Subsidence history of the Jurassic sequence in the Danish Central Graben

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Subsidence diagrams for three of the structural units in the Danish Central Graben, the Southern Salt-dome Province, the Tail End Graben and the area east of the Dogger High show that the main subsidence took place in the Late Jurassic and in the Neognene/Quaternary with maximum subsidence rates of 160 m per M.y. and 125 m per M.y., respectively. The influence of compaction is considered to be of minor importance while a correction for uplift and erosion is necessary for the understanding of the dynamic history of the area.

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During recent years a detailed knowledge of subsidence history has become of increasing importance for areas with a hydrocarbon potential. The combination of burial depth and time for a given formation must be known in studies of source rock maturation, reservoir properties and timing for hydrocarbon maturation and accumulation, (cf. Waples 1980). Subsidence diagrams can also be used as a basis for the construction of temperature curves (see Jensen 1983). Further, the diagrams illustrate in a convenient way the dynamic history of an area.

The present study is a continuation of the work on the geology of the Danish Central Graben, published in Michelsen (1982). Focus has been put on the Jurassic sequence for two main reasons. First, the main source rock formation in the Danish Central Graben, informally named the J-4 unit, is Jurassic in age, and also other Jurassic formations are believed to have a source rock potential (Lindgreen et al. 1982). Second, the Jurassic sequence contains potential reservoir formations of importance as targets for the hydrocarbon exploration.

Framework

The Danish Central Graben has been subdivided into eight structural units (Andersen et al. 1982, Michelsen & Andersen 1983) (fig. 1). Subsidence

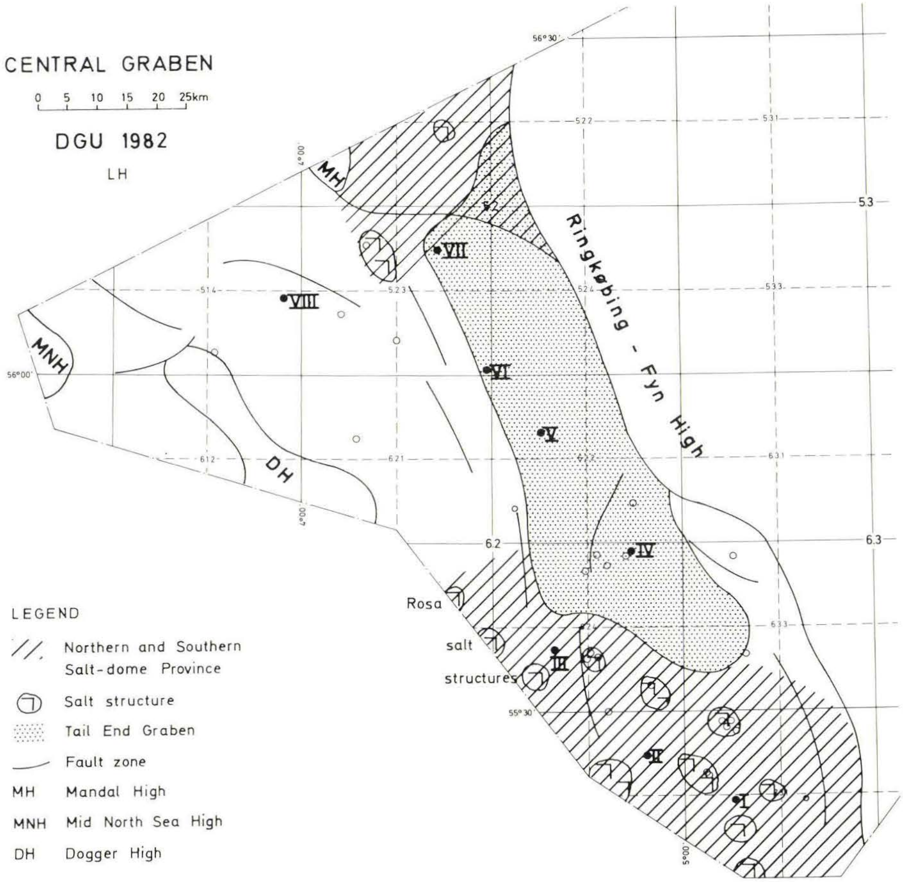

Fig. 1. Location map. Structural units of the Central Graben are indicated. After Michelsen & Andersen (1983).

diagrams have been constructed for three of these units, the Southern Salt-dome Province, represented by 3 subsidence diagrams, the Tail End Graben with 4 diagrams, and one diagram from the area east of the Dogger High.

In the Southern Salt-dome Province, the depth to the top Palaeozoic is approximately 6 km. In the Tail End Graben, the depth to the top Palaeozoic is in the region of 10–11 km, in contrast to a depth of about 3 km on the adjacent parts of the Ringkøbing-Fyn High. In the area east of the Dogger High, the depth to the top Palaeozoic is approximately 5 km. This area is the least known of the structural units dealt with in this paper.

Method

The subsidence diagrams (figs. 2 and 3) have been constructed with the use of seismic sections, seismic maps and well data. Interval velocities used for depth conversion (table 1) have been chosen after general velocity-depth relationships for the three areas (J. C. Olsen pers. comm. 1981). The following seismic reflectors have been used:

top mid Miocene,
top Chalk Group,
base Chalk Group,
top Jurassic,
internal Jurassic reflector,
and base Jurassic.

The internal Jurassic reflector is considered to be close to the base of the J-4 unit. In areas where this reflector has not been identified, the thickness of the J-4 unit has been estimated for ajacent wells and from the regional setting. To simplify the diagrams, the age of this horizon has been defined as the beginning of the Kimmeridgian (150 M.y. ago), on all curves. In the Cenozoic, an extra horizon on the curves has been added, which gives the Quaternary a thickness of 500 m for all three provinces.

No corrections have been made for compaction, isostatic uplift, and erosion. The implications of this approach will be discussed later.

The error of the depths given here is mainly dependent on the error of the interval velocities and is probably within +/–10%. The velocities are generally chosen conservatively and thus the depths and thicknesses tend to be minimum rather than maximum values. In table 1, the two-way travel times, the interval velocities and the calculated depths are presented.

Each of the diagrams has been constructed to show the subsidence history for a small local area, but the diagrams are considered to represent the general Jurassic development of the structural unit in question at the same time.

Results

The general pattern of all the diagrams shows two main episodes of increased subsidence for the three areas, one in the Late Jurassic and the other in the Neogene/Quaternary. The latter is the period with the most widespread and rapid subsidence, with rates of 110–125 m per M.y. The subsidence rate

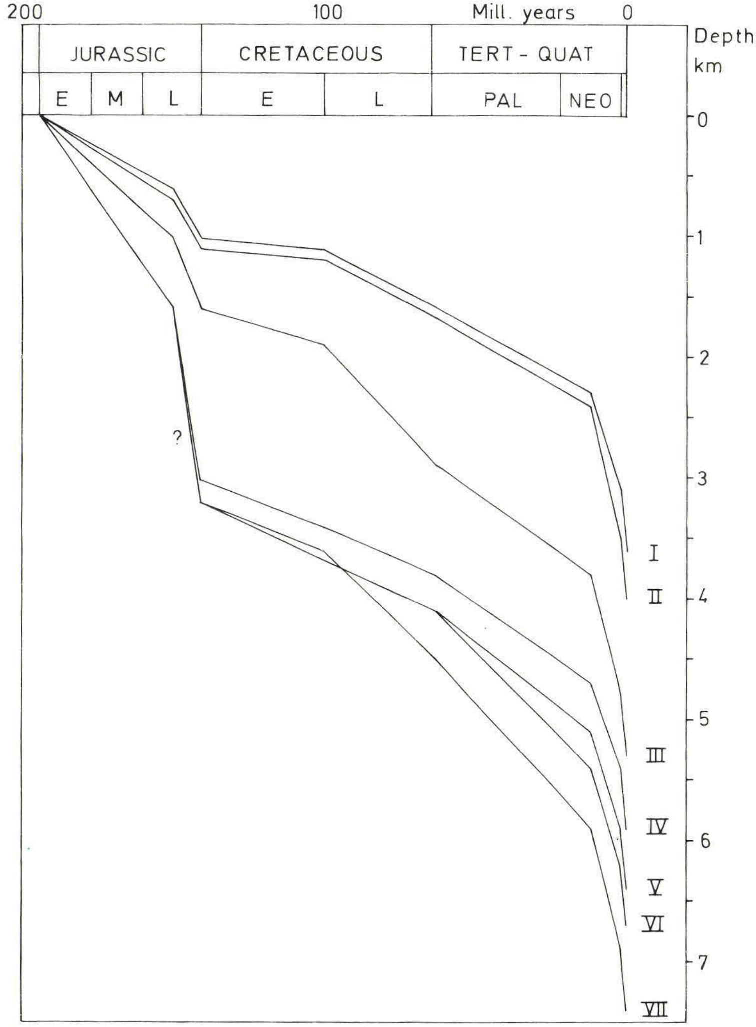

Fig. 2. Subsidence diagrams for the Southern Salt-dome Province and the Tail End Graben.

- I Southern Salt-dome Province. "Mean depth" for the Jurassic sequence.
- II Southern Salt-dome Province. Deep-seated Jurassic sequence.
- III Southern Salt-dome Province. Deep-seated Jurassic sequence east of the Rosa structures.
- IV Tail End Graben. Southern part, near the well E-1.
- V Tail End Graben. Middle, southen part.
- VI Tail End Graben. Middle, northern part.
- VII Tail End Graben. Northern part.

increases with time during the Neogene as seen from the difference in subsidence rates between the Middle and Late Miocene and the Pliocene on one hand and the Quaternary on the other hand. These are 80 m, respectively 250 m per M.y.

The rate of subsidence during deposition of the J-4 unit is, within the Central Graben, varying from 40 m to 160 m per M.y. (fig. 2). The maximum figure is uncertain, however, since it is based on seismic data only. All the figures can only be regarded as minimum values for the rate of subsidence as no correction for compaction has been made.

It should be noted that the thickness of the Lower Cretaceous sequence locally is very varying (Andersen et al. 1982, fig. 15) so a generalized picture of the Early Cretaceous subsidence is of limited value.

By comparison of the individual structural units, the following picture arises.

Since the end of the Early Cretaceous, the area east of the Dogger High has undergone the strongest subsidence of all the provinces dealt with. The top of the Jurassic sequence is here situated at a depth of 4.5 km. The Jurassic sequence is relatively thin in this area, being generally less than 1 km.

This is in strong contrast to the Tail End Graben which came into existence in Jurassic time. More than 3 km, locally 4 km of Jurassic sediments were deposited in the central part of this half-graben. The depth to the top of the Jurassic is here 3–4 km. This is due to a relatively strong Palaeogene subsidence. Besides, the Early Cretaceous sequence is relatively thick in the Graben.

Among the structural units discussed here, the Southern Salt-dome Province has suffered the most moderate subsidence since the beginning of the Jurassic.

A comparison of diagrams from a single structural unit, reveals a more detailed picture than given above. The position of the three curves for the southern Salt-dome Province (fig. 2) has been chosen to represent the Jurassic sequence at different depths and with different thicknesses: One covers the area with a mean depth (~2.5 km) to the top Jurassic reflector and a mean thickness (~1000 m) of the Jurassic sequence. The second represents areas with a deeper seated (~2.8 km) and thicker (~1200 m) Jurassic sequence, and the third curve shows the area with greatest depth (3.5–4 km) and thickest sequence (~1600 m). This last mentioned area is relatively small. The areas with the most shallow Jurassic sequence in the Southern Salt-dome Province have not been treated here.

The difference in depth between the two first areas in the Southern Salt-dome Province is due to increased subsidence of the second area since the Late Miocene. The variation in the Jurassic thickness is dependent on the position in relation to the salt structures, as the thicker sequences are found between the structures. The relatively thick and deep-seated Jurassic sequence (fig. 2, curve no. III) is related to a major synsedimentary *en echelon* fault system (compare Michelsen 1982, fig. 13), and to the development of a rimsyncline around the Rosa salt structures, situated to the west.

Four curves have been constructed for the Tail End Graben, one in the very southern part and three along a northwestward trending line through the graben (fig. 2). The thickness of the Jurassic sequence here is 3000–4000 m with maximum thicknesses in the eastern and northern part of the graben. The depth to the top Jurassic increases from south to north, from 3 km to more than 4 km. This is a result of increasing subsidence which has happened in the Cenozoic, especially during the Palaeogene. The northernmost location, represented by curve no. VII (fig. 2), shows that the relatively thin Lower Cretaceous sequence here is overlain by a thick Chalk Group (compare profile 4 in Michelsen & Andersen 1983). This is due to inversion tectonics during the Sub-Hercynian or possibly the Laramide tectonic event (Andersen et al. 1982).

The area east of the Dogger High is only represented by one diagram (fig. 3) due to the limited knowledge of the area. The curve is considered to show a mean depth of the Jurassic sequence in that area. Only the J-4 unit is included in the diagram, with an assumed thickness of 800 m.

Discussion

As mentioned earlier, no correction has been made for compaction, isostatic uplift or erosion. Some comments will be given here on the influence on the subsidence diagrams by using this approach.

Compaction: Sediments normally become compacted with increasing depth. Thus the rate of subsidence, as calculated from the present thickness becomes increasingly different (i.e. smaller than) from the "true" subsidence rate with depth. This difference is to some extent compensated by overpressuring, which tends to keep a relatively high porosity in the sediments (Magara 1978).

In the Danish Central Graben, Upper Jurassic and Lower Cretaceous shales, the Chalk Group and the Tertiary claystones below the top of the mid Miocene horizon are normally overpressured (cf. Lieberkind 1978, fig. 5). This implies that most of the sequence dealt with here in general is overpressured and thus has not suffered strong compaction.

Preliminary calculations on the compaction effect on the normally pres-

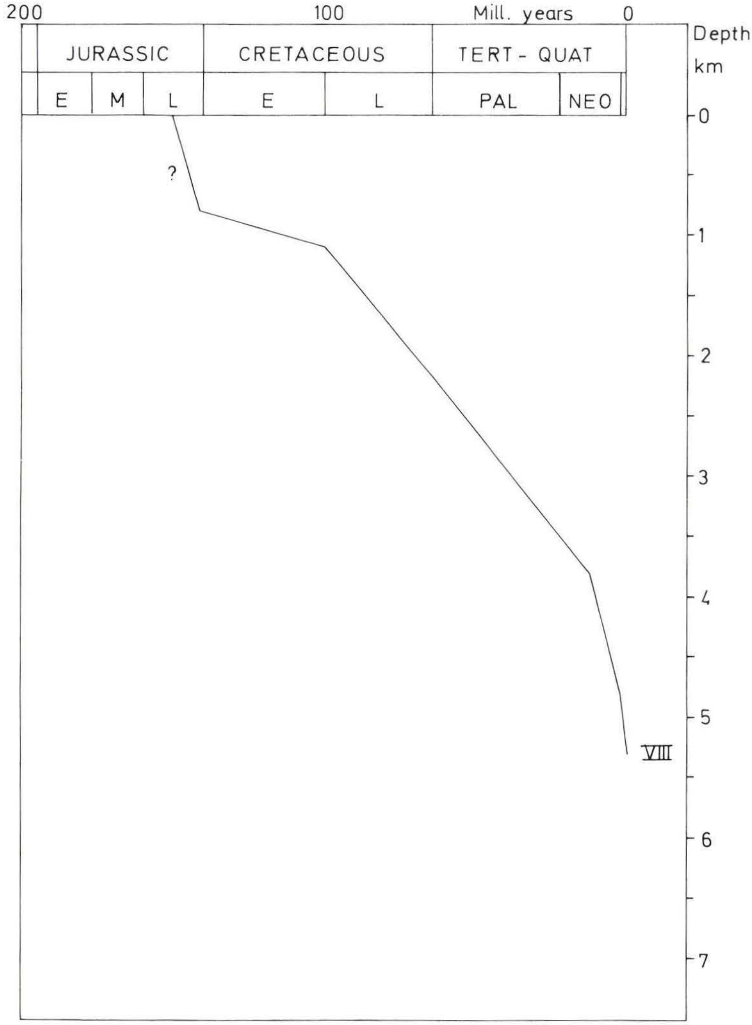

Fig. 3. Subsidence diagram from the area east of the Dogger High. Please note that the diagram starts at the base of the Kimmerigian.

sured CEN-5 and CEN-6 units, of Neogene and Quaternary age (Kristoffersen & Bang 1982) have been carried out by P. Klint Jensen (pers. comm. 1982). These calculations show that the increase in subsidence rate, from the Neogene to the Quaternary, is smaller than indicated on the diagrams, whereas the increase itself is a reality.

In summary, the lack of correction for compaction for this area is considered to be of only minor importance.

Isostatic uplift and erosion: Isostatic uplift can in some cases be recorded as changes in depositional environment, for instance from deep to shallow water environment, and/or as erosion of the sediments. These features can however, also be caused by eustatic fall of the sea level.

In the sequence dealt with in this paper, the greatest difference in depth of sedimentation is between the Lower Jurassic and the Middle Jurassic formations. During the deposition of these formations, the sedimentary environment in the Central Graben changed from marine shelf to terrestial.

This difference in the depths of sedimentation is probably in the region of a few hundred metres. The magnitude of the erosion caused by the mid-Cimmerian event can be estimated by regarding the present distribution of the Lower Jurassic Fjerritslev Formation. In the wells drilled till now, only the lowest part of the Formation (member F-I) is thought to be present. The thicknesses of the two sub-members Ia and Ib of the F-I member are the same as in the Danish Subbasin, and the palaeogeographic pattern suggests similar sedimentation in the two areas in the Early Jurassic. Therefore it is assumed that the Fjerritslev Formation in the Central Graben orignally had a similar thickness as in the Danish Subbasin. This implies that more than 500 m of the Formation has been removed by erosion.

Thus, the relatively uplift is in the region of 600–800 m. It is due to a combined effect of isostasy and eustacy. The isostatic movement may be related to a regional crustal arching in the North Sea area occuring at end-Toarcian (Eynon 1981). He suggests a rising mantle plume centred in the Outer Moray Firth area as the probable causal phenomenom. The eustatic changes include a regional regression at the end of the Toarcian, and a regional transgression, beginning in the Callovian and continuing into the Late Jurassic (Vail & Todd 1981). In Vail et al. 1977, fig. 2, the range of eustatic sea level changes from the Lower to the Middle Jurassic is estimated to be in the region of 100 m. This implies that isostatic uplift is the major factor in the development of the mid-Cimmerian unconformity in the Danish Central Graben.

The tectonic events in the Late Jurassic-Early Cretaceous caused erosion and/or non-deposition in the area around and on the Dogger High, and in the Northern Salt-dome Province. In the area east of the Dogger High, marked unconformities are present at this level but the magnitude of the erosion is not known. In the Tail End Graben and the Southern Salt-dome Province, no major hiatus from this period is known (compare Birkelund et al. 1983), but the very top of the Upper Jurassic J-4 unit is absent in many wells, indicating minor erosion. According to Rawson & Riley (1982), the unconformities in the latest Jurassic-Early Cretaceous in the North Sea Basin are of eustatic

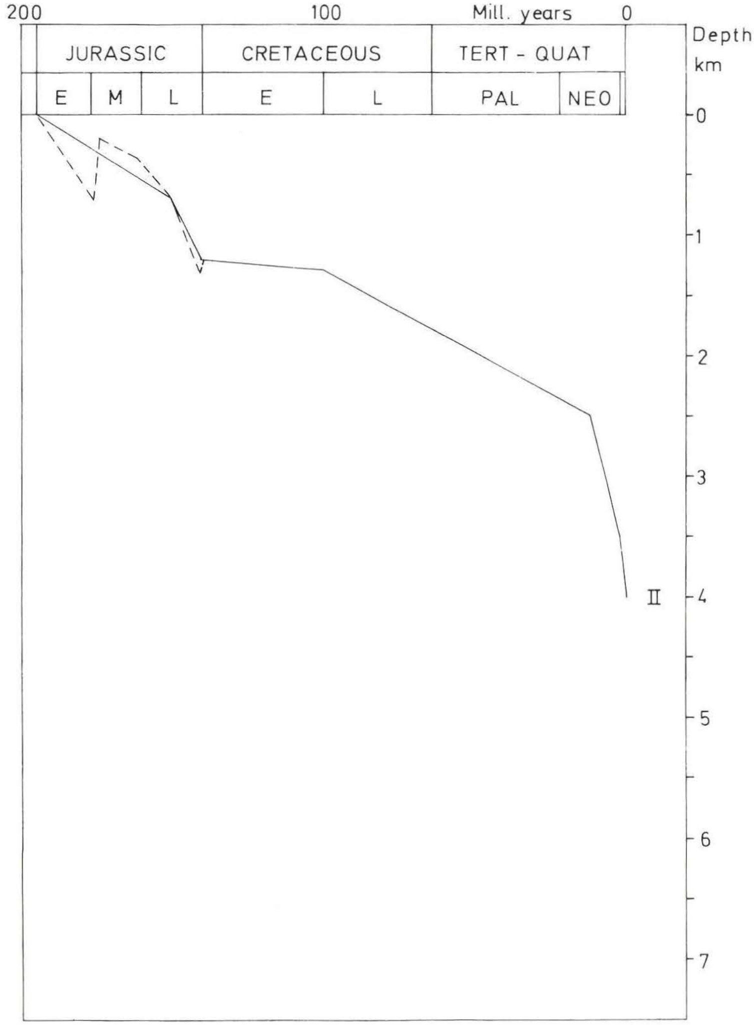

Fig. 4. Subsidence diagram from the Southern Salt-dome Province. The stippled curve is corrected for uplift and erosion.

origin. The associated isostatic uplifts have probably been limited in magnitude.

In relation to the Sub-Hercynian and the Laramide tectonic events, non-deposition rather than extensive erosion is thought to have taken place.

In summary, incorporation of isostatic uplift and erosion in the subsidence diagrams would only have changed the diagrams significantly in relation to the mid-Cimmerian event. In fig. 4, a diagram is shown which has been roughly corrected for uplift and erosion. The example is from the Southern Salt-dome Province which is the best known structural unit. The diagram shows that the subsidence in the Early Jurassic in this province was in the same order as in the Late Jurassic. The uplift in the Middle Jurassic was in the region of 500 m.

The subsidence diagrams show the general subsidence history of the structural units. If the diagrams are used to show the dynamic history of the area, a correction for uplift and erosion is necessary while the correction for compaction is of minor importance.

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Dansk sammendrag

Indsynkningsdiagrammer på basis af seismiske data er konstrueret for 3 strukturelle enheder i Central Graven. Disse omfatter Den sydlige saltstruktur Provins, Tail End Graven og området øst for Dogger Højdestruktur.

Diagrammerne viser, at hovedindsynkningen fandt sted i sen Jura og i Neogen/Kvartærtiden med maksimumshastigheder på henholdsvis 160 m og 125 m per million år. I Jura fandt den største indsynkning sted i Tail End Graven, mens den største indsynkning i sen Kridt, Tertiær og Kvartærtiden foregik i området øst for Dogger Højdestrukturen.

Betydningen af at korrigere diagrammerne for isostatisk hævning og erosion diskuteres. I forbindelse med den midt Cimmeriske tektoniske fase er der sket en hævning og erosion af Fjerritslev Formationen i størrelsesordenen 500 m. Erosion i forbindelse med de sen Cimmeriske og Laramiske faser skønnes at være lille i Den sydlige saltstruktur Provins og i Tail End Graven. I området øst for Dogger Højdestruktur kendes omfanget af erosionen ikke.

Betydningen af at korrigere for kompaktion i diagrammerne diskuteres og vurderes til at være af underordnet betydning for forståelse af den dynamiske udvikling af området.

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Table 1.

Table 1. Two-way travel times (TWT), interval velocities (V_{int}), and calculated thicknesses and depths for some seismic reflectors. TMM = top mid Miocene, TCh = top Chalk Group, TLCr = base Chalk Group, TJ = top Jurassic, JI = internal Jurassic reflector, TTr = base Jurassic.

	TWT sec.	TWT thickness sec.	V_{int} km/sec.	Thickness km	Depth km
I Southern Salt-dome Province. "Mean-depth" for the Jurassic sequence					
		1.3	2.0	1.3	
TMM	1.3				1.3
		0.7	2.0	0.7	
TCh	2.0				2.0
		0.3	3.6	0.5	
TLCr	2.3				2.5
		0.1	2.8	0.1	
TJ	2.4				2.6
		0.65	3.0	1.0	
TTr	3.05				3.6
(J-4 Unit				0.4)	

	TWT sec.	TWT thickness sec.	V_{int} km/sec.	Thickness km	Depth km
II Southern Salt-dome Province. Deep-seated Jurassic sequence					
TMM	1.5	1.5	2.0	1.5	1.5
TCh	2.2	0.7	2.0	0.7	2.2
TLCr	2.5	0.3	3.6	0.5	2.7
TJ	2.6	0.1	2.8	0.1	2.8
TTr	3.4	0.8	3.0	1.2	4.0
(J-4 Unit				0.5)	
III Southern Salt-dome Province. Deep-seated Jurassic sequence east of the Rosa structures					
TMM	1.5	1.5	2.0	1.5	1.5
TCh	2.4	0.9	2.0	0.9	2.4
TLCr	2.9	0.5	4.0	1.0	3.4
TJ	3.1	0.2	3.0	0.3	3.7
TTr	4.1	1.0	3.2	1.6	5.3
(J-4 Unit				0.6)	
IV Tail End Graben. Southern part, near the well E-1					
TMM	1.2	1.2	2.0	1.2	1.2
TCh	2.1	0.9	2.0	0.9	2.1
TLCr	2.3	0.2	3.6	0.4	2.5
TJ	2.6	0.3	2.8	0.4	2.9
JI	3.5	0.9	3.0	1.4	4.3
TTr	4.6	1.1	3.0	1.6	5.9
V Tail End Graben. Middle, southern part					
TMM	1.3	1.3	2.0	1.3	1.3
TCh	2.3	1.0	2.0	1.0	2.3
TLCr	2.5	0.2	3.6	0.4	2.7
TJ	2.85	0.35	2.8	0.5	3.2
TTr	>4.85	>2	3.2	>3.2	>6.4
(J-4 Unit				1.6)	

	TWT sec.	TWT thickness sec.	V_{int} km/sec.	Thickness km	Depth km
VI Tail End Graben. Middle, northern part					
		1.3	2.0	1.3	
TMM	1.3	1.3	2.0	1.3	1.3
TCh	2.6	0.2	4.0	0.4	2.6
TLCr	2.8	0.35	3.0	0.5	3.0
TJ	3.15	1.0	3.2	1.6	3.5
JI	4.15	1.0	3.2	1.6	5.1
?TTr	5.15				?6.7
VII Tail End Graben. Northern part					
TMM	1.5	1.5	2.0	1.5	1.5
TCh	2.9	1.4	2.0	1.4	2.9
TLCr	3.3	0.4	4.4	0.9	3.8
TJ	3.57	0.27	3.0	0.4	4.2
?JI	4.57	1.0	3.2	1.6	?5.8
?TTr	5.57	1.0	3.2	1.6	?7.4
VIII Area east of Dogger High					
TMM	1.5	1.5	2.0	1.5	1.5
TCh	3.1	1.6	2.0	1.6	3.1
TLCr	3.55	0.45	4.8	1.1	4.2
TJ	3.75	0.2	3.4	0.3	4.5
(J-4 Unit				0.8)	