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Geothermal Gradient Anomalies of Hydrocarbon Entrapment, UKCS Quadrants 35 to 54

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ABSTRACT

Geothermal Gradient anomalies have long since been recognised to accompany hydrocarbon traps. The anomalies are most probably by-products of heat transporting processes of hydrocarbon migration and entrapment. Therefore, couldn't identical anomalies be used to locate undiscovered or bypassed traps?

This study used BHT data of exploration and development wells in UKCS quadrants 35 to 54 of the North Sea to: produce contour maps of the geothermal gradients, identify geothermal gradient anomalies associated with proven hydrocarbon traps then use the models identified to delineate potential, probable and possible anomalies indicative of undiscovered hydrocarbon traps or migration paths in the same quadrants.

A computer programme (CGG-ESTI) was used to correct and test for reliability the BHT records of 238 wells in order to identify boreholes with statistically significant BHT data. Discriminative computer contouring technique was used to produce non-interactive, un-biased contours similar to the manual after-the-fact contours. This technique utilised statistically significant as well as undifferentiated control points to generate compensated geothermal gradient contours (CGG), extrapolated surface temperature intercept contours (ESTI) and map geothermal gradient anomalies of hydrocarbon entrapment.

The study delineated 50 PROVEN and 46 POTENTIAL, PROBABLE and POSSIBLE geothermal gradient (CGG-ESTI) anomalies of hydrocarbon entrapment.

INTRODUCTION

The Southern North Sea (Gas) Basin has over 5000 meter thick Palaeozoic, Mesozoic and Cenozoic rocks, trapping no less than 1000 billion cubic meters of proven recoverable natural gas reserves.

The studied quadrants (35, 36, 37, 38, 39, 41, 42, 43, 44, 47, 48, 49, 50, 52, 53 and 54) are located within the UK's continental shelf of the North Sea between Latitudes 52 and 56 North (Figure 1).

References and illustrations are at the end of paper

Fig. 2 is a composite stratigraphic section of the southern North Sea Basin, showing important proven source, reservoir and cap rocks. The studied area covers the Mid North Sea High, The East Midland Shelf and the Southern Gas Basin (Figure 1).

Previous geothermal maps (1-7) of

the Southern North Sea were based on a relatively small numbers of control points, hence delineated geothermal gradient variations associated with major tectonic elements.

Heat flow studies of the Southern North Sea Basin reached a dead-end by mid eighties, as outlined by Andrews-Speed et al (7) in their conclusion:

"4. In sedimentary basins such as the western North Sea, heat-flow maps are at best difficult to interpret, and at worst may be meaningless."

However, geothermal gradient anomalies associated with hydrocarbon entrapment have been recognised since the early days of exploration (8, 9).

The Bottom-hole temperature (BHT) is unique among logging tools in having a uniform measuring technique that transgress across oil companies, logging companies and national boundaries throughout the hydrocarbon exploration era.

Today, there are millions of uniformly recorded BHTs going back to the early days of exploration when many wells were reported as "dry, wet, tight, P&A, etc. under extinct logistics, drilling and exploration technologies, economic or political conditions. Among such "dry holes" are commercially producible wells under present environments.

Such wells can be extracted out of large data bases using their BHT data as they may display similar anomalous geothermal gradients to those of nearby oil and gas fields.

Using a new geothermal gradient mapping method (10-15) that compensate for geothermal variations due to subsurface fluid movements by plotting an extrapolated surface temperature contours as well as compensated geothermal gradient contours of the studied wells; this study's main objectives are:

1. Generate a BHT data base using 500 exploration and development wells drilled in the studied quadrants (available at the Well Record Library of the Department of Energy, London).

2. Apply a practical correction to normalize these data.

3. Use corrected BHTs to calculate compensated (average) geothermal gradient (CGG) and extrapolated surface temperature intercept (ESTI) of control boreholes.

4. Analyze geothermal gradients and extrapolated surface temperature intercepts for anomalous associations with producing and suspended gas wells.

5. Define the CGG/ESTI cluster boundaries of producing and suspended wells.

6. Contour the compensated geothermal gradients and extrapolated surface temperature intercepts using discriminative computer contouring technique to identify PROVEN CGG-ESTI anomalies associated with known hydrocarbon traps.

7. Use the proven CGG-ESTI model(s) of producing wells identified to delineate POTENTIAL, PROBABLE and POSSIBLE geothermal gradient (CGG-ESTI) anomalies of hydrocarbon entrapment, graded according to degree of similarity with the identified model(s) of (CGG-ESTI) anomalies and significance of BHT, CGG and ESTI values that induced the anomaly.

GEOTHERMAL GRADIENT FOR HYDROCARBON EXPLORATION

In sedimentary basins, lateral and vertical heat convection via fluid flow caused by compaction, structural attitudes and topographic relief are known to cause and associate with hydrocarbon traps.

Such events impose mappable geothermal gradient anomalies on the regional geothermal gradient background (16-20).

The main limitations of traditional geothermal gradient mapping methods are:

1. Graphically or statistically calculated mean geothermal gradient involve a surface temperature intercept; such as mean air, mean ground surface, mean sea bed or extrapolated surface temperature.

By forcing one regional surface temperature on the BHT gradient of every control well may result in a gradient that differ from a geothermal gradient calculated by normal linear least square regression of the same data (Figure 3).

2. A geothermal gradient derived via normal linear least square regression, may include two control wells having similar geothermal gradients but different surface temperature intercepts. This implies that a single geothermal gradient does not mean equal depths to an isotherm (Figure 4).

3. Heat flow maps assume uniform crustal heat flow (Qz) over the entire studied areas. However, most basins are like the North Sea, have massive heat transportation via fluid movements (6, 16-20).

4. An isotherm contour map does not summarize nor represent the status of the entire drilled rock section. Furthermore, being a derivative of the above mapping methods it indeed inherits their errors and limitations.

TESTING, ANALYSIS AND MAPPING METHODS USED IN THE STUDY

The previous section has highlighted the fact that any geothermal gradient contour map cannot be interpreted without a complementary surface temperature contour map.

As the last stages of subsidence and deeper thermal zones have the most significant effect on generation, migration and accumulation of hydrocarbon while shallow or surface temperatures have nearly no effect at all; therefore geothermal gradient should be representative of the overall subsurface thermal profile.

Ibrahim (1986) proposed a "compensated geothermal gradient mapping method" to utilize the dormant BHT data of the oil and gas industry to detect geothermal gradient anomalies of hydrocarbon entrapment. For detailed account of the method reference can be made to publications 10-13.

The method combines corrected geothermal gradient generated through linear least square regression, which extrapolate a complementary surface temperature, as in the equation:

$$Tz = To + (Z * (dt/dz)) \quad ......(1)$$

Where To is the extrapolated surface temperature intercept (ESTI) in temperature units and the dt/dz is the compensated geothermal gradient (CGG) in temperature units / depth units.

Testing the BHT Data

A sophisticated BHT correction does not improve the reliability of a geothermal gradient derived from poorly spread BHT measurements in a borehole. Hence, a type of statistical "T" test was developed and incorporated into the CGG-ESTI programme to test the degree of spread (significance) of BHT measurements in the studied boreholes.

The Sample Significance Test determines the significance of the BHT data and the significance of the subsequently calculated CGG and ESTI values of the control well.

Out of 500 wells examined at the DOE Well Record Library, 238 wells were found to be usable, among them 120 wells found to be significant control wells.

Cross-plot Analysis

Clustering of producers versus non producers can be interactively explored by cross-plotting the CGG / ESTI to identify and establish optimum CGG and ESTI boundaries that seclude the anomalous CGG and ESTI contour closures.

Average regional CGG-ESTI limits of 1.5 F/100 ft and 75 F were found to be the optimum limits in most quadrants. However, the cross-plot of quadrant 44 (Figure 5) revealed that the local optimum limits are 1.75 F/100 ft and 50 F.

Discriminative Computer Contouring

Using only significant control points (120 wells) would generate contours that reflect the regional structural elements and trends. Therefore by using the whole data base (238 wells) but awarding significant control wells three times the weight to influence the contour value, un-biased, non-interactive contours were generated and found to be very similar to the after-the-fact interpretive hand-drawn CGG and ESTI contours.

A discriminative CGG contour map and an ESTI contour map were produced for the whole of the study area.

A CGG-ESTI anomaly map was produced by combining diluted forms of both contours in the CGG-ESTI anomaly map (part of which is shown in Figure 6).

ANALYSIS AND INTERPRETATION OF THE GEOTHERMAL GRADIENT MAPS

Hydrocarbon traps function as focal points of migrating connate or recharge waters, passing through or past the trap leaving behind the hydrocarbons (16-20).

In general, higher geothermal gradient - low extrapolated surface temperature anomalies (High CGG-Low ESTI) signals vertical water movement (and hydrocarbon if available) into shallower traps.

In old compacted basins with deep traps the above anomalies indicate seepage along young faults and may signal dissipation of entrapped hydrocarbon and breach of sealing rocks. In this environment the Low CGG-High ESTI anomalies can be associated with high impedance seals and undamaged traps.

GEOTHERMAL GRADIENT ANOMALIES OF HYDROCARBON ENTRAPMENT IN THE SOUTHERN NORTH SEA BASIN

There is a regional gradient in the geothermal background from CGG = 1.0 F/100 ft and ESTI = 100 F in the south-western part to 2.0 F/100 ft and 50 F in the north-eastern corner of the study area.

The East Midland Shelf has a low CGG-high ESTI background reflecting low thermal impedance stratigraphy and shallow basement.

In the deep central part of the Southern Gas Basin a high CGG-low ESTI background of the high thermal impedance stratigraphy is severely distorted by fluid convecting faults and thick heat conductive salt structures. There, deep Rotliegend gas traps are generally associated with low CGG-high ESTI anomalies indicative of thick, effective highly conductive Zechestein salt sealing deep gas trapping reservoirs.

Geothermal gradient anomaly (CGG-ESTI) map of quadrant 44 (Figure 6) show three anomalies A/44, B/44 and C/44.

A/44:

This is a possible low CGG-high ESTI anomaly, induced by AMOCO's statistically significant dry hole 44/07-01 (1.4 F/100 ft and 94 F).
It is represented by a single closed high ESTI contour in a low CGG area. This anomaly is interpreted as indicative of possible deep, sub-salt gas potential.

C/44:

This is a proven high CGG-low ESTI anomaly associated with BP's statistically significant gas wells 44/23-01 and 02 of Caister Gas Field and to some extent Texaco's gas well 44/23-03.

B/44:

This anomaly was first generated as potential high CGG-low ESTI, closed contours anomaly around Burmah's 1968 dry hole 44/19-02 (2.3 F/100 Ft and 25.2 F). Then, changed to proven when the status of the 1989 Sovereign Carboniferous gas discovery via well 44/19-03 was confirmed by the DOE in 1990.
Records of well 44/19-03 are yet to be released, hence B/44 is a proven anomaly generated by a "dry hole".

APPLICATIONS

The CGG-ESTI anomalies mainly delineate subsurface fluid migration, entrapment and dissipation sites.

By cross-plot analysis, anomalous CGG-ESTI association with hydrocarbon traps can be identified, and their relationship can be explained in terms of migration or impedance processes. Subsurface fluid migration pattern do not change nor the process stop with hydrocarbon entrapment, both may continue long after that sending the geothermal signal of hydrocarbon entrapment (17, 18).

Therefore, the CGG-ESTI anomalies of hydrocarbon entrapment are a significant addition to the integrated approach to prospects generation, and probabilistic risk assessment of areas, wells and seismic anomalies (9, 16-20).

Basin Review, Re-evaluation and Prospects Generation and Ranking

Bottom hole temperature records of large number of boreholes can be screened via CGG/ESTI cross-plots and CGG-ESTI maps for "dry holes" or areas displaying geothermal gradient anomalies similar to those of nearby fields. Such anomalies may provide justification for:

1. Re-examining lithological description, correlation, well-site report, wire-line logs, DST results, drilling record, or simply asking the right person, what is the story of this "dry hole”?

2. Reviewing the seismic records for fresh or alternative interpretation, reprocessing, or acquisition of additional seismic lines as the "dry hole" may have been positioned off or stopped short of a hydrocarbon trap.

3. Deepening old dry boreholes to test newly realized exploration target(s) in areas where shallow plays were hitherto the primary targets.

Pre-Drilling Prognosis and Risk Assessment

1. If the model of the CGG-ESTI anomalies are known, then the type of anomaly may reflect the depth and type of the trap. This can give away the depth of stratigraphic or seismic level to be targeted or reviewed.

2. Thermal profile of the explored stratigraphic section can be synthesised. Subsequently, the normal geothermal gradient background or the expected anomalous CGG-ESTI can be simulated. Adding such information to the drilling prognosis can help in detecting anomalous BHT measurements during drilling.

Risk Assessment and Decision Making During Drilling

Several case-studied have shown that deep interim CGG/ESTI cross-plots of a borehole were almost identical to the final CGG/ESTI cross-plots realized after hydrocarbon discovery at TD (12, 13).
Therefore, an anomalous interim CGG/ESTI cross-plot can be a during-drilling input to the decision tree to justify drilling deeper target(s) when shallow target(s) found to be low, dry, wet, tight, etc.

CONCLUSIONS

Geothermal gradient (CGG-ESTI) anomalies delineate subsurface fluid migration, entrapment and dissipation sites. They provide an important input to the integrated approach of hydrocarbon exploration.

In the studied quadrants of the Southern North Sea: anomalous high CGG-low ESTI are associated with shelf or shallow hydrocarbon traps, while low CGG-high ESTI anomalies are mainly associated with deep sub-salt traps at or near the centre of the Southern Gas Basin.

Fifty proven geothermal gradient (CGG-ESTI) anomalies of hydrocarbon entrapment were identified. This amounts to a success ratio of 54 to 75%.

The study also identified 10 POTENTIAL, 11 PROBABLE and 26 POSSIBLE geothermal gradient anomalies of hydrocarbon entrapment.

The success rate of identifying proven anomalies reflect the potential success rate of discovering hydrocarbon in the potential, probable and possible anomalies; because the discriminative computer contouring procedure does not differentiate between producing, suspended or dry holes.

The CGG-ESTI method can provide significant inputs into basin review, area re-evaluation, prospect generation, drilling prognosis and during drilling decision making.

NOMENCLATURE AND CONVERSIONS

1 F/100 ft = 1.822 C/100 m
C = (F-32) * (5/9)
CGG = Compensated Geothermal Gradient in F/ 100 ft
dt/dz = Geothermal Gradient
ESTI = Extrapolated Surface Temperature Intercept in F.
To = Surface Temperature
Tz = Temperature at depth Z

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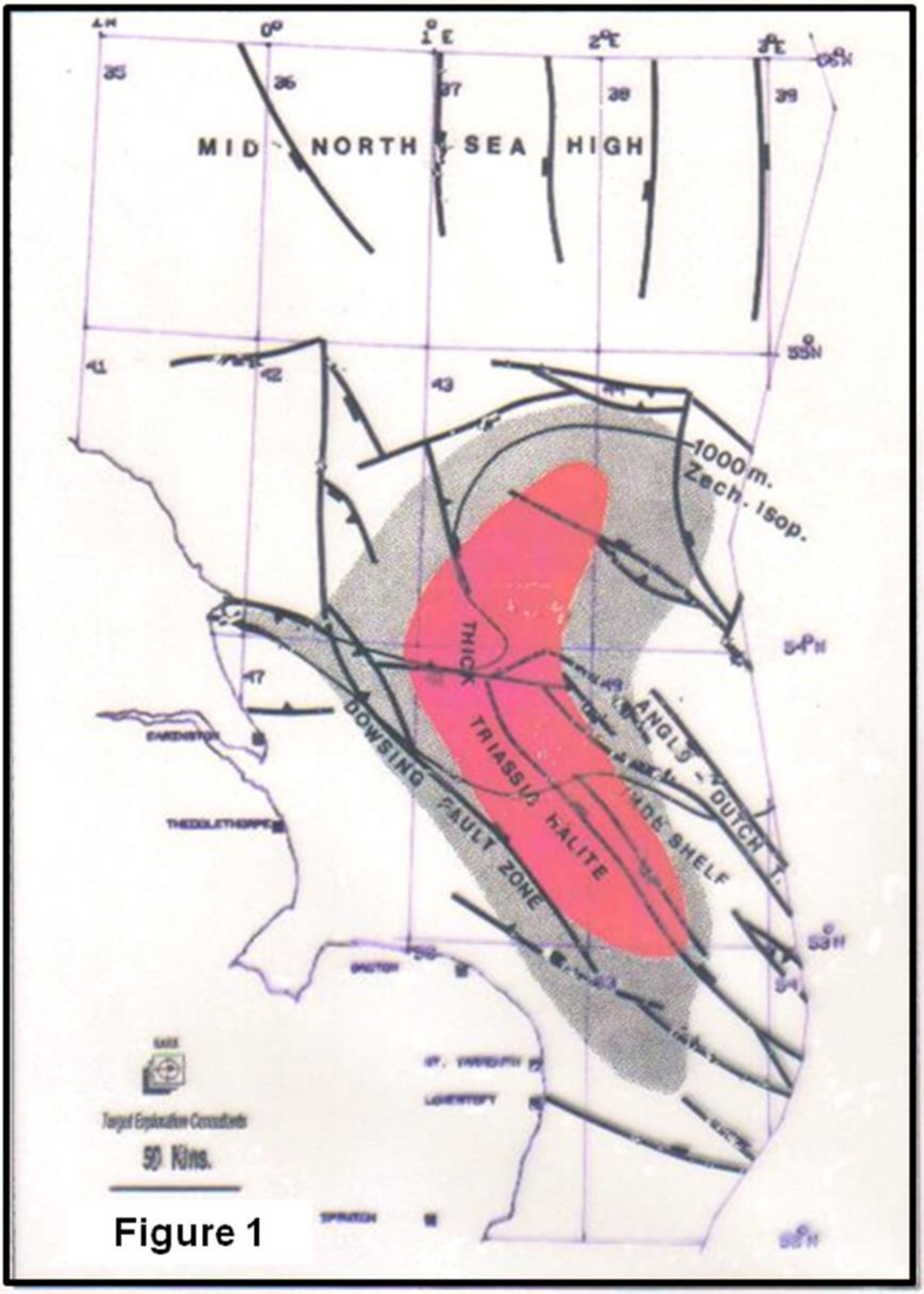

MID NORTH SEA HIGH
1000 m.
Zech. Isop.
THICK TRIASSIC HALITE
DOWSING FAULT ZONE
ANGLO - DUTCH
Target Exploration Consultants
50 Kms.

Figure 1

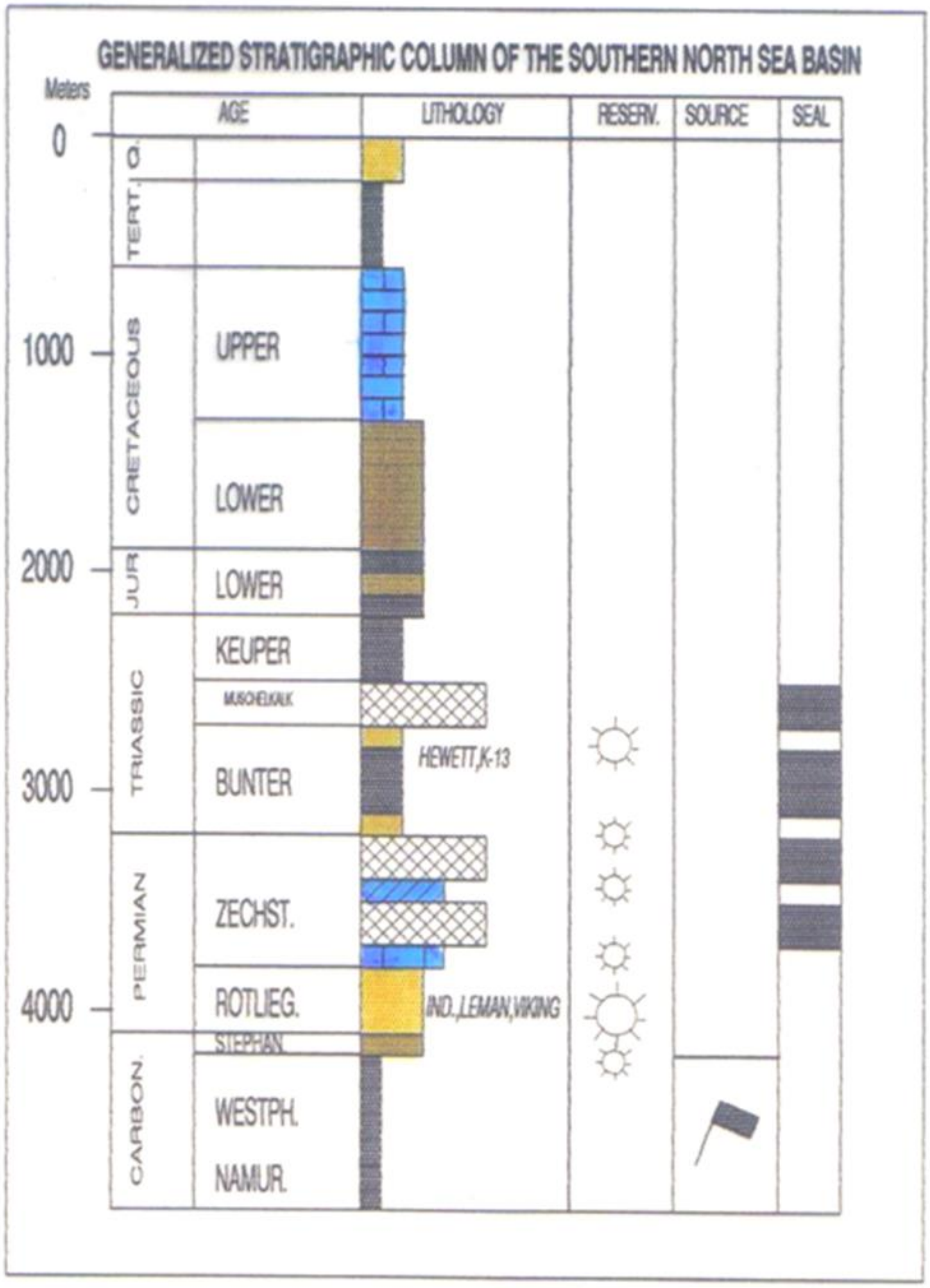
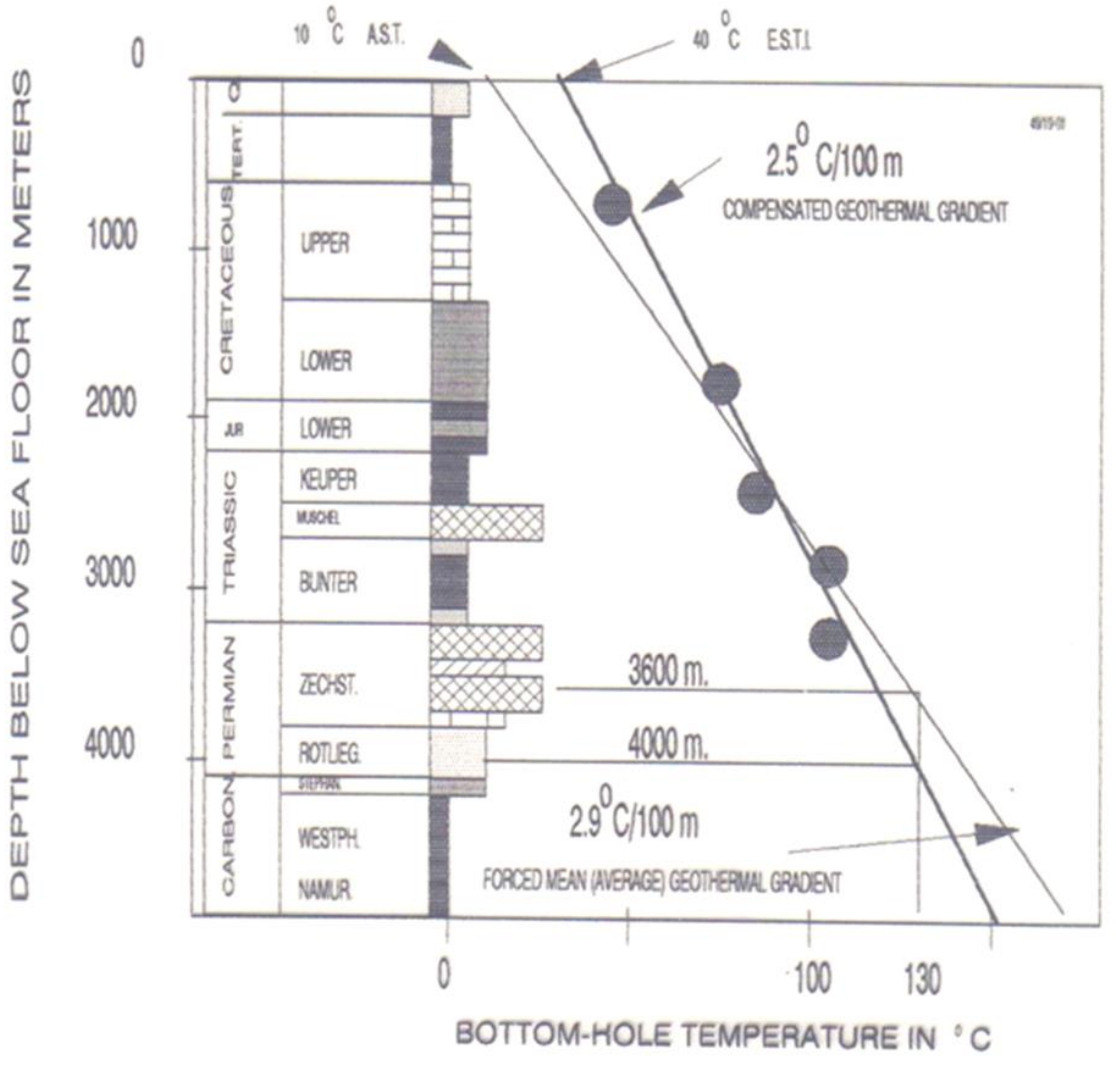
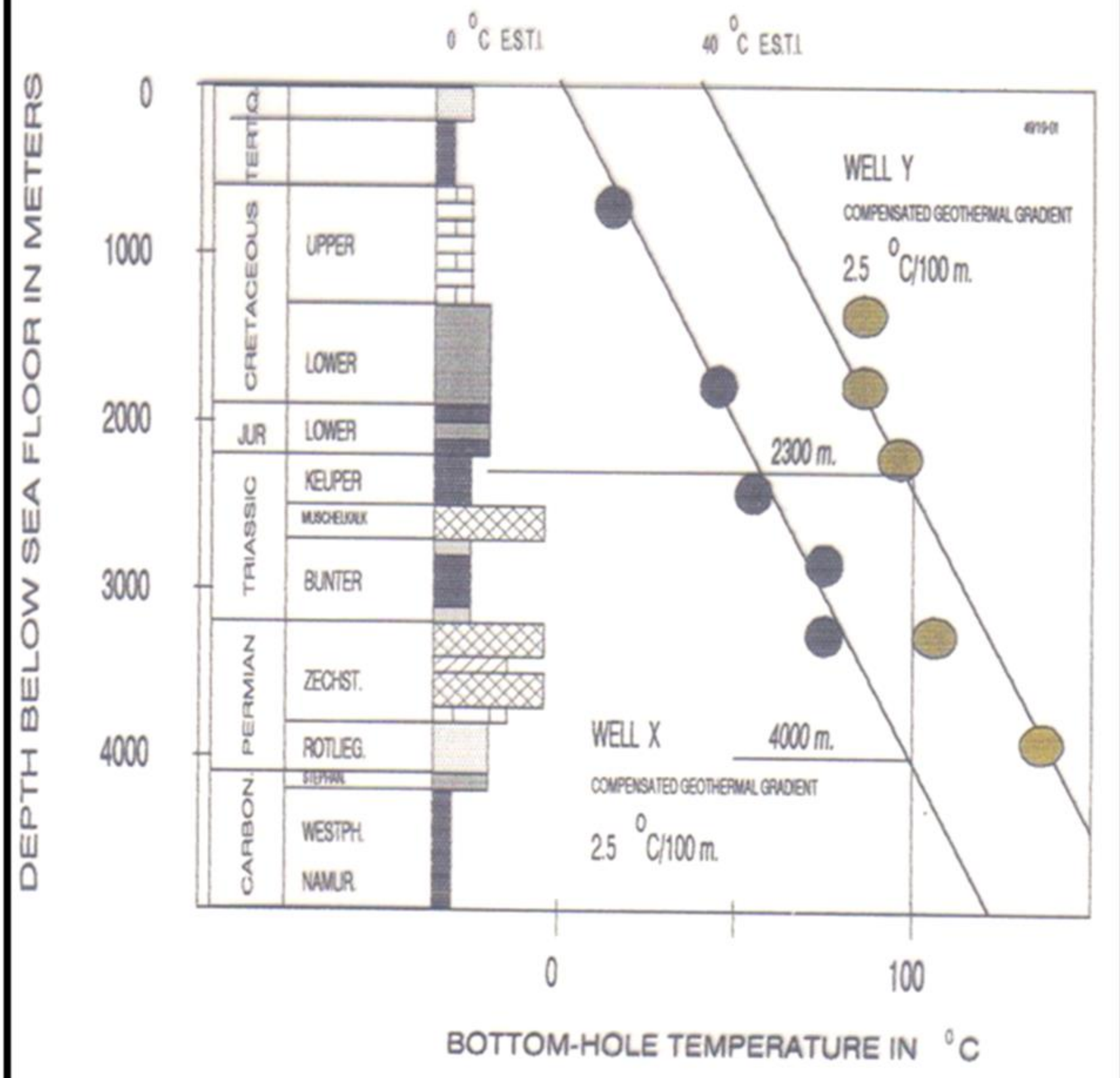

GENERALIZED STRATIGRAPHIC COLUMN OF THE SOUTHERN NORTH SEA BASIN
Meters
0
1000
2000
3000
4000
AGE
LITHOLOGY
RESERV.
SOURCE
SEAL
TERT.
Q.
CRETACEOUS
UPPER
LOWER
JUR
LOWER
TRIASSIC
KEUPER
MUSCHELKALK
BUNTER
HEWETT,K-13
PERMIAN
ZECHST.
ROTLIEG.
IND.,LEMAN,VIKING
CARBON.
STEPHAN.
WESTPH.
NAMUR.

Figure 2



10 °C A.S.T.
40 °C E.S.T.I.
2.5 °C/100 m
COMPENSATED GEOTHERMAL GRADIENT
0
1000
2000
3000
4000
DEPTH BELOW SEA FLOOR IN METERS
TERT.
CRETACEOUS
JUR
TRIASSIC
PERMIAN
CARBON
UPPER
LOWER
LOWER
KEUPER
MUSCHEL
BUNTER
ZECHST.
ROTLIEG.
STEPHAN
WESTPH.
NAMUR
3600 m.
4000 m.
2.9 °C/100 m
FORCED MEAN (AVERAGE) GEOTHERMAL GRADIENT
0
100
130
BOTTOM-HOLE TEMPERATURE IN °C

Figure 3



0 °C E.S.T.I.
40 °C E.S.T.I.
WELL Y
COMPENSATED GEOTHERMAL GRADIENT
2.5 °C/100 m.
2300 m.
WELL X
4000 m.
COMPENSATED GEOTHERMAL GRADIENT
2.5 °C/100 m.
DEPTH BELOW SEA FLOOR IN METERS
0
1000
2000
3000
4000
TERTIQ.
CRETACEOUS
UPPER
LOWER
JUR
LOWER
TRIASSIC
KEUPER
MUSCHELKALK
BUNTER
PERMIAN
ZECHST.
ROTLIEG.
CARBON.
STEPHAN.
WESTPH.
NAMUR.
0
100
BOTTOM-HOLE TEMPERATURE IN °C

Figure 4

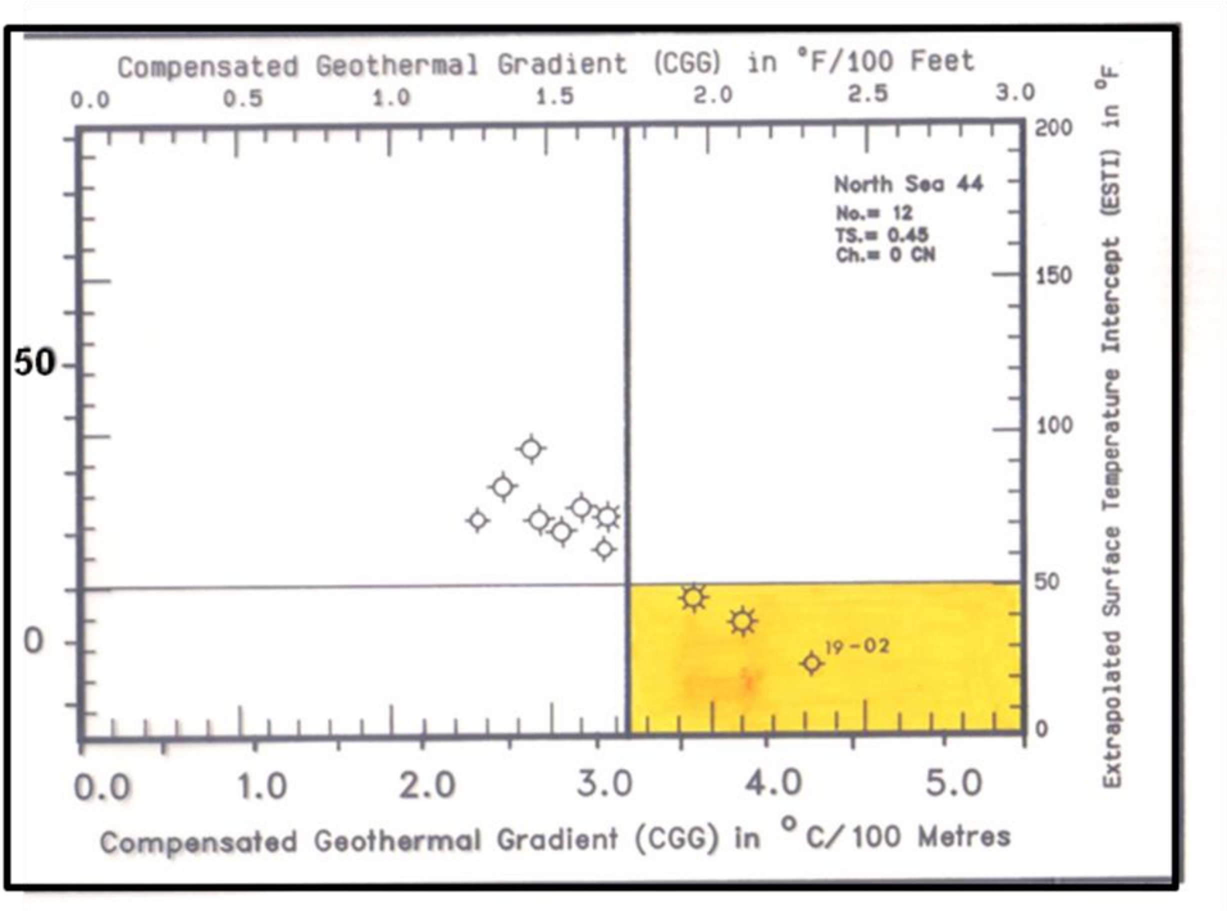

Compensated Geothermal Gradient (CGG) in °F/100 Feet
0.0
0.5
1.0
1.5
2.0
2.5
3.0
North Sea 44
No.= 12
TS.= 0.45
Ch.= 0 CN
50
0
19-02
200
150
100
50
0
Extrapolated Surface Temperature Intercept (ESTI) in °F
0.0
1.0
2.0
3.0
4.0
5.0
Compensated Geothermal Gradient (CGG) in °C/100 Metres

Figure 5

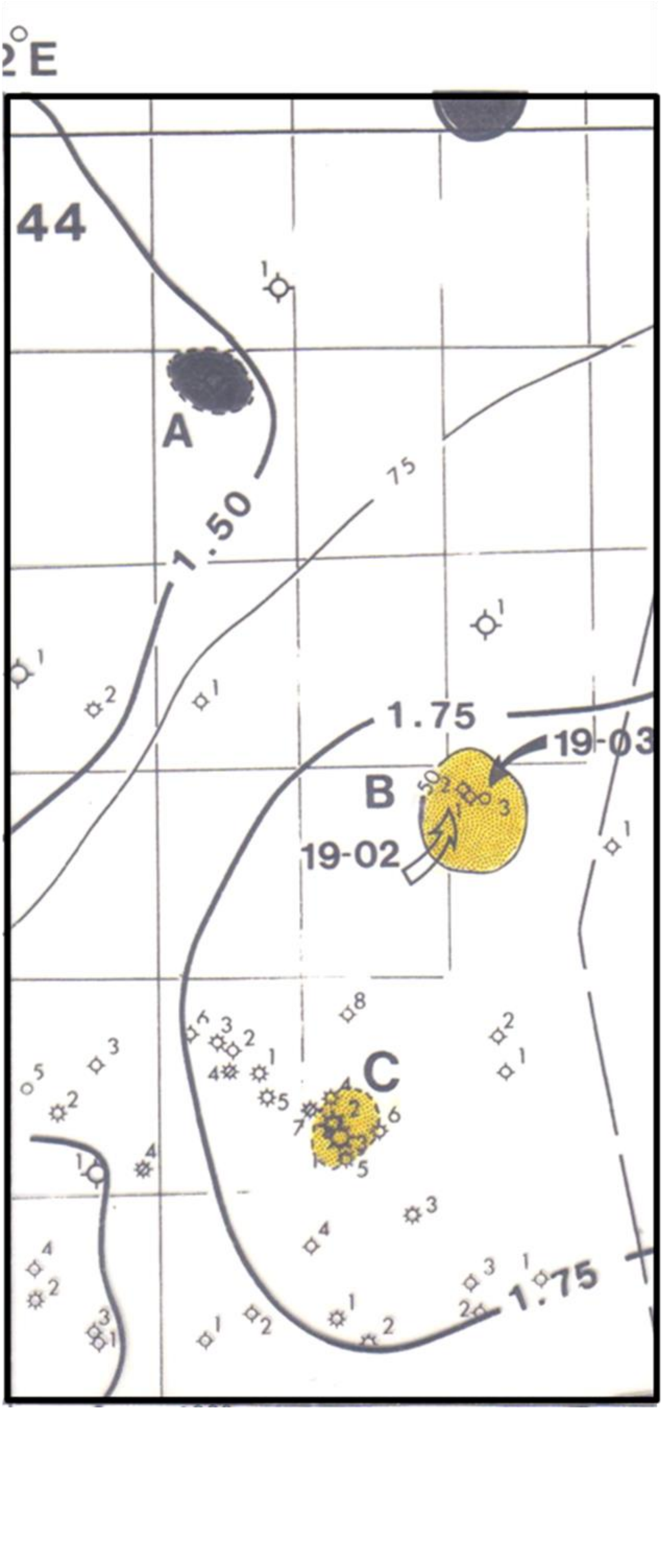


Figure 6