Seismic Interpretation of the West Sole Gas Field

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The first seismic data across the West Sole gas field were shot during 1962, the field discovery well (48/6–1) was drilled in 1965 and production well 48/6–22 and 23 were drilled during 1973. This paper demonstrates the gradual evolution over those eleven years of our knowledge of the structural configuration of the field, from the earliest simple time map to the current picture obtained by multi-layer, three dimensional migration using sophisticated velocity functions. The formulation of these functions using all available seismic and well information for each of the major lithologic intervals is discussed, and the overall accuracy of the structural picture is analysed. West Sole is of particular geophysical curiosity because the final depth map on the Base Zechstein bears no direct resemblance for the time map, in fact the shortest reflection times are associated with the deepest part of the feature.

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Introduction

This paper tells the geophysical story of just one of the many hundreds of licence blocks in the UK sector of the North Sea. Block 48/6 contains part of just one of the hundreds of salt features which litter the Zechstein Salt Basin and lying largely beneath the south-western flank of this salt pillow in the West Sole Gas field, just one, and a modest one, of the several gas fields discovered so far in the North Sea.

Sole Pit is a sea bed depression approximately 50 miles east of the mouth of the River Humber. The area is always crowded with trawlers from Grimsby and Hull in search of the fish which give the feature its name. The West Sole Gas Field was so named, as it lies at a depth of approximately 3000 metres beneath the western edge of the Sole Pit.

The first seismic data were recorded in the West Sole area in the summer of 1962 using 50 lb. dynamite charges shot single cover into a straddle spread of 400 metres on each side of the shot. The analogue tapes thus recorded were plagued with heavy ringing and very strong multiples and the seismic sections produced were almost unreadable at all but the very shallow levels. Despite the general poor quality of the data, however, it was possible to demonstrate that the Zechstein evaporite series which was known to extend from Poland, through North Germany and Northern Holland, also extended across the North Sea practically to the English Coast.

The reflection from the top of the Zechstein Salt is easily recognised as being immediately above a series of very pronounced broad diffraction patterns. This is a characteristic and therefore diagnostic feature of the Permian Salt reflection over most of the Southern North Sea, and is probably caused by the diffraction of energy from the edges of fractured rifts of the brittle Z3 anhydrite, which is usually present near the top of the salt section.

The Basal Zechstein anhydrite was readable intermittently and this was mapped where possible in the hope that the Rotliegendes Sands, which lie beneath this unit at Groningen, also extended across the North Sea.

Although it was recognised in the early stages of exploration that there were various potential hydrocarbon bearing targets in the North Sea, the initial search in the south was of course for duplication of the conditions present at Groningen, where several thousand feet of Upper Permian (Zechstein) salt form the cap to the gas reservoir of high porosity Lower Permian (Rotliegendes) sand. The underlying, unconformable Carboniferous Coal Measures are probably the source of the gas. The presence of all these conditions cannot be determined by reflection seismology alone. In the reconnaissance Seismic Surveys of 1963 and 1964 the Base Zechstein anhydrite was the deepest reflector that could be reliable indentified, the existence of the Rotliegendes sand and Coal Measures could only be postulated.

The seismic problem

The principal seismic objective therefore became that of finding closed Base Zechstein Structures, and the seismic section in Plate 1 (a) illustrates the difficulty of achieving this object with the data available in 1962.

Subsequently the seismic method developed rapidly as illustrated in the historical summary in Fig. 1, and with the most recent seismic data in the area it is now possible to read the Basal Zechstein anhydrite reflection with considerable confidence and precision. The two lines illustrated in Plate 1 demonstrate the improvement in seismic quality which can be attributed to the improved recording and processing techniques summarised in Fig. 1. It is clear therefore, that the evolution of the structural interpretation of the field has been directly related to this improving seismic quality. As more seismic data were shot, not only did the quality improve, but the density of data increased, more and more well information became available and greater understanding of the velocity problems developed.

In some parts of the southern North Sea, reliable reflections could be obtained from several horizons. Studying the scanty data obtained from the velocity profiles that were shot in the reconnaissance stages of 1963 and 1964 it was soon clear that there were considerable variations in interval velocities with depth, and that many more data were required in order to determine velocity-depth functions that would be adequate to convert the reflection sections into depth profiles.

If all reflection horizons were conformable, erroneous velocity functions would have little effect on the structural picture. Isochron highs would still exist as highs when converted to depth; the actual depth to any point would be wrong but the general shape of the structure would still be valid, and the choice of a drilling location would not depend on the velocity function used.

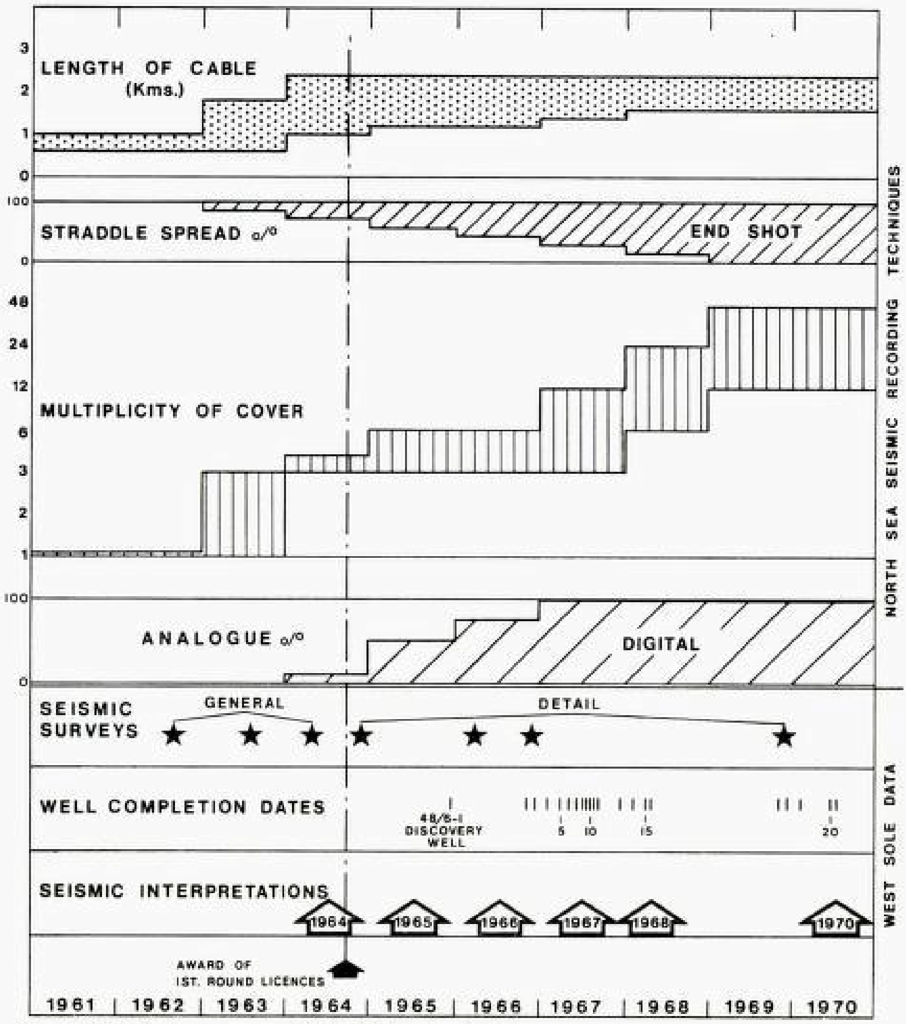


Fig. 1. Historical summary of West Sole seismic data.

In the southern North Sea, it is an understatement to say that the horizons are not always conformable! Due to the diapiric nature of the Permian salt and the subsequent rapid lateral changes in thickness, depth and interval velocity of the overlying Mesozoic and Tertiary, closed isochron features on the Base Zechstein cannot necessarily be assumed to exist as genuine closed structures. In fact there are many cases in which the use of inaccurate velocity functions can create apparent structure where none exist, and closed, attractive looking isochron features can often be attributed to velocity 'pull-up' due to overlying, high-velocity salt pillows or domes. It was very soon recognised that accurate interval velocity information is as important as the reflection sections themselves, and although we may be primarily interested in the Base Zechstein, it is usually essential to follow a number of shallower horizons merely to facilitate the conversion of the Basal Zechstein reflection times into depths.

Many wells have been drilled during the last few years, but these are generally on or near the top of Mesozoic highs and so yield very limited data on the variation of interval velocity with depth. The bulk of velocity data must therefore come from move-out studies or from development wells on Basal Zechstein highs that are overlain by offset salt wells. This entails penetrating the Mesozoic intervals at a wide range of depths whilst drilling crestal production wells in the Rotliegendes reservoir.

The West Sole field provides an ideal example of this, and in order to be able to see the effect of the growth of data on the evolving picture of the structure, we will consider the interpretation year by year.

INTERPRETATION 1964

The first isochron map on the Basal Zechstein in the West Sole area was completed in July 1964 and showed (Plate 2) a loosely defined high with a closure of at least 100 millisec. lying with a N.N.-Westerly axis across the 48/6 block. The block was applied for on the basis of this map, it being considered at the time that the problems of depth conversion were too complex for a simple method to give a valid conversion, and the data too poor to justify a more complicated approach.

INTERPRETATION 1965

After the allocation of concessions by the Ministry of Power in September 1964, four lines were shot within the block during October and November, 1964. All the 1962, 1963 and 1964 data were used in the construction of the isochron map (Plate 2) which, although using data which were largely fragmentary, were considered reasonably reliable.

Conversion to depth presented a problem as, at this time, there had been no wells drilled in the North Sea and most of the seismic data were too poor to yield reliable velocity data from move-out analysis on the Basal Zechstein reflection. The top and bottom of the salt, however, could be mapped with confidence, and various wells drilled through the Zechstein Salt in Germany and Holland had shown a reasonably constant salt velocity of approximately 4,400 m/sec.; the main problem, therefore, was the identification of the Mesozoic reflection (Tertiary being absent locally) and the selection of suitable velocity functions for the Mesozoic. Papers by S. M. Wyrobek (1959) and Muhlen & Tuchel (1953) yielded interval velocity data for the Mesozoic in both England and N.W. Germany, but without positive identification of the various Mesozoic intervals, and the knowledge that their lithological characteristics remained constant across the North Sea, this information was of no great help. It was clearly necessary therefore, to build up local velocity information on the interval between sea-bed and top Zechstein Salt. Fortunately, although the top Salt reflection is not generally of good quality it was possible to develop the velocity function from move-out studies over a limited range of reflection times. Corrections were applied to this velocity function for the effect of dip but, unfortunately, the feathering angle was not measured

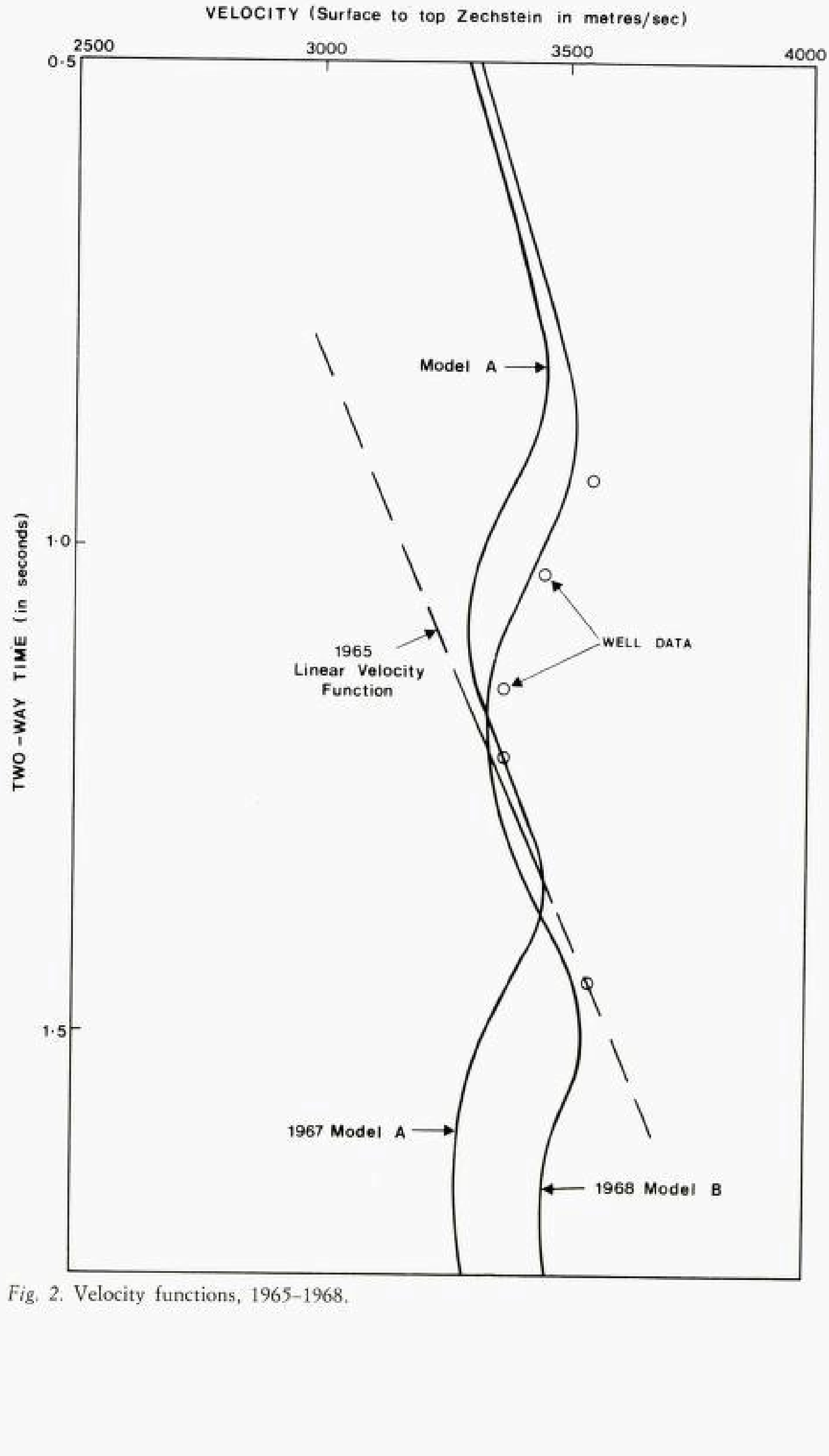


Fig. 2. Velocity functions, 1965–1968.

in these early surveys, so could not be accounted for. This analysis yielded a surface to Top Zechstein Salt average velocity curve, but only for a very limited range of reflection times (1.1 to 1.4 sec see Fig. 2) as reflection quality decayed beyond these limits.

It has been generally found in other areas that over quite large depth ranges, the interval velocity-depth curves approximate to straight lines. Since the surface to Top Permian average velocity curve was approximately linear over the observed time range, it was assumed, for the purposes of depth conversion, and in the absence of any contrary data, that this straight line could be extrapolated in both directions. This velocity function was then used to convert reflection times to the Top Salt depth and a constant salt velocity (4400 m/sec.) was again used for the incremental interval to Basal Zechstein. It was decided to test the Base Zechstein structure at the highest point indicated on this interpretation and the well 48/6–1 was spudded in by the drilling platform Sea Gem.

INTERPRETATION 1966

Following the discovery of commercial quantities of gas in the 48/6–1 well (December 1965), a detail seismic survey was shot over the structure in the summer of 1966. The general shape of the time high was similar to that of 1965 but the faults which could not be correlated in 1965 because of insufficient coverage and poor quality data have now been mapped.

Since the Mesozoic events could still not be followed with confidence, a velocity model was constructed using the 48/6–1 well data. This model (Model 'A' in Fig. 2) was developed by creating interval velocity versus depth functions for all the major stratigraphic units in the well using move-out data, UK and Continental European published data, adjusting them to 'best fit' the move-out data for the Top Zechstein Salt (Hornabrook 1967).

The model was extended up and down flank from the 48/6–1 well using what scanty seismic data were available to control the thickness variations in the Mesozoic intervals. It was then assumed that the Mesozoic intervals maintained a constant thickness in the Mesozoic strike direction. This enabled a velocity function for surface to Top Salt to be constructed and used even where the individual Mesozoic units could not be followed.

Again a constant salt velocity was used. The resulting depth map has clearly reduced the crestal area of the main structure.

INTERPRETATION 1967

Additional seismic detail shot towards the end of 1966 was incorporated into the 1967 interpretation. The same velocity function (Model A) was used as for the 1966 interpretation.

In the depth map we see for the first time a third lobe developing in the north west corner of the block; in the interpretations of 1964, '65 and '66 only two separate culminations appeared on the structure.

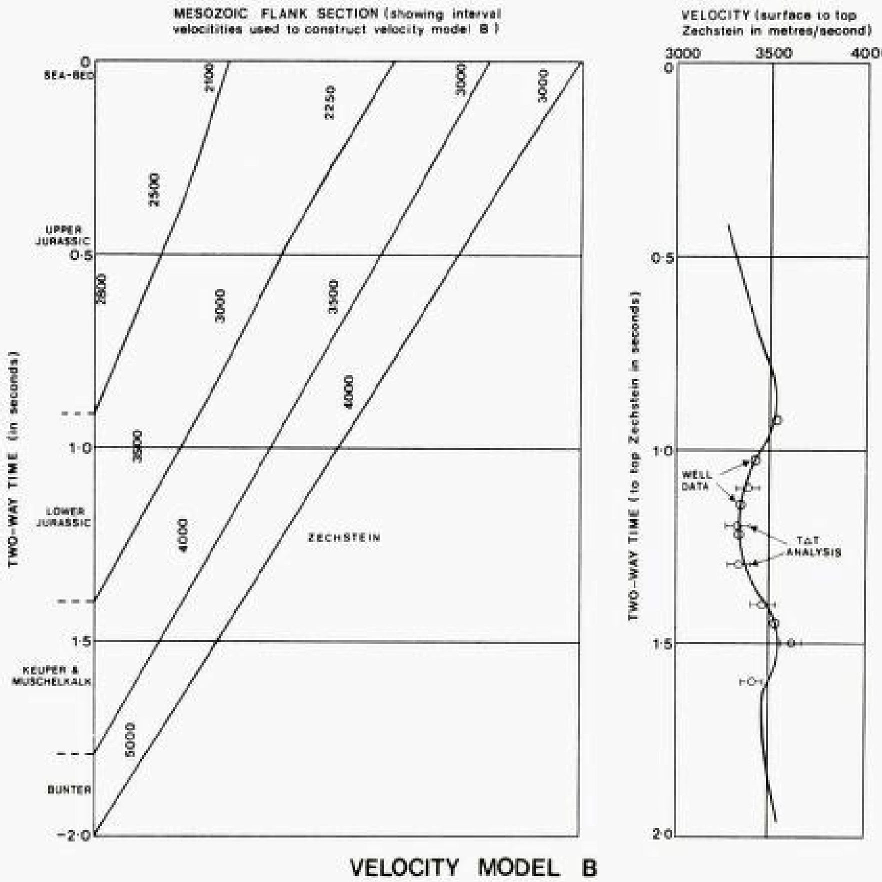


Fig. 3. Velocity model B.

INTERPRETATION 1968

This interpretation used the same time map as the 1967 version but used a more sophisticated velocity treatment, which we shall refer to as velocity model B (Figs. 2 and 3). This was constructed in a similar fashion to model A, but had access to stratigraphic data from the various wells (up to 48/6–7) on the West Sole Field and from several other wells in the vicinity. The individual interval velocity functions were modified outside the limits of well control to give a best fit to the shapes of an extensive move-out velocity analysis (from surface to Top Permian) by an iterative process.

Model B fitted the available well data to better than 2%, but the bulk of these wells lay in the southern portion of the field and it was important to estimate the validity of the model further north. By its method of construction the model shows the postulated velocity situation along a section perpendicular to the salt axis. There could possibly be minor variations in both the thicknesses and interval velocities of the various stratigraphic intervals in the direction of the salt axis, but a comparision of the move-out data from both ends

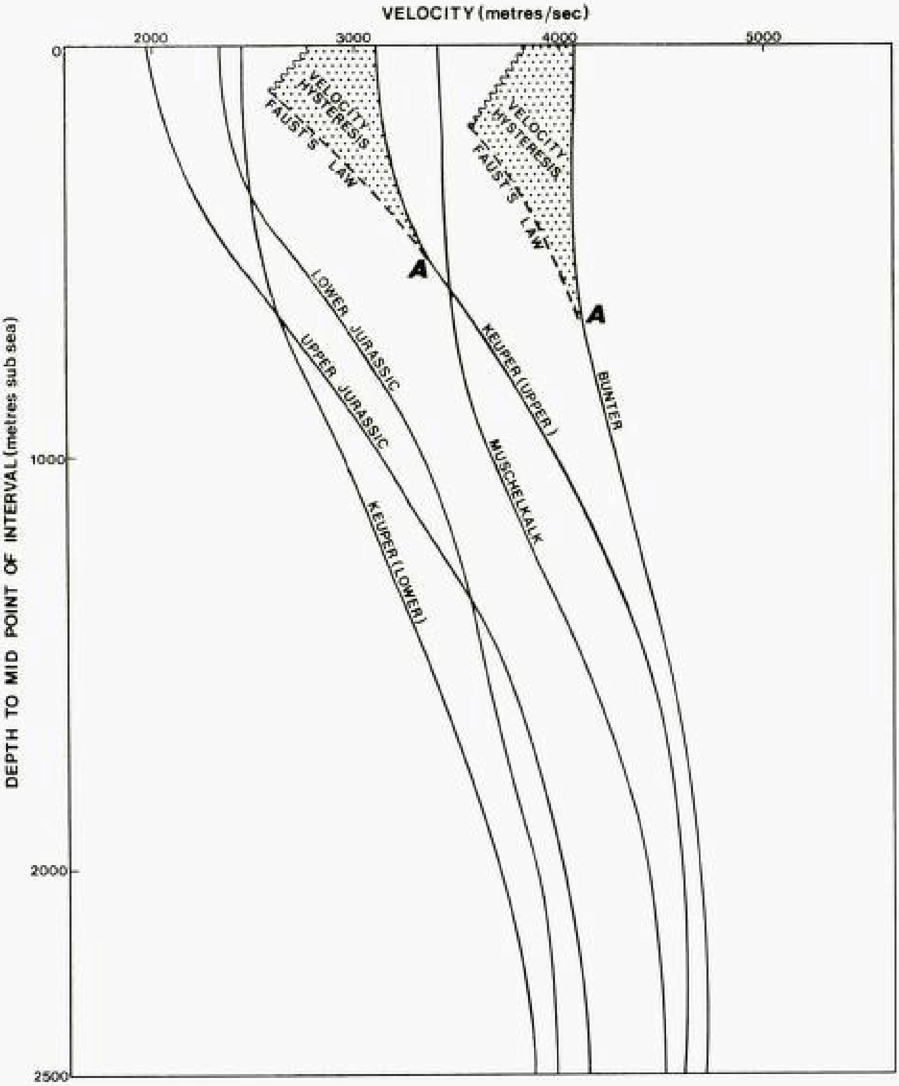


Fig. 4. Interval velocity functions, 1970.

of the salt axis showed that any variation in the model from south to north was less than the statistical error of the analysis (i.e. less than 3%).

From the first seven West Sole wells, and many others in the North Sea and onshore Holland, 4400 m/sec. appears the best assumption for salt velocity, but the Zechstein velocity problem lies in defining the thicknesses and velocities of the various non-salt layers within the Zechstein column. If these were always present, and of a constant velocity and thickness, their effects on Base Zechstein depths could easily be calculated. Unfortunately, when the salt starts to flow the anhydrite is broken into a number of blocks or rafts, and some of these are carried by the salt flow, and often deformed beyond seismic recognition. Generally, therefore, we cannot define the limits of these beds, and so a constant velocity must be used until sufficient Zechstein data are available for a more elaborate treatment.

Locally we find that the Z3 anhydrite is sometimes a very good reflection, and in the southwestern part of the 48/6 block it can be followed on all the lines. On most of the lines in this area, the limit of the Z3 can be seen (Plate 3), and the zone of unfractured Z3 is shown in Fig. 5. To the northeast of this zone the anhydrite has been broken up and carried by the salt. There are various fragments of strong reflection and diffraction which are probably derived from the Z3 anhydrite, but it cannot be plotted with any certainty.

Where the anhydrite exists in its unfractured state, its thickness is of the order of 120 metres, and velocity approximately 6000 m/sec.; when it is fractured and carried away by the salt flow, it is replaced by salt with a velocity of 4400 m/sec., and this has the effect of apparently lowering the Base Zechstein depth profile by 32 metres (just over 1%). Over most of the area we cannot say whether the Z3 is present in the salt column or not. There is therefore a possible error at any point on the Base Zechstein depth profile owing to this uncertainty of the order of 1%.

The depth map resulting from this more elaborate velocity treatment looks markedly different, especially in the central part of the field, than the 1967 interpretation of the same time data. A typical section across this part of the structures is shown in Fig. 7 and illustrates the difference between this version and that of 1967.

INTERPRETATION 1970

The survey of late 1969 was designed to look for possible extensions to the productive area of the West Sole field. At this stage 21 wells had been drilled of which 19 were production wells.

With the improved quality of the 1969 data it was possible to follow several Mesozoic horizons over the entire field area; it was therefore worth considering the construction of individual interval velocity functions for all the mappable units.

Interval velocity function

Interval functions were built up using the same general approach as for models A and B, but there were now 21 wells available over the feature, and although they were generally on the Crestal area in the Basal Zechstein they straddled quite a wide range of depths through the Mesozoic intervals. It was still necessary, however, to extrapolate the function beyond the limits of well control and the simple straight line approach gives in many cases ridiculously low velocities at shallow depths and improbably high velocities at large depths.

If the change of interval velocity with depth is due only to the increased compaction due to the greater weight of overburden then Gassman (1951) and Faust (1953) have both produced laws that allow a gradual increase in velocity with depth of burial. When we have subsequent uplift of a deeply

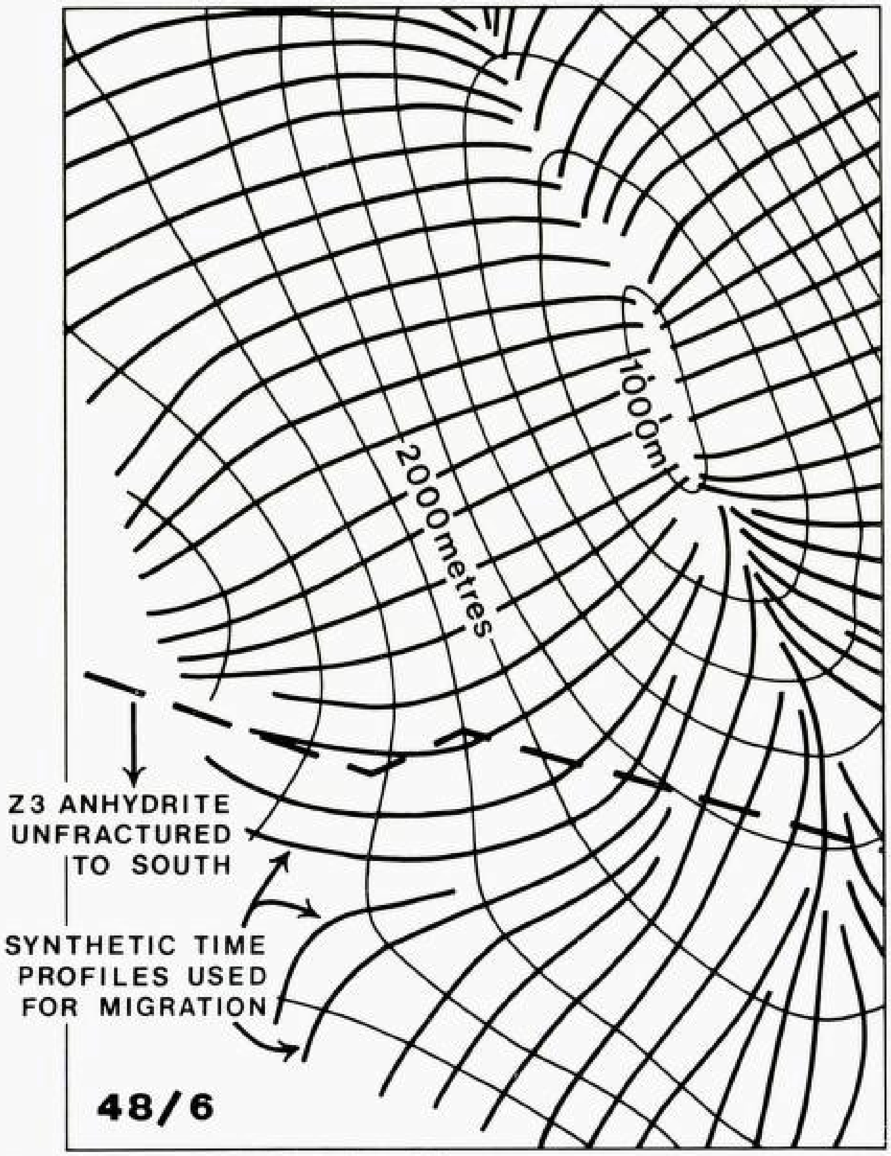


Fig. 5. Depth contours on Top Zechstein Salt.

buried interval, however, we would not generally expect that its interval velocity will decrease to fit these simple laws. This would assume perfect elasticity over very long periods of time, and ignores any effects of in situ cementation. So, we might expect the interval velocity for, say, the Bunter Sandstones or Upper Keuper over the top of a Salt swell, to be controlled more by the greatest depth of burial during its geological history than by its present depth. The Faust or Gassman curve probably still applies for intervals now lying at their historically greatest depth but must be modified as suggested in Fig. 4 for intervals subsequently uplifted. The choice of starting point for this modification is complicated by continuing depression and deposition regionally in addition to the localized salt uplift. The extent of the velocity relaxation, or hysteresis above point A (on the Upper Keuper curve of Fig. 4) depends on the lithology, extent of cementation and time scale of the movement. If well data fail to give control over the shape above A it is probably better to assume a constant or slightly decreasing velocity at shallow depth than the values given by either a straight line extrapolation or Faust or Gassman laws.

It is clear, therefore, that this velocity 'hysteresis' effect will be influenced by the entire burial history of the interval. Since the well velocity data we have available only cover the middle range of the curve, and we wish to study the Base Zechstein structure beneath the salt swell, where all the intervals are much shallower, an attempt had to be made to extrapolate the functions through this 'hysteresis' zone.

A study of the well data suggests the salt flow was initiated in the Upper Bunter, but was of small vertical extent at this stage (20–30 metres). As the entire area progressively depressed, and the weight of sediment increased, the velocity of Salt movement also increased, so that 100 metres or so of movement had taken place by the end of the Keuper. The bulk of the movement took place during the Jurassic (2000 metres).

The velocity function used in the depth conversion attempted to use this history in estimating the 'hysteresis' effect on the velocity curves. The functions actually used for depth conversion and migration are indicated on Fig. 4, each function being approximated to three straight lines for presentation to the computer. Although we believe these functions accurately define the velocities over the West Sole field, they clearly should not be used over other features in the area, as apart from regional variations in the individual lithologies, which affect the entire velocity curve, the 'hysteresis' effect will be different over each Salt uplift.

Depth conversion

Seven horizons were mapped and these are indicated on the seismic section of Plate 3; the main purpose of interpreting these horizons was of course to obtain a more accurate depth conversion to the Basal Zechstein. By using the individual interval velocities allowance could be made for outcropping beds and varying formation thickness.

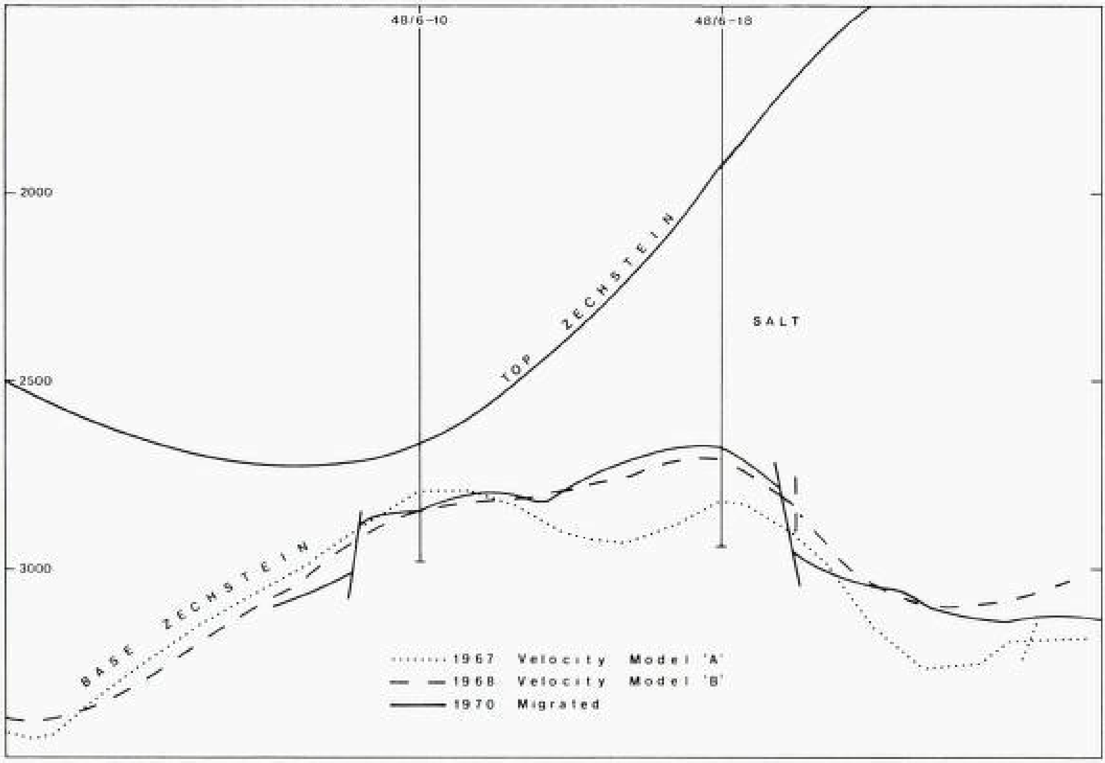
The time map produced shows the same general high area as previously, but is further complicated by additional faults.

In order to convert to depth and to account for migrated travel paths a full migration using all seven intervals mapped was performed. Isochron maps were drawn on these horizons and synthetic time profiles prepared. Because Zechstein salt flows are responsible for most of the Mesozoic structure, which exhibits dips up to 20%, compared with less than 4% for the Basal Zechstein level, these profiles were constructed along dip lines on the Top Zechstein

Fig. 6. Comparison of time and depth sections, 1970.

Salt horizon (Fig. 5). In this manner, an attempt to treat a three-dimensional migration has been made using only two dimensions. Care was taken to ensure that the horizontal curvatures of the synthetic time profile are not too great to introduce distortion.

The migration method, once these synthetic time profiles were created, was to take the first layer and to construct a fan of possible wave paths for each reflection point. The envelope to the series of wavefronts thus generated was taken as the depth profile. The same process was repeated for the next layer using the depth profile already obtained for the first. This was repeated



EFFECT OF VARIOUS VELOCITY MODELS ON DEPTH PROFILE OVER WEST SOLE FIELD

Fig. 7. Depth profiles based on various velocity functions.

for all seven layers. An example of time and migrated depth profile is shown in Fig. 6, and a comparison with earlier velocity models is shown in Fig. 7. Since the synthetic time profiles used for the migration were dip lines within the Mesozoic, this method produced an accurate three-dimensional migration down to the top Salt. For the Basal Zechstein reflection the component of dip perpendicular to the synthetic time profile was considered; and a comparatively crude attempt was made to allow for migration in this direction. Since these dips are much smaller than the Mesozoic dips, this 'second order' effect was small and caused only slight modification of the Basal Zechstein contours. After comparing the depths calculated using the initial velocity functions with the known well depths, some of the functions were slightly modified; also, a correction was applied to the Basal Zechstein depths in an attempt to account for the amount of Z3 anhydrite/dolomite present in the Zechstein. As an indication of the accuracy of the final map, it is found that the calculated depths are within 40 metres of the well depths for the 21 wells on the field. Residual differences, such as these, are bound to remain since no model can consider all the parameters; inevitably errors due to unaccounted small thickness variation and velocity inhomogeneities within the formation must remain.

One of the problems that we have looked at but have insufficient data to reach sensible conclusions on is that of anistropy. With dips in the Mesozoic overburden of up to 20° and with deviated holes both up and down dip of up to 40° from the vertical, it has not been possible to separate out the contribution of anistropy from the depths effect on the velocity variation.

Accuracy of final maps

The further we stray from well control, the more uncertain our velocity functions become, but we believe that within field area the velocity functions used are in error by no more than 2%.

There are several possible minor sources of error in the reflection travel time but generally we believe they are accurate to within 10 msec (0.7%). The plotted positions of the seismic shot points themselves are not beyond some doubt; various survey chains were used including Seashell, Seasearch I and Humber Hifix and the first two were used at night beyond the hours of reliability. Quite large positional errors (several hundred metres) undoubtedly occur on some of the early lines, but these lines, also of poor seismic quality, have not been used in the 1970 interpretation. The bulk of the data used in this last interpretation used Humber Hifix which were considered to give positional accuracy of better than 30 metres.

Even if we accept the plotted positions of the shotpoints, however, the depth estimate attached to it does not necessarily refer exactly to that point. With 2400 metre cables, feathering angles of up to 15° can easily occur, and for angles of this magnitude the reflection time picked on the section is the mean value along a line 300 metres long at right angles to the seismic line, not the actual value at the shotpoint. An attempt has been made to take account of this in the contouring, but in the earlier data the feathering angle was not recorded, so an unresolved uncertainty persists. Since the depth of an horizon is the product of its reflection time (one-way) and the overburden velocity, the accuracy of the depth map for the Basal Zechstein depends on the accuracy of both time and velocity, and, since the probable errors of the time data are considerably less than that of the velocity function, the shooting of additional lines, although improving the time map, will not greatly influence the accuracy of the depth map, for although there would be additional depth estimates, their accuracy will be dominated by the accuracy of the velocity function.

The accuracy of depth estimates at points which are not on seismic lines will depend on all the above factors, but the effect of contouring would also need to be considered. The amount of interpolation involved varies enormously over the area, and the general trend, local complexity, possible faults and distance from seismic control would all need to be considered; the question is too involved to discuss in general terms, and each case would have to be considered separately.

Summarising the factors which influence the accuracy of the Base Zechstein depth map, we have:

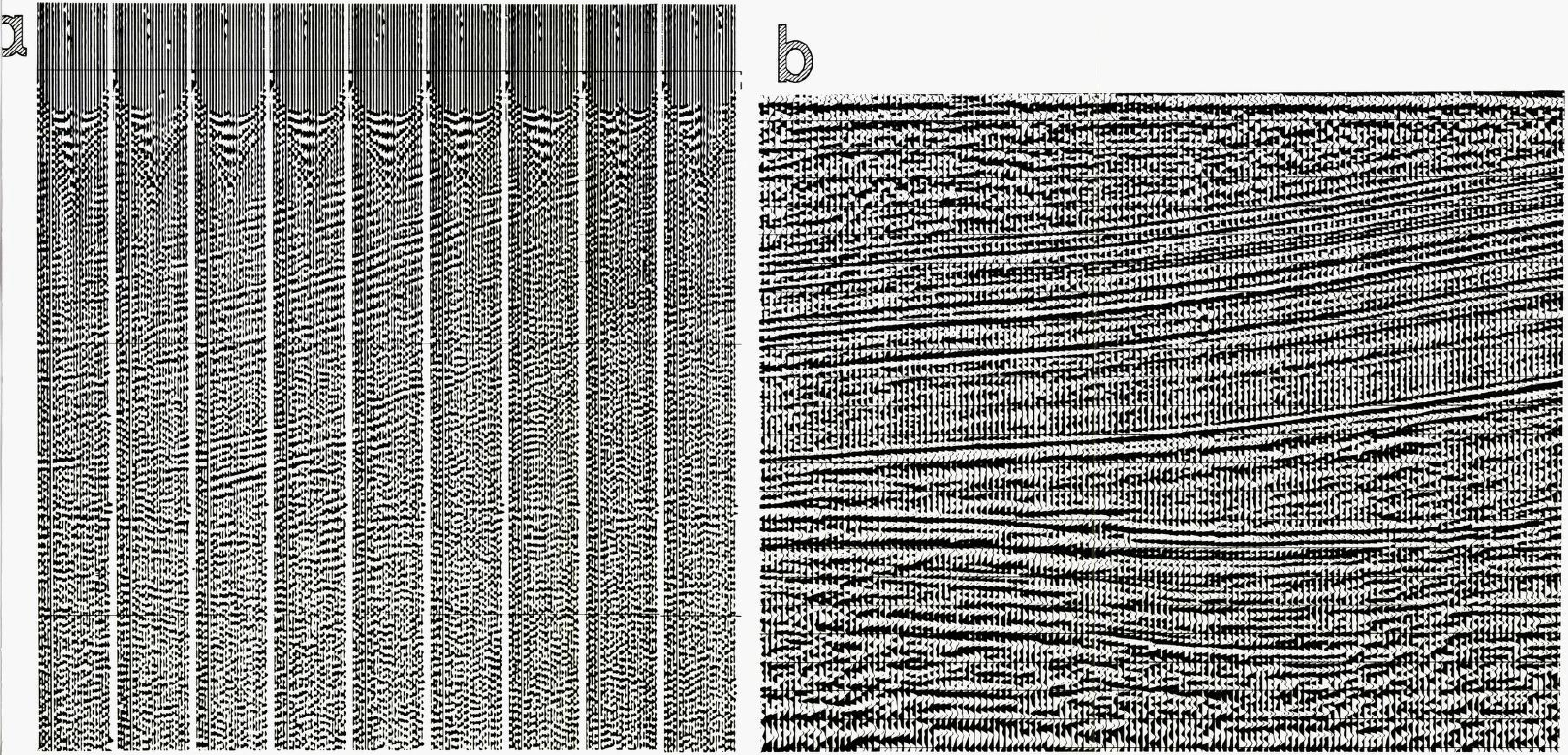


Plate 1. Seismic sections across the West Sole Field. (a) 1962; (b) 1970.

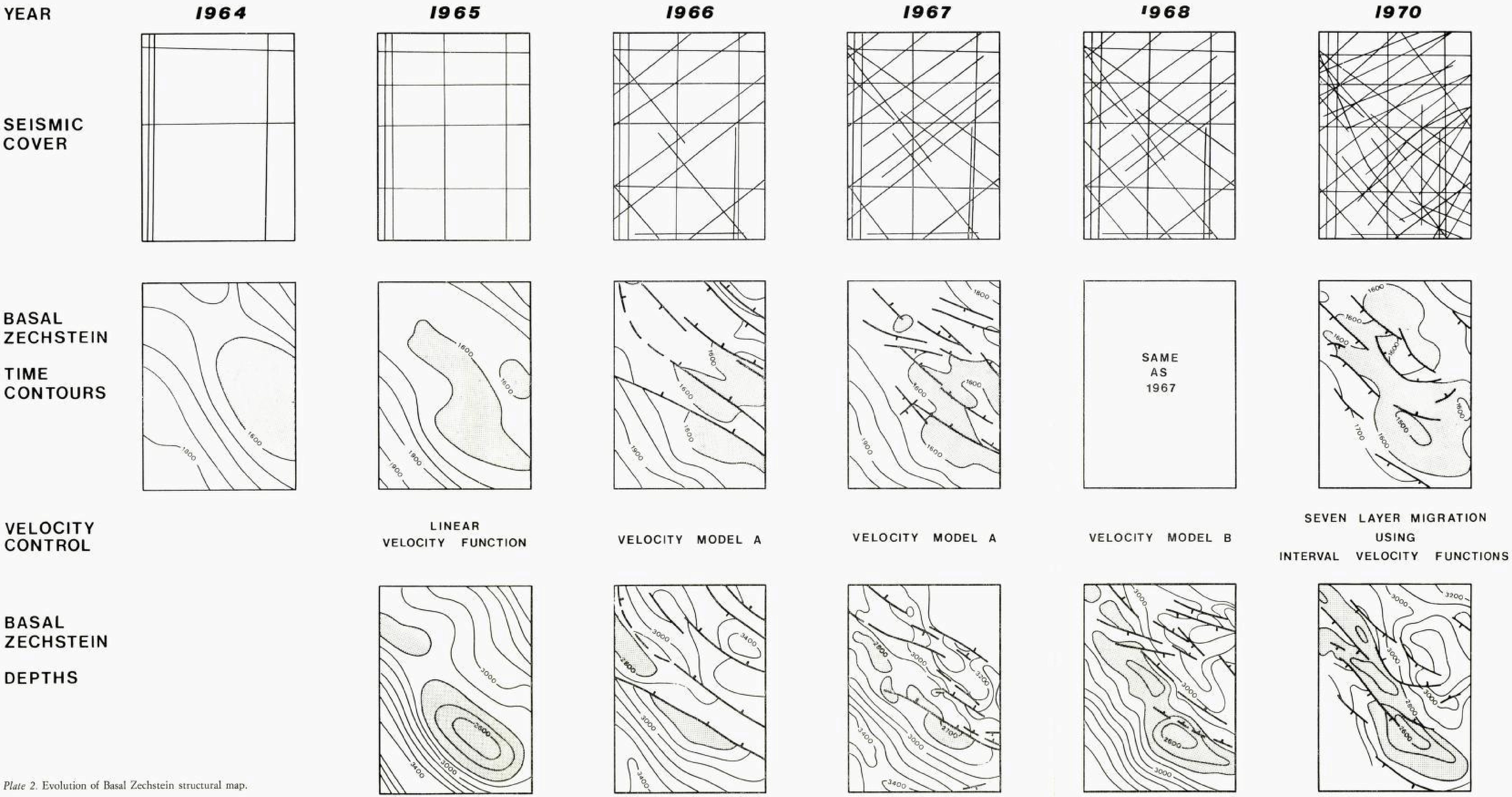


Plate 2. Evolution of Basal Zechstein structural map.

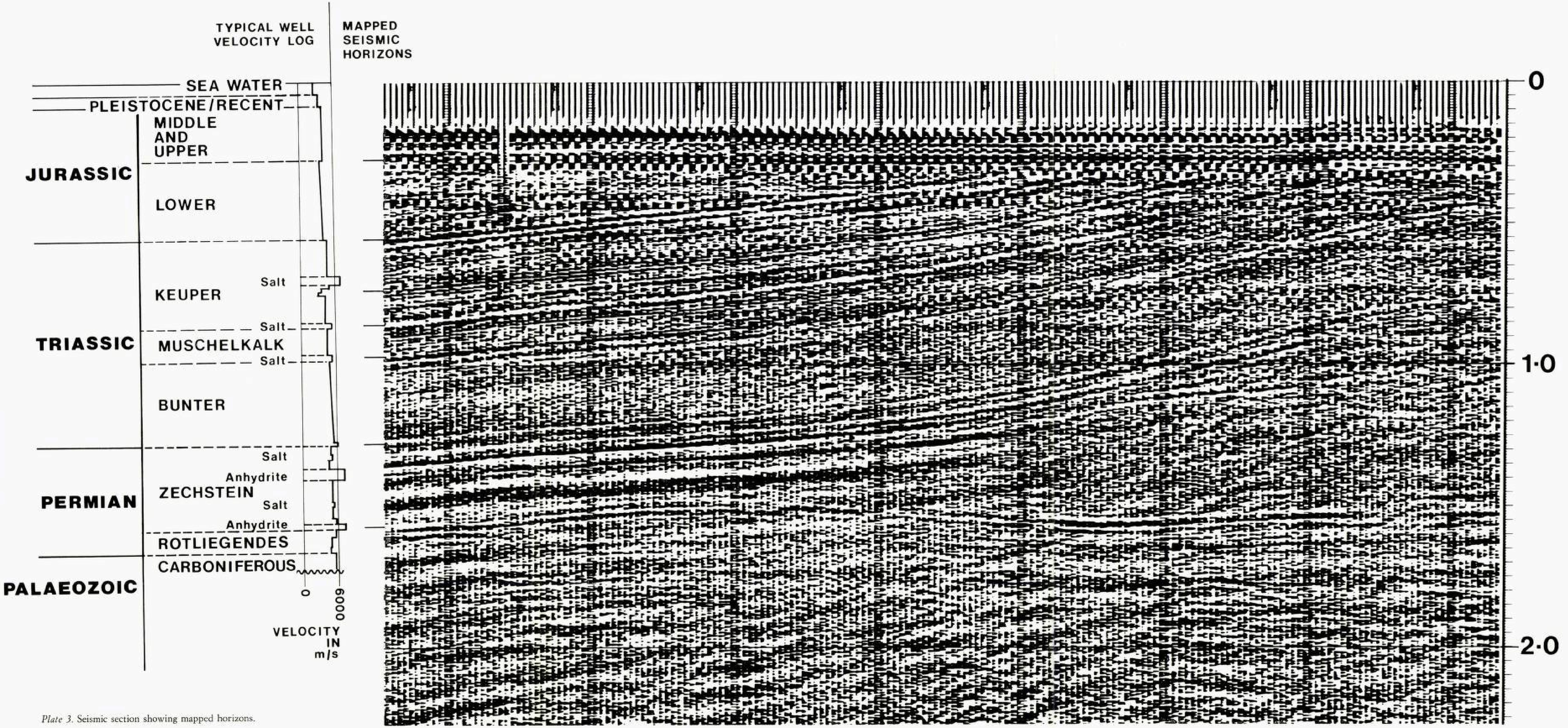


Plate 3. Seismic section showing mapped horizons.

	Probable error of Base Zechstein Depth
1) Reflection time to Top Salt	0.6%
2) Overburden velocity for Top Salt	2.0%
3) Interval time through Salt	0.7%
4) Interval velocity in Salt	1.0%
5) Migration and contouring effects	1.0%
6) Survey errors	0.5%

The probable error for the Base Zechstein depth estimate at any particular shot point on the West Sole structure is therefore less than 3%, i.e. less than 75 metres.

Conclusion

The series of maps show a progressively more complicated picture emerging as more and better data are added, until the final depth conversion (1970), which suddenly simplifies what has become a rather grotesque looking time feature. It is apparent, therefore, that much of the apparent structural complication on the time maps is due to the distortive effects of variable overburden velocities, and it is also clear that the only way to eliminate these effects is to develop local velocity functions which are related to the structural history of the feature.

There is little doubt that many of the early exploration holes in the Rotliegendes gas area were drilled on apparent, but not real structures, and that several genuine structures are so distorted by velocity effects that they have yet to be recognised.

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