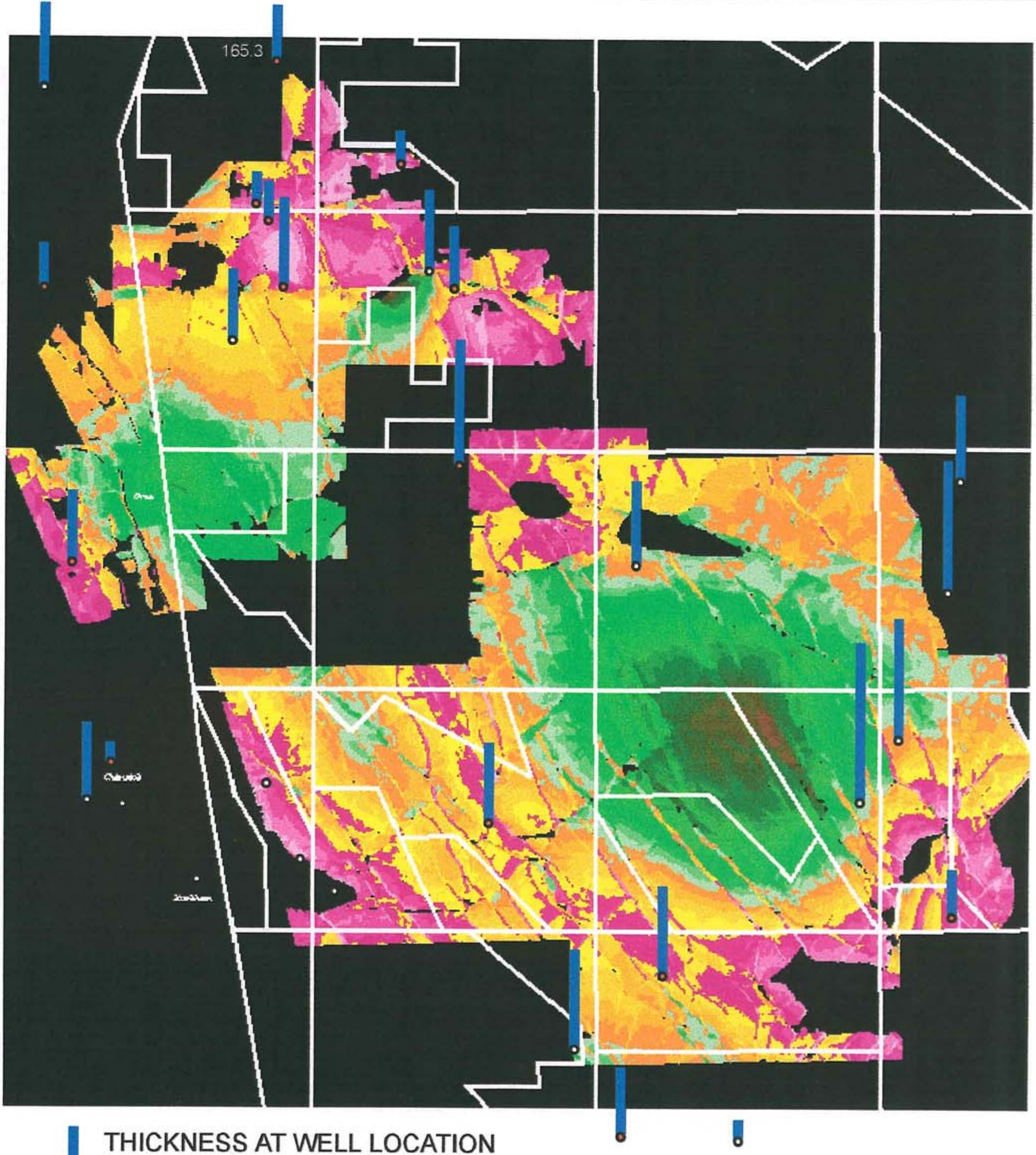
THICKNESS DEVELOPMENT OF CSP W510
PROJECTED ON TOP CARBONIFEROUS SUBCROP MAP



THICKNESS DEVELOPMENT OF CSP W510tbs
PROJECTED ON TOP CARBONIFEROUS SUBCROP MAP



THICKNESS DEVELOPMENT OF CSP W520
PROJECTED ON TOP CARBONIFEROUS SUBCROP MAP

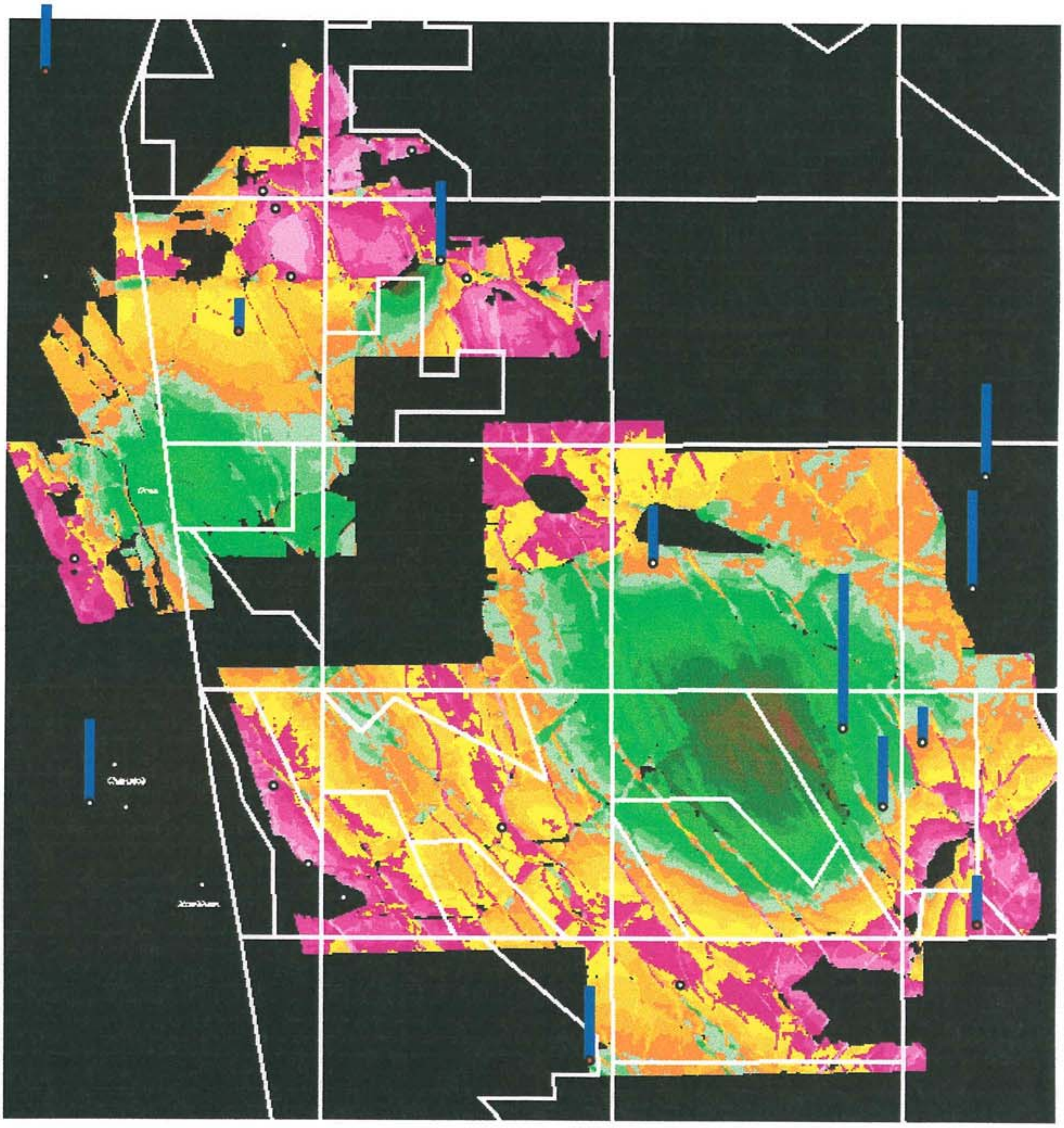


THICKNESS AT WELL LOCATION
(SCALE 100m)

TRUNCATED THICKNESS AT WELL LOCATION
(SCALE 100m)

● THICKNESS LESS THAN 10m

THICKNESS DEVELOPMENT OF CSP W520tbs
PROJECTED ON TOP CARBONIFEROUS SUBCROP MAP

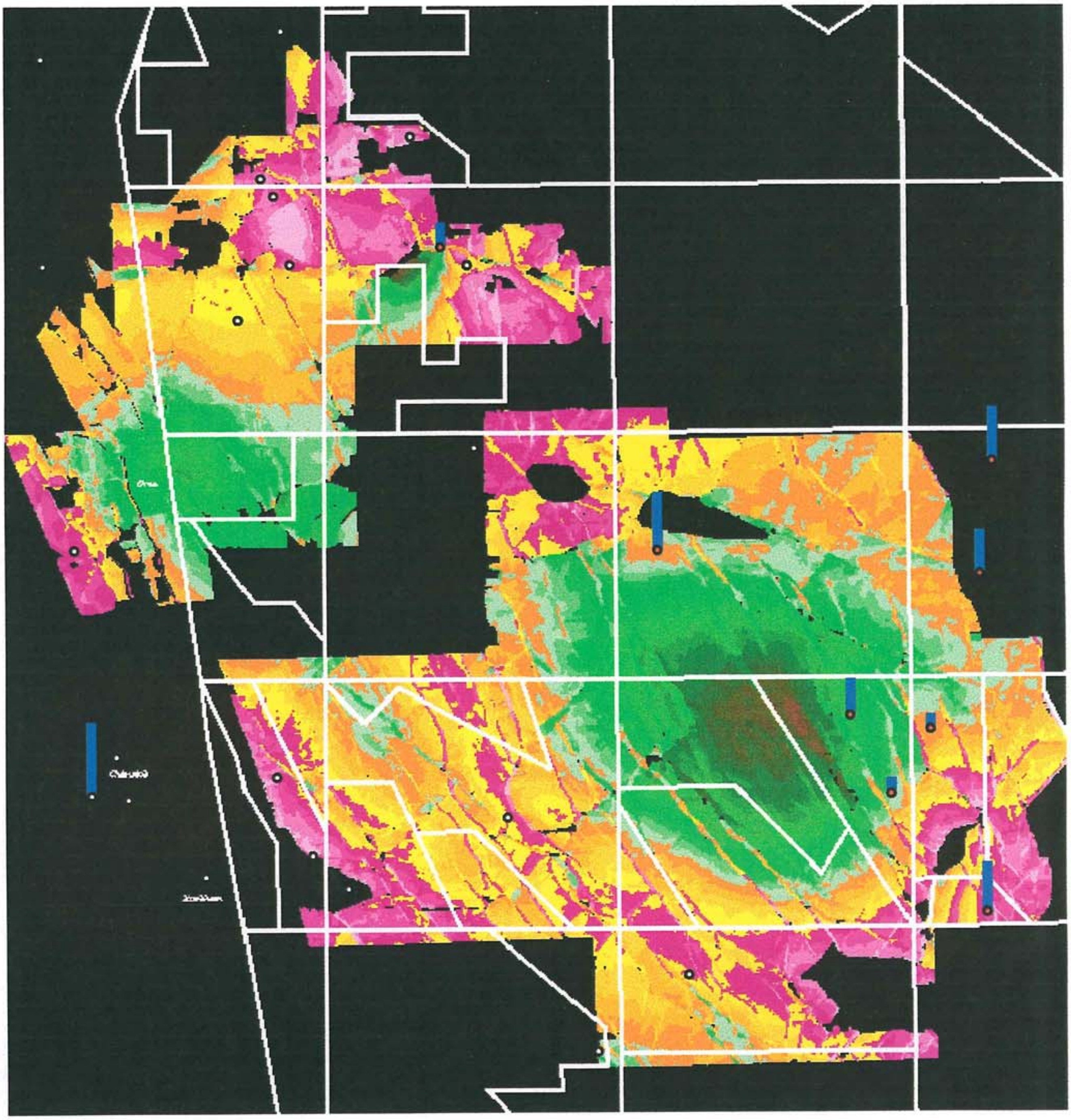


THICKNESS AT WELL LOCATION
(SCALE 100m)

TRUNCATED THICKNESS AT WELL LOCATION
(SCALE 100m)

● THICKNESS LESS THAN 10m

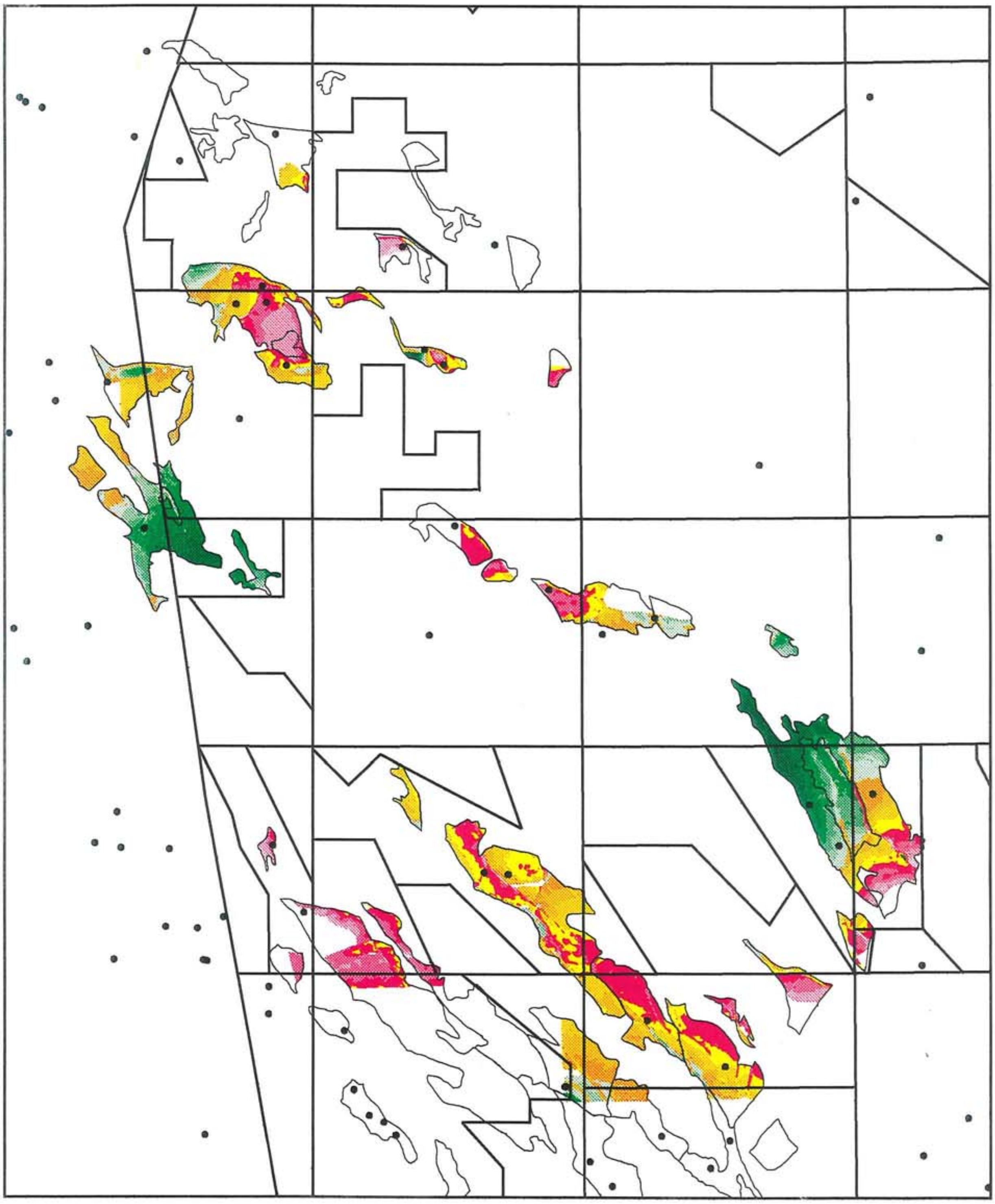
THICKNESS DEVELOPMENT OF CSP W600
PROJECTED ON TOP CARBONIFEROUS SUBCROP MAP



- THICKNESS AT WELL LOCATION (SCALE 100m)
- TRUNCATED THICKNESS AT WELL LOCATION (SCALE 100m)
- ● THICKNESS LESS THAN 10m

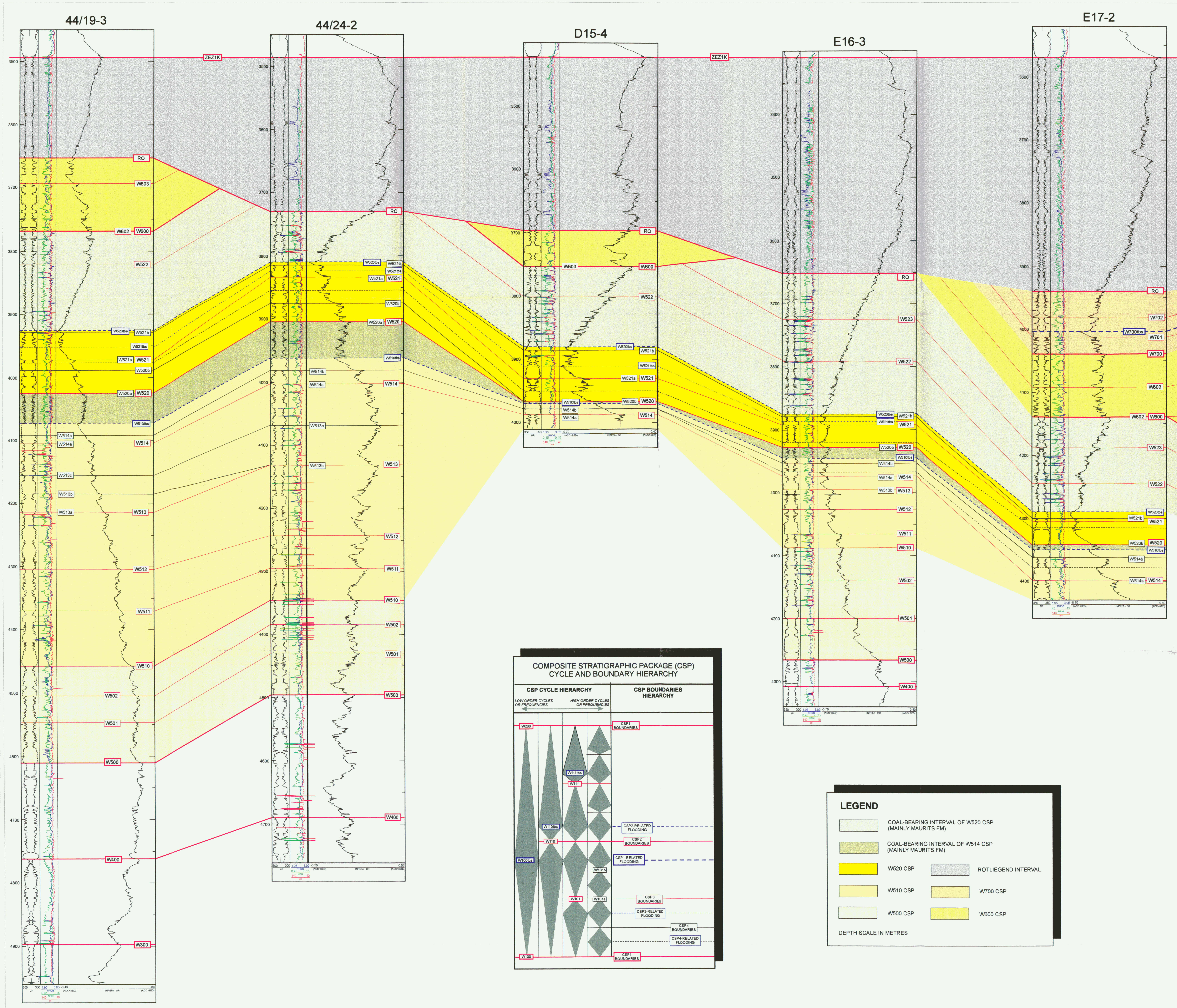
THICKNESS DEVELOPMENT OF CSP W700

PROJECTED ON TOP CARBONIFEROUS SUBCROP MAP



Carboniferous units subcropping the Rotliegend unconformity, superimposed on structures defined at top Carboniferous. (colour coding as in enclosure 3.5)

Figure 5.1 : Prospective structures



COMPOSITE STRATIGRAPHIC PACKAGE (CSP) CYCLE AND BOUNDARY HIERARCHY

CSP CYCLE HIERARCHY

LOW ORDER CYCLES OR FREQUENCIES — *HIGH ORDER CYCLES OR FREQUENCIES*

CSP BOUNDARIES HIERARCHY

LEGEND

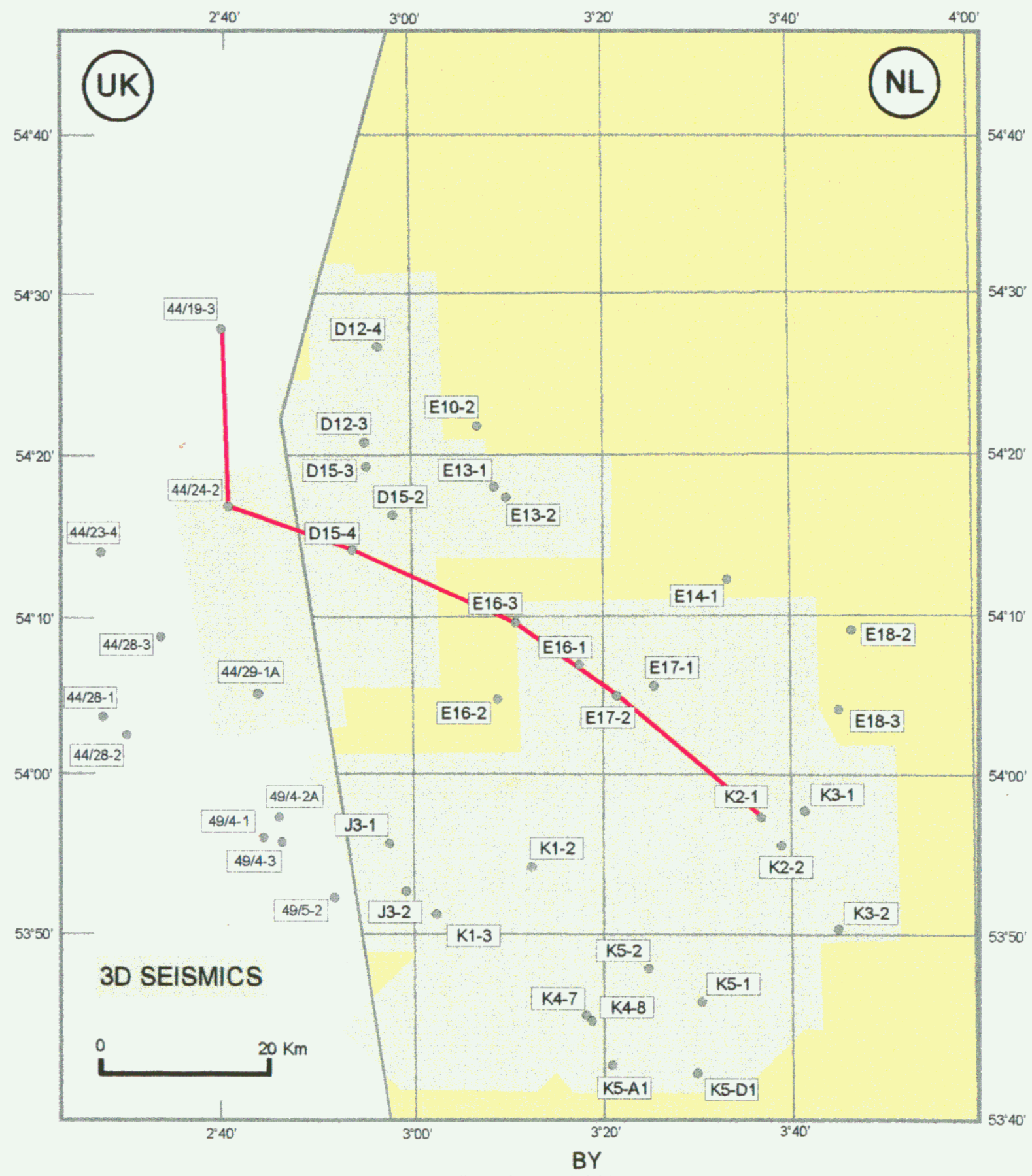
▭	COAL-BEARING INTERVAL OF W520 CSP (MAINLY MAURITS FM)		
▨	COAL-BEARING INTERVAL OF W514 CSP (MAINLY MAURITS FM)		
■	W520 CSP	▨	ROTLIEGEND INTERVAL
▭	W510 CSP	▭	W700 CSP
▭	W500 CSP	▭	W600 CSP

DEPTH SCALE IN METRES

SEQUENCE AND CYCLOSTRATIGRAPHIC CORRELATION FRAMEWORK

UPPER CARBONIFEROUS OF THE NETHERLANDS OFFSHORE
FOR
NETHERLANDS INSTITUTE OF APPLIED GEOSCIENCE TNO
NATIONAL GEOLOGICAL SURVEY
HAARLEM, NETHERLANDS

ENCLOSURE 2 - 1



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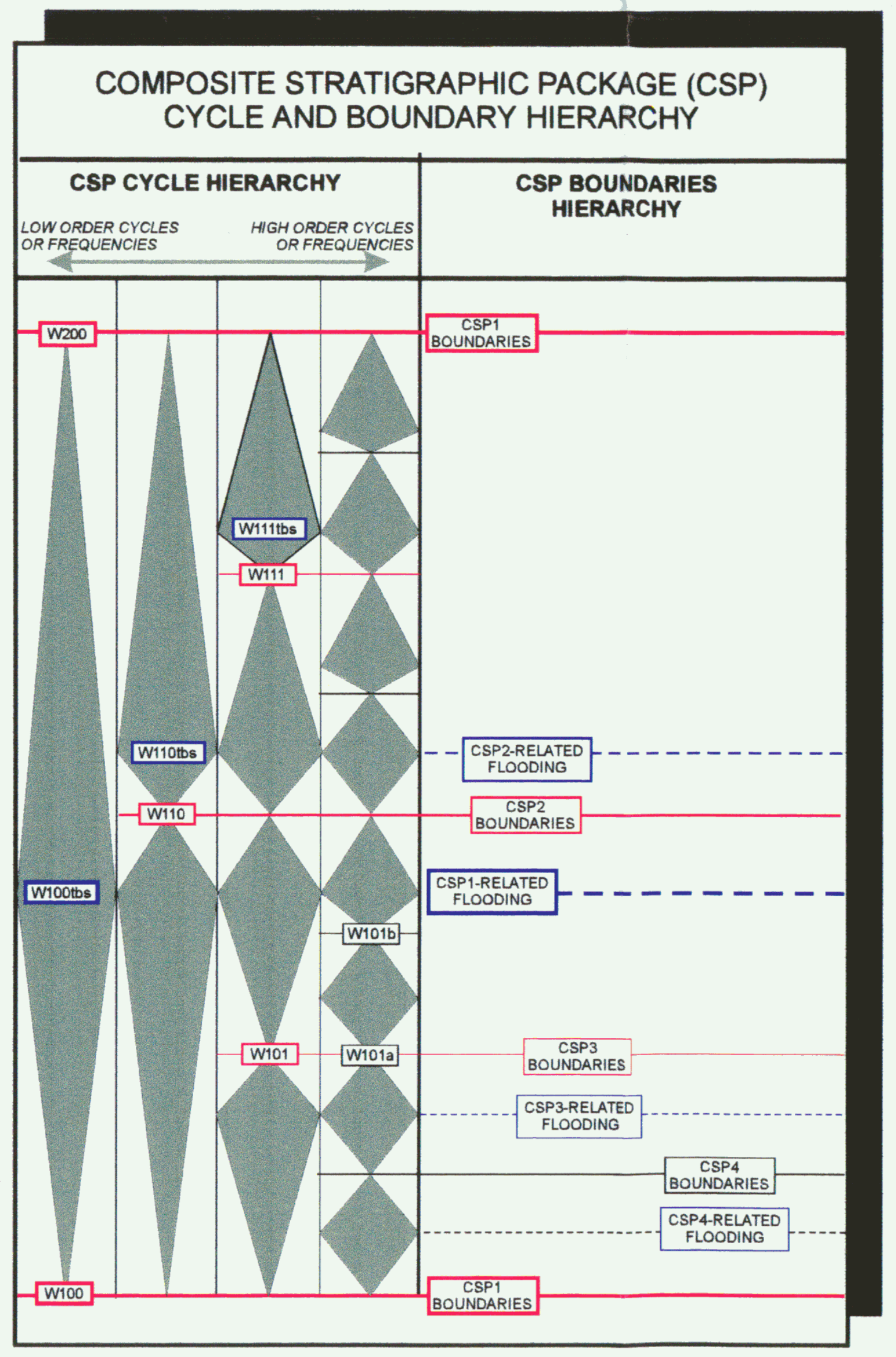
235CP03.CDR/DN


COMPOSITE STRATIGRAPHIC PACKAGE (CSP)
CYCLE AND BOUNDARY HIERARCHY

LEGEND

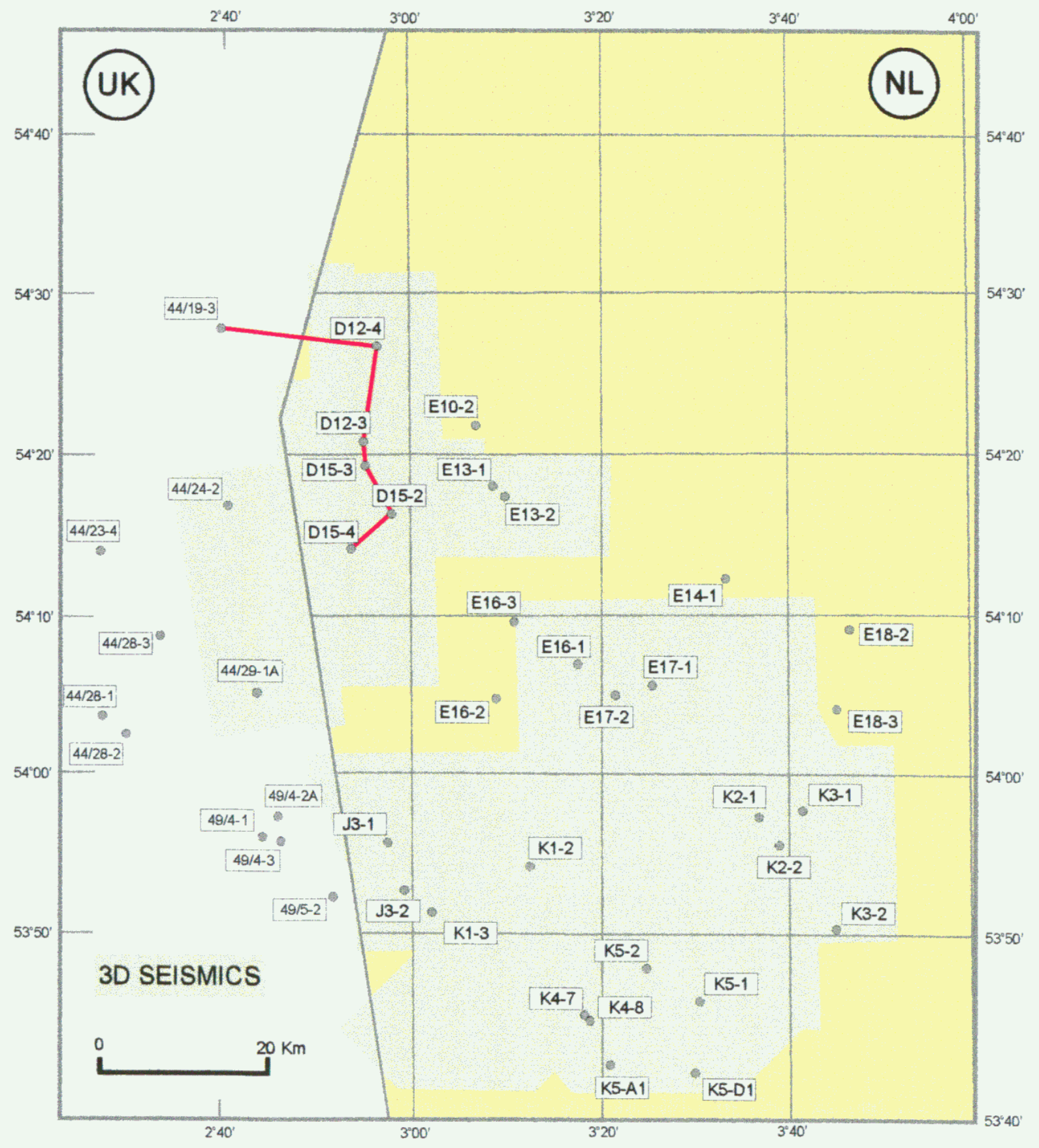
▨	COAL-BEARING INTERVAL OF W520 CSP (MAINLY MAURITS FM)		
▨	COAL-BEARING INTERVAL OF W514 CSP (MAINLY MAURITS FM)		
▨	W520 CSP	▨	ROTLIEGEND INTERVAL
▨	W510 CSP	▨	W700 CSP
▨	W500 CSP	▨	W600 CSP

DEPTH SCALE IN METRES

SEQUENCE AND CYCLOSTRATIGRAPHIC CORRELATION FRAMEWORK

UPPER CARBONIFEROUS OF THE NETHERLANDS OFFSHORE
FOR
NETHERLANDS INSTITUTE OF APPLIED GEOSCIENCE TNO
NATIONAL GEOLOGICAL SURVEY
HAARLEM, NETHERLANDS

ENCLOSURE 2 - 2



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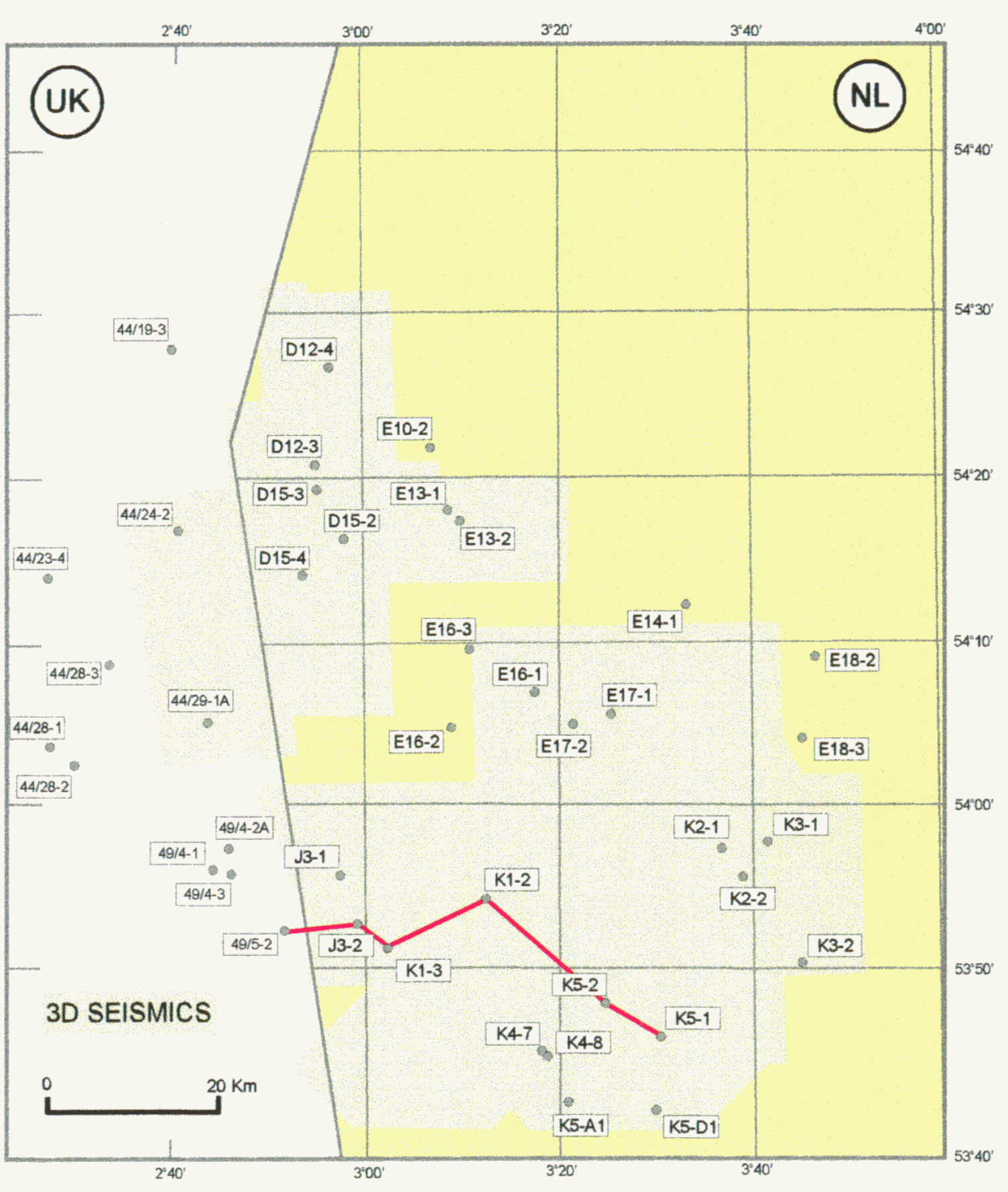
NATIONAL GEOLOGICAL SURVEY
HAARLEM, NETHERLANDS

ENCLOSURE 2 - 3



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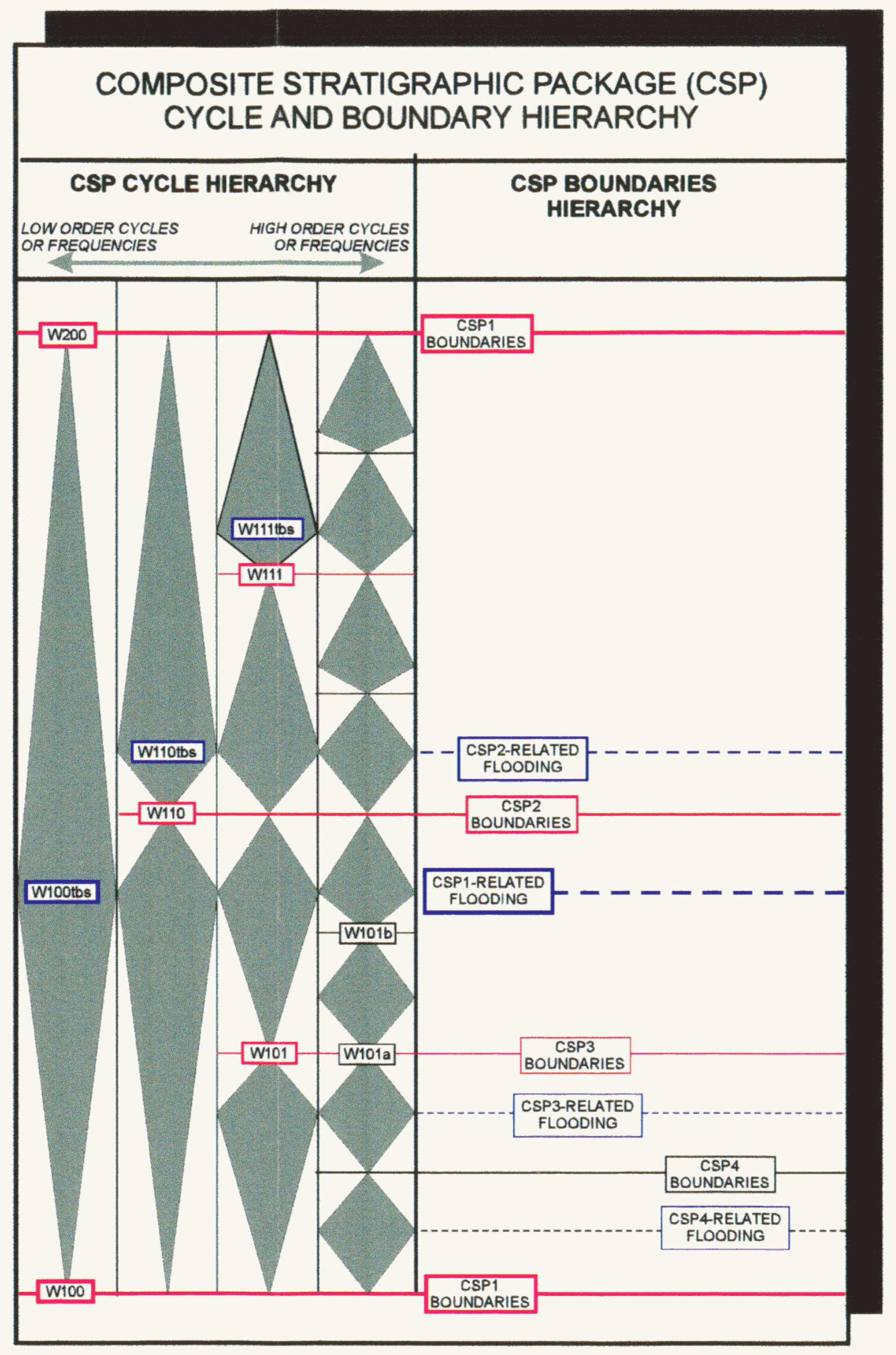
JULY 1997
ENRES/GRAD/97.235-CP01
235CP01.CDR/DN

LEGEND

- ▭ COAL-BEARING INTERVAL OF W520 CSP (MAINLY MAURITS FM)
- ▨ COAL-BEARING INTERVAL OF W514 CSP (MAINLY MAURITS FM)
- 🟨 W520 CSP
- ▭ W510 CSP
- ▭ W500 CSP
- ▨ ROTLIEGEND INTERVAL
- ▭ W700 CSP
- ▨ W600 CSP

DEPTH SCALE IN METRES

COMPOSITE STRATIGRAPHIC PACKAGE (CSP) CYCLE AND BOUNDARY HIERARCHY



SEQUENCE AND CYCLOSTRATIGRAPHIC CORRELATION FRAMEWORK

UPPER CARBONIFEROUS OF THE NETHERLANDS OFFSHORE

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ENCLOSURE 2 - 4

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235CP02.CDR/DN

LEGEND

- ▨ COAL-BEARING INTERVAL OF W520 CSP (MAINLY MAURITS FM)
- ▨ COAL-BEARING INTERVAL OF W514 CSP (MAINLY MAURITS FM)
- ▨ W520 CSP
- ▨ W510 CSP
- ▨ W500 CSP
- ▨ ROTLIEGEND INTERVAL
- ▨ W700 CSP
- ▨ W600 CSP

DEPTH SCALE IN METRES

COMPOSITE STRATIGRAPHIC PACKAGE (CSP) CYCLE AND BOUNDARY HIERARCHY

CSP CYCLE HIERARCHY

LOW ORDER CYCLES OR FREQUENCIES

HIGH ORDER CYCLES OR FREQUENCIES

CSP BOUNDARIES HIERARCHY

CSP1 BOUNDARIES

CSP2-RELATED FLOODING

CSP2 BOUNDARIES

CSP1-RELATED FLOODING

CSP3 BOUNDARIES

CSP3-RELATED FLOODING

CSP4 BOUNDARIES

CSP4-RELATED FLOODING

CSP1 BOUNDARIES

SEQUENCE AND CYCLOSTRATIGRAPHIC CORRELATION FRAMEWORK

UPPER CARBONIFEROUS OF THE NETHERLANDS OFFSHORE

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ENCLOSURE 2 - 6

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JULY 1997

LEGEND

▨	COAL-BEARING INTERVAL OF W520 CSP (MAINLY MAURITS FM)
▨	COAL-BEARING INTERVAL OF W514 CSP (MAINLY MAURITS FM)
🟨	W520 CSP
▨	W510 CSP
▨	W500 CSP
▨	ROTLIEGEND INTERVAL
▨	W700 CSP
🟨	W600 CSP

DEPTH SCALE IN METRES

SEQUENCE AND CYCLOSTRATIGRAPHIC CORRELATION FRAMEWORK

UPPER CARBONIFEROUS OF THE NETHERLANDS OFFSHORE

FOR
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ENCLOSURE 2 - 7

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JULY 1997
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235CP07.CDR/DN

LEGEND

▭	COAL-BEARING INTERVAL OF W520 CSP (MAINLY MAURITS FM)		
▨	COAL-BEARING INTERVAL OF W514 CSP (MAINLY MAURITS FM)		
▨	W520 CSP	▨	ROTLIEGEND INTERVAL
▨	W510 CSP	▨	W700 CSP
▭	W500 CSP	▨	W600 CSP

DEPTH SCALE IN METRES

LEGEND

▨	COAL-BEARING INTERVAL OF W520 CSP (MAINLY MAURITS FM)
▨	COAL-BEARING INTERVAL OF W514 CSP (MAINLY MAURITS FM)
▨	W520 CSP
▨	W510 CSP
▨	W500 CSP
▨	ROTLIEGEND INTERVAL
▨	W700 CSP
▨	W600 CSP

DEPTH SCALE IN METRES

COMPOSITE STRATIGRAPHIC PACKAGE (CSP) CYCLE AND BOUNDARY HIERARCHY

CSP CYCLE HIERARCHY

LOW ORDER CYCLES OR FREQUENCIES — *HIGH ORDER CYCLES OR FREQUENCIES*

CSP BOUNDARIES HIERARCHY

SEQUENCE AND CYCLOSTRATIGRAPHIC CORRELATION FRAMEWORK

UPPER CARBONIFEROUS OF THE NETHERLANDS OFFSHORE

FOR
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ENCLOSURE 2 - 8

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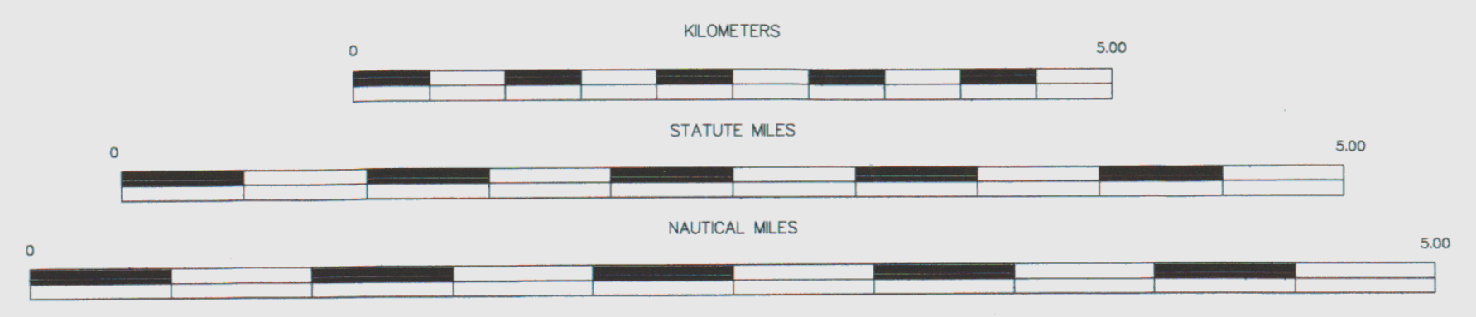
Enclosure 3.1



General Plot Parameters

Screen Dump ☐ Part Section ■ Whole Section ☐

Color Bar ■ Rotated ☐ Interpolation ■

j3k123

RGD
Rijks Geologische Dienst

Seismic Interpretation
Random Line Section

Scale: 1:50000
20.0 cm/sec

Date: 25–JUL–97

Author:

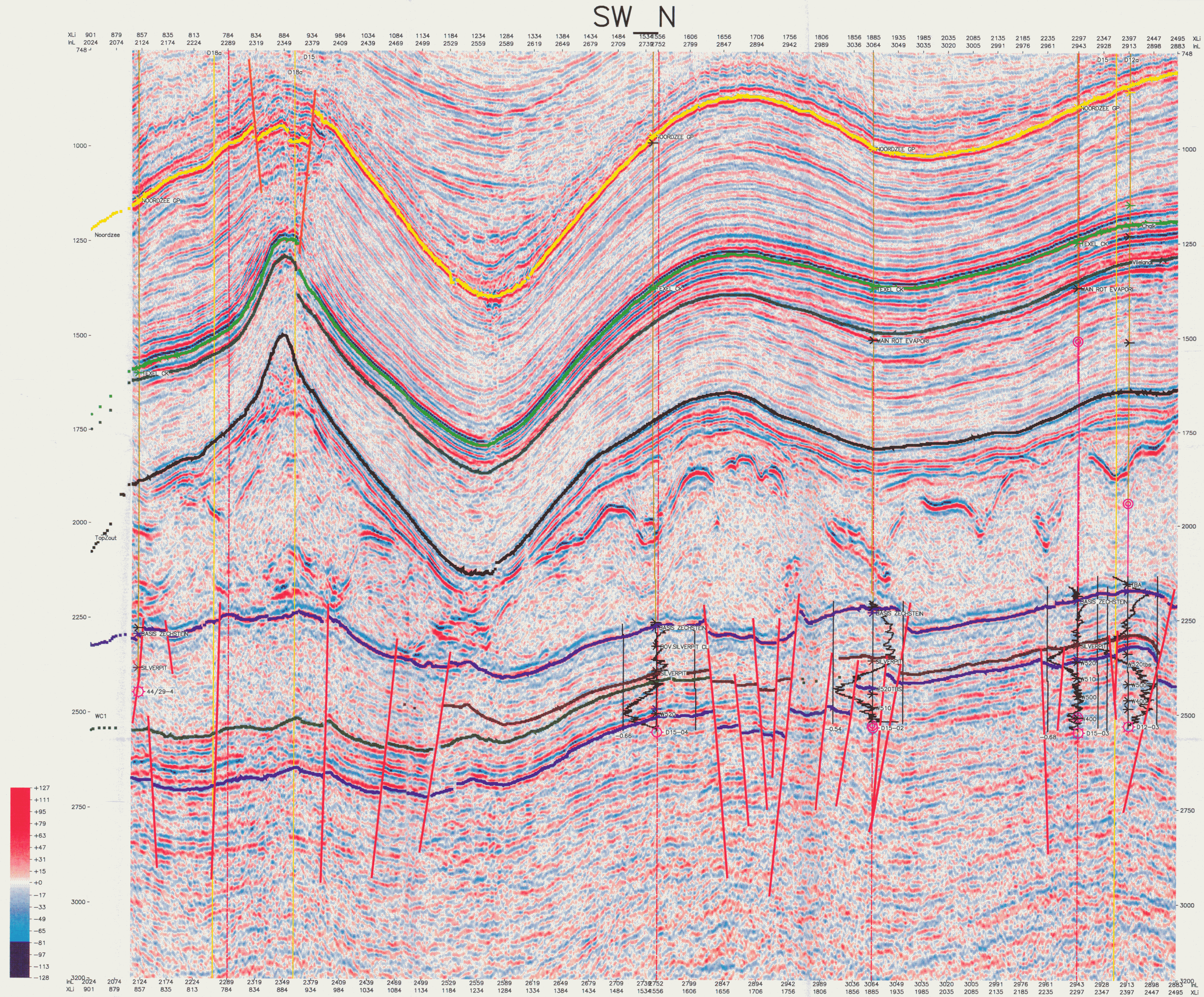
Approved:

Plot Name

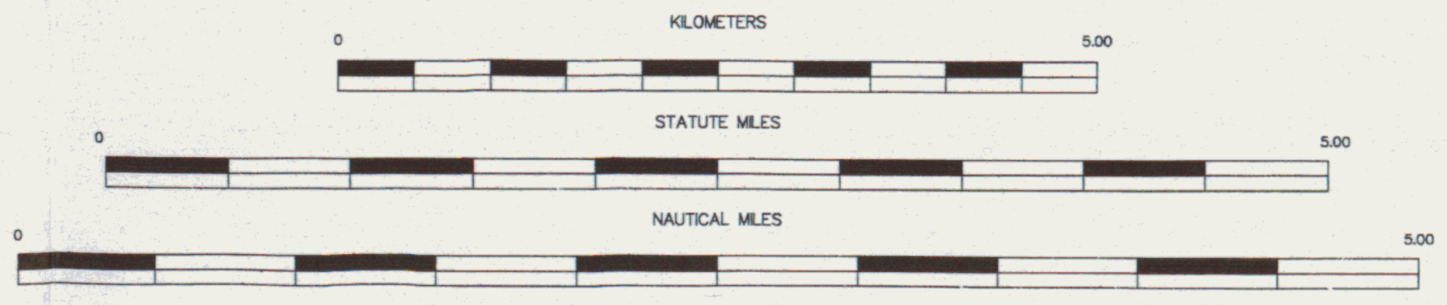
HCPLOT003P.HCPL

REVISIONS

By	Date	Remarks



Enclosure 3.2



General Plot Parameters

Screen Dump ☐ Part Section ■ Whole Section ☐

Color Bar ■ Rotated ☐ Interpolation ■

D12_D15

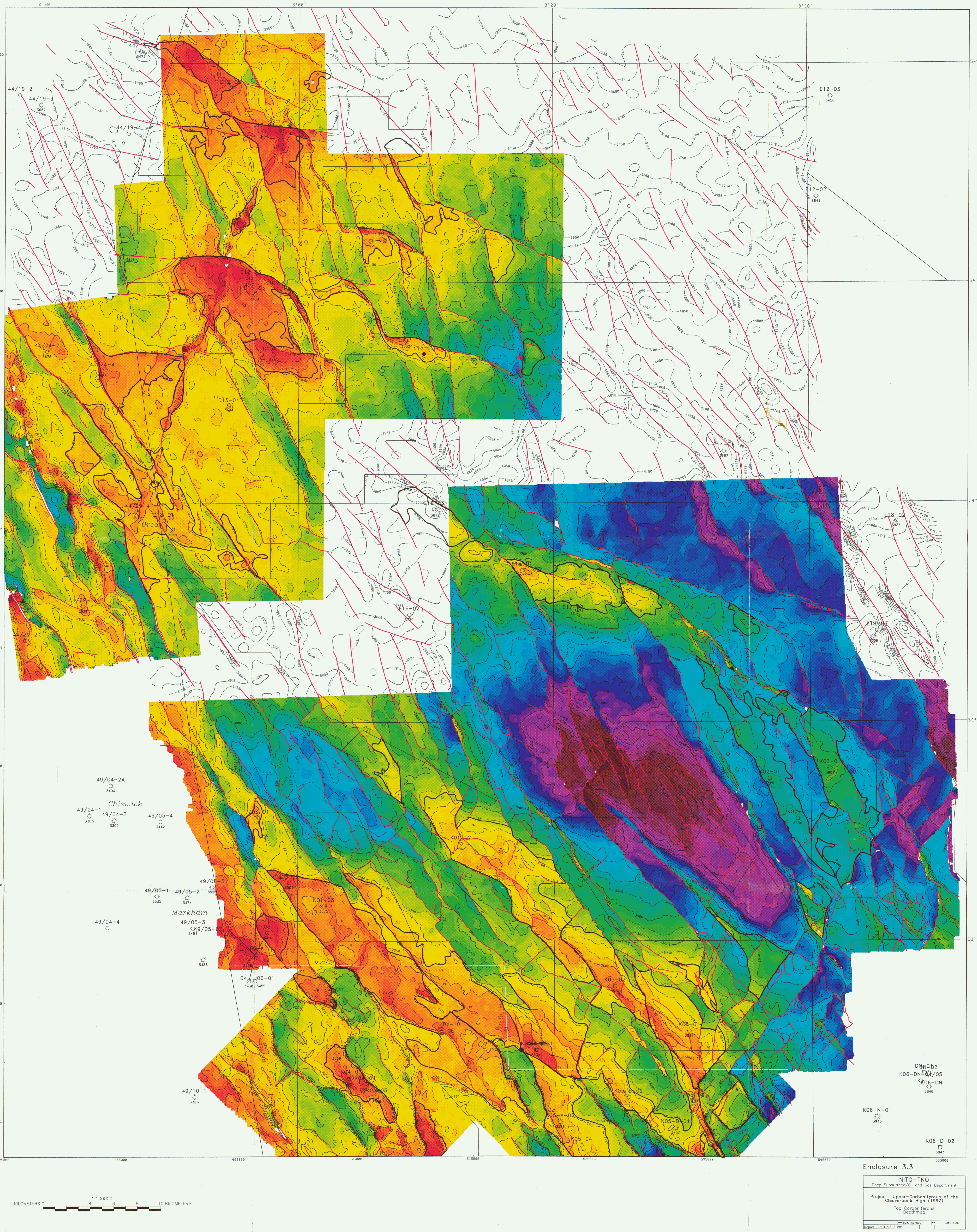
RGD
Rijks Geologische Dienst

Seismic Interpretation
Random Line Section

Scale:	1:50000 20.0 cm/sec
Date:	28-JUL-97
Author:	
Approved:	
Plot Name	
HCPLOT001P.HCPL	

REVISIONS

By	Date	Remarks



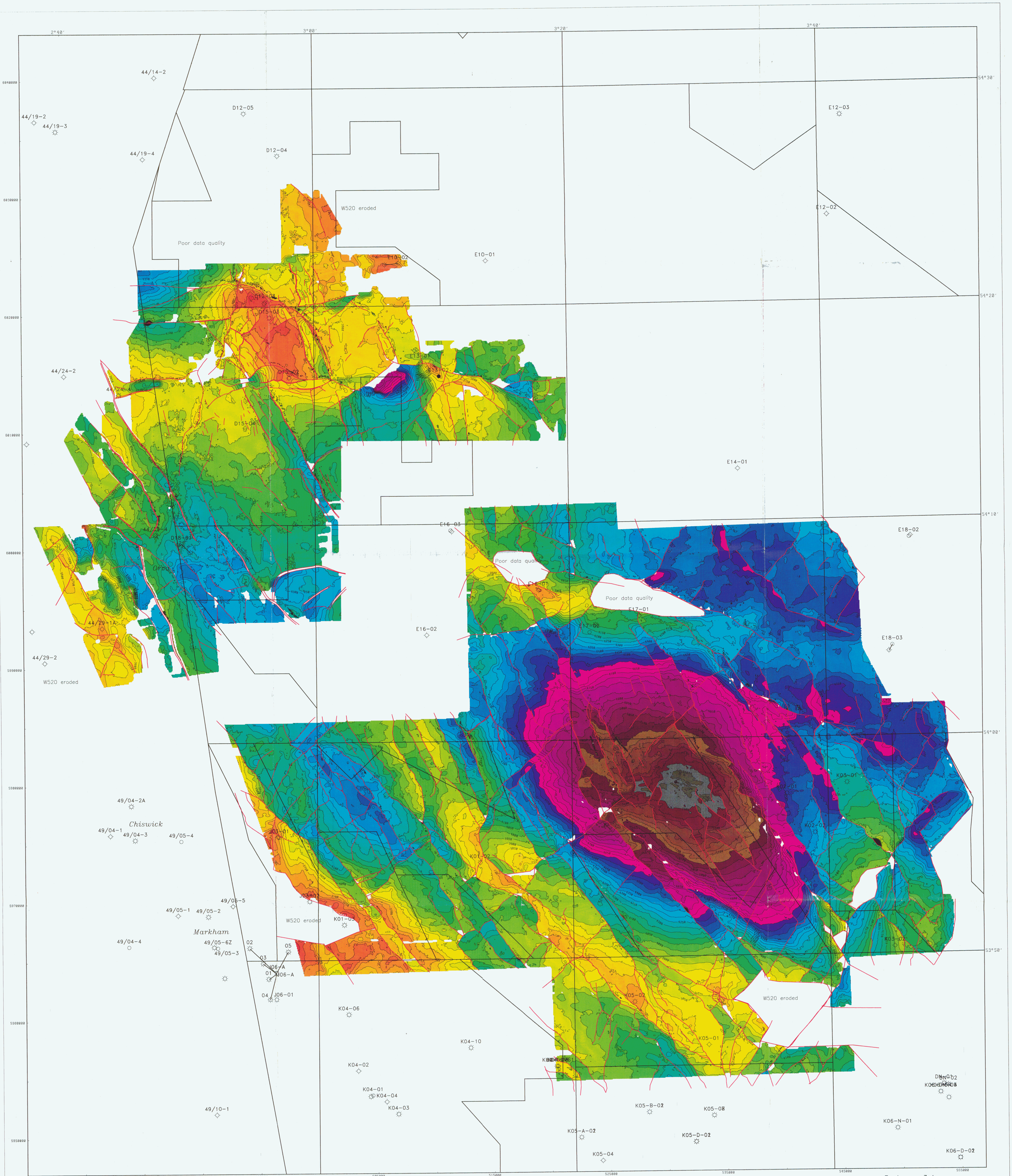
Enclosure 3.3

NITG-TNO
Deep Subsurface/Oil and Gas Department

Project : Upper-Carboniferous of the
Cleaverbank High (1997)

Top Carboniferous
Depthmap

	DRAWN B.M. SCHROOT	DATE JUNE 1997
Report : NITG.97-138C		



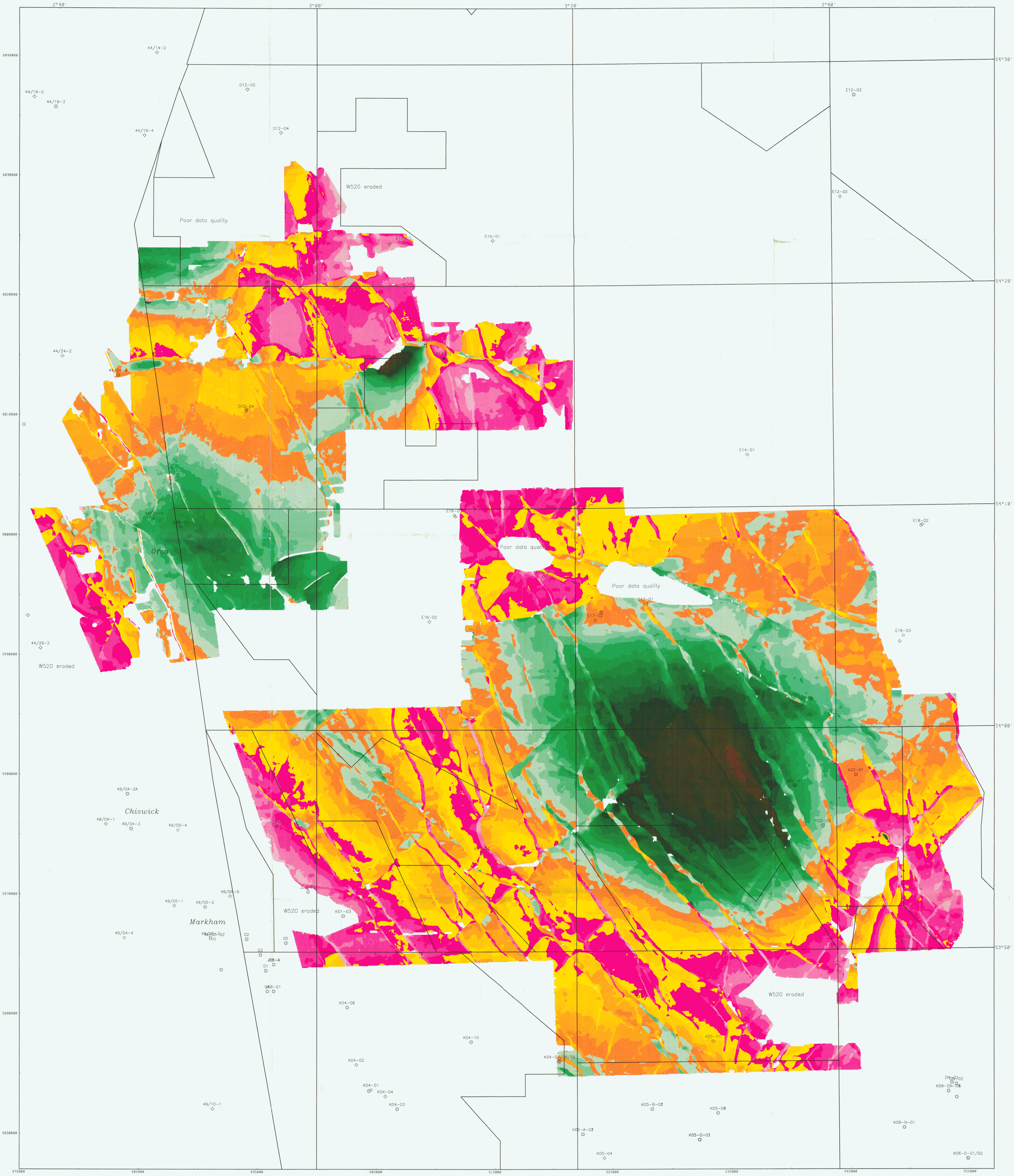
Enclosure 3.4

NITG-TNO
Deep Subsurface/Oil and Gas Department

Project : Upper-Carboniferous of the
Cleaverbank High (1997)

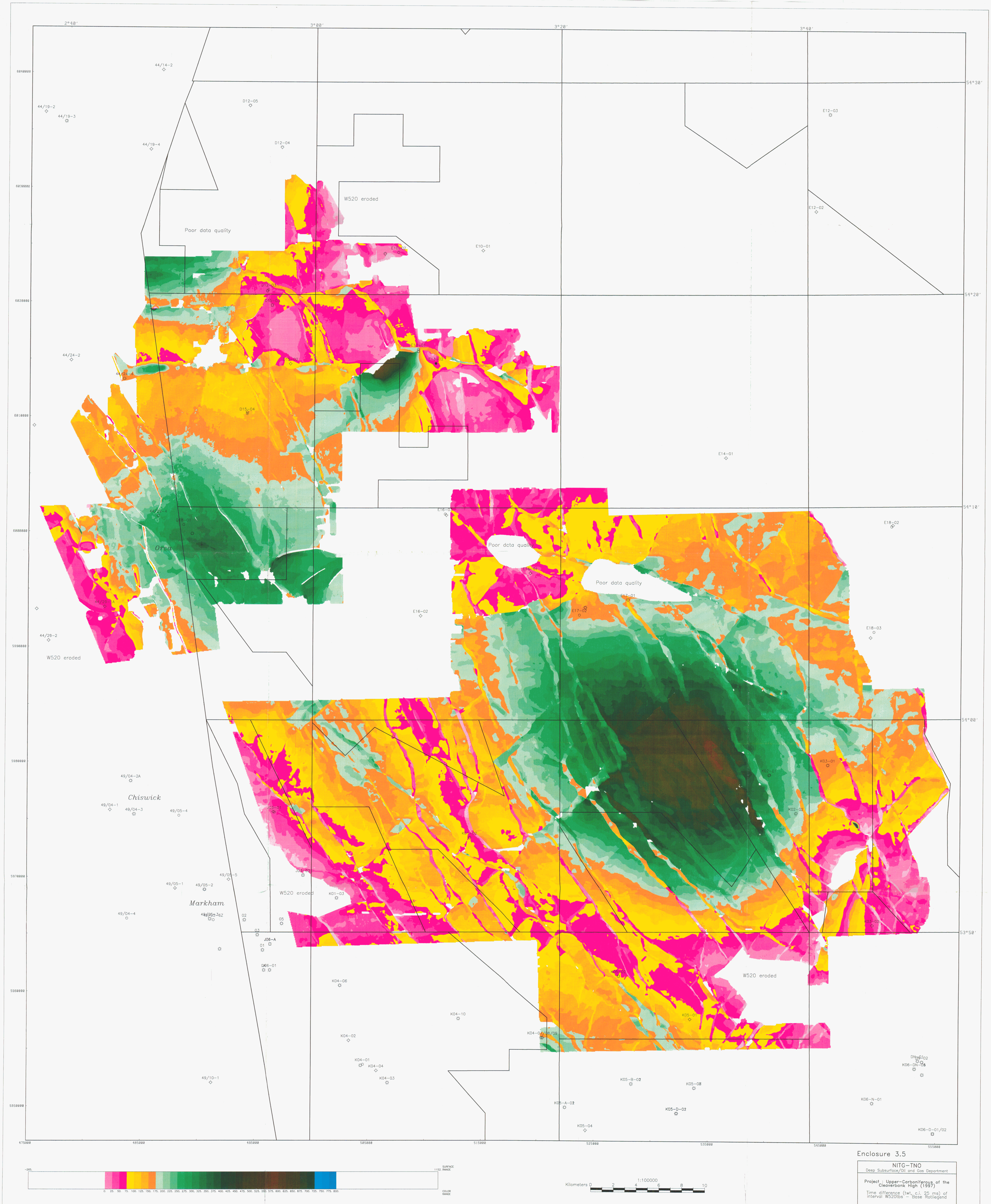
W520tbs Sequence stratigraphic marker
Depth map

	DRAWN B.M. SCHROOT	DATE JUNE 1997
Report : NITG.97-138C		



Enclosure 3.5

NITG-TNO Deep Subsurface/Oil and Gas Department				
Project : Upper-Carboniferous of the Cleaverbank High (1997) Time difference (twt, c.i. 25 ms) of interval W520tbs - Base Rotliegend				
	DRAWN B.M. SCHROOT		DATE JUNE 1997	
Report : NITG.97-138C				



Enclosure 3.5

NITG-TNO
Deep Subsurface/Oil and Gas Department

Project : Upper-Carboniferous of the Cleaverbank High (1997)

Time difference (twt, c.i. 25 ms) of interval W520tbs - Base Rotliegend

	DRAWN B.M. SCHROOT	DATE JUNE 1997
Report : NITG.97-138C		