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Regional distribution of diagenetic carbonate cement in Palaeocene deepwater sandstones: North Sea

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ABSTRACT: Sandstones of the Palaeocene Montrose Group were deposited in a deepwater fan environment, and form a major oil reservoir in the North Sea. Calcite concretions occur commonly within thick-bedded and structureless sandstones. These concretions have been identified by sonic logs and well reports, and were cross-checked with available core data. Regionally, 101 wells have been examined and carbonate concretions form 0.6–7.2% of the core. Concretions are most abundant along the flank of the Fladen Ground Spur, the north Witch Ground Graben (WGG), the east south Viking Graben and East Central Graben (ECG). Concretions of the ECG formed at deep burial, with C from decarboxylation. Geochemical inheritance of Mn and Sr from Cretaceous## chalk clasts may occur. Concretion growth may also have been influenced by vertical expulsion of fluids (leak-off) localized above salt tectonics. Isotopic and petrographic evidence indicates that much carbonate C in the WGG was derived from biodegradation of migrating oil in meteoric water at shallow depth. The locations of abundant carbonate with characteristic negative C isotope signatures can be used as shallow exploration guides to leak-off points located above deep overpressured structures.

KEYWORDS: hydrocarbon, structure, overpressure, bacteria, degradation.

Carbonate-cemented horizons are commonly found in oil-field cores. This study attempts to make a large-scale regional examination of the distribution of carbonate cements within one sandstone formation. This gives insight into the basin-scale processes which controlled the sources of C for cements, the timing of concretion growth and the locations of concretion growth. Particularly important is the concept of vertical interconnection of fluids within the basin. Thus fluids can transfer vertically by leak-off from overpressured deep reservoirs (Darby *et al*., 1996). This vertical transfer is controlled structurally and can localize the import of reactants and consequent cement growth in shallow reservoirs of the same basin (Darby *et al*., 1997). Most work on the occurrence of carbonate concretions has focused on the small scale, and use of geochemical and isotopic tracers to elucidate processes which are of importance locally. Even at this local scale, compilations of larger data sets have shown that different formations had sources of C which were distinct. In the North Sea, mid Jurassic cements were sourced by C sources mixed from detrital shell debris, and fermentation (Macaulay *et al*., 1998). Upper Jurassic carbonate cements were derived predominantly from carboxylic acids in the adjacent Kimmeridge Clay oil source rocks (Macaulay *et al*., 1998). By contrast, Palaeogene carbonate cements contain a major component derived from biodegradation of hydrocarbon (Macaulay *et al*., 2000).

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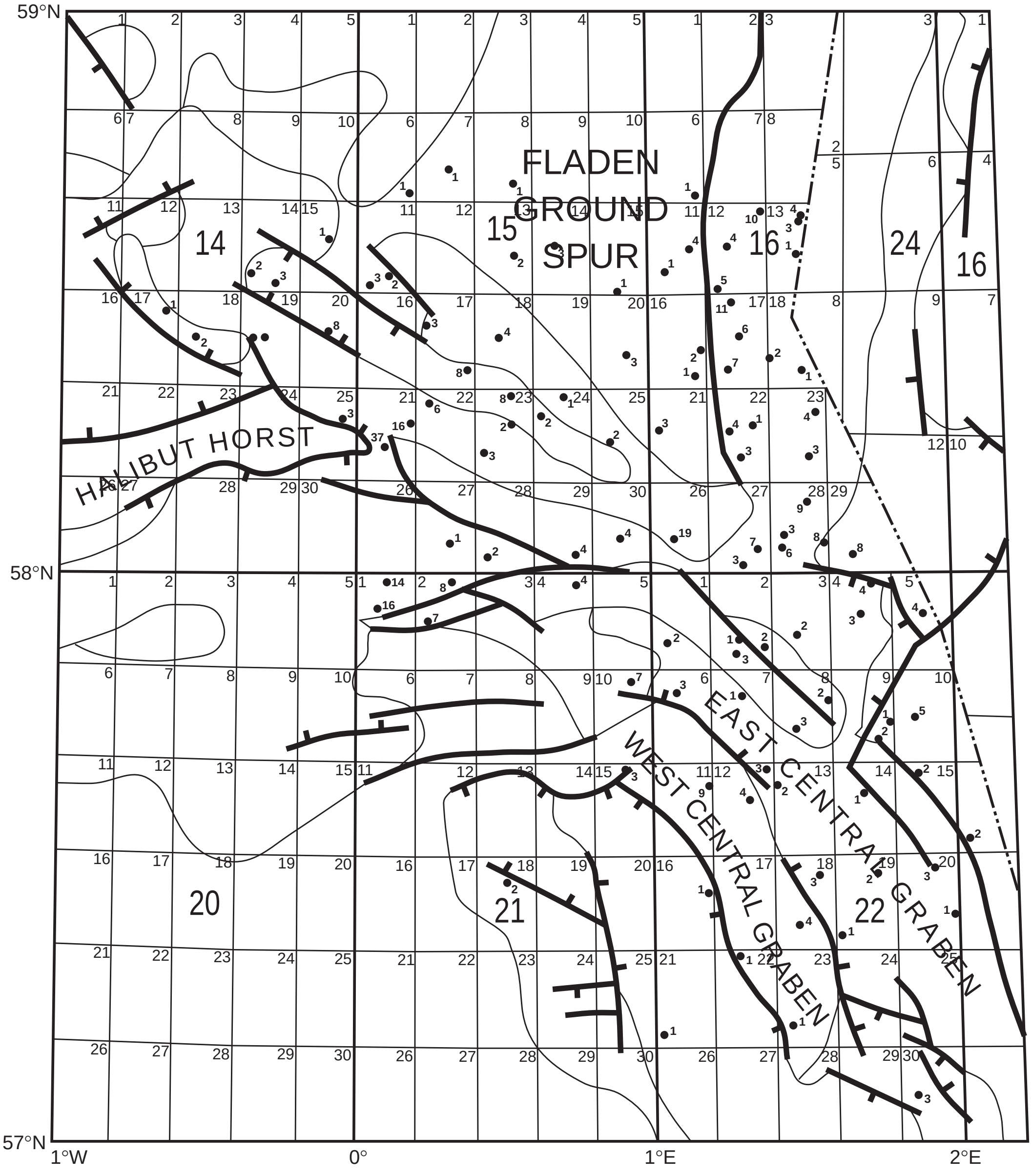


FIG. 1. Location map of the Central North Sea showing base Cretaceous structural elements. Wells sampled in the study are illustrated.

Many case study approaches have used isotopic evidence ($\delta^{13}C_{PDB}$) from the North Sea to indicate that concretions precipitated as a result of organic-mediated reactions during shallow burial (Giles *et al.*, 1992; Stewart *et al.*, 1993), and by inorganic thermal breakdown of organic material at depths >1.5 km (Irwin *et al.*, 1977). Within the Rannoch Formation of the Brent Group, sandstones contain >5% carbonate cement; this is significantly more than other formations in the Brent Group (Giles *et al.*, 1992). Larger percentages of cement are associated with shallow marine sandstones which

Table 1. Wells studied with wireline information. This shows the percentage of carbonate cement in each borehole calculated by measurement of sonic and resistivity traces off wireline logs (cf. Figs. 3, 4), and then calculated as a percentage of the total Montrose Group stratigraphic thickness. This assumes an initial porosity of 40% in all geographical areas. The calculated values >2.5% are plotted geographically on Fig. 5.

Borehole	Measured thick thickness (m)	Calculated carbonate %	Borehole	Measured thickness (m)	Calculated carbonate %
14/14-2	3.45	1.38	16/23-4	3.67	3.67
14/14-3	5.00	2.00	16/26-19	4.78	1.91
14/15-1	4.83	1.93	16/27-2	5.00	2.00
14/17-1	4.15	1.66	16/27-3	3.93	1.57
14/18-7	4.70	1.88	16/28-3	6.83	2.73
14/19-17	6.85	2.74	16/28-6	8.28	3.31
14/19-18	3.58	1.43	16/28-7	7.78	3.11
14/20-8	1.62	0.61	16/28-8	11.43	4.57
14/24-2	6.73	2.69	21/1-14	6.28	2.51
15/6-1	2.20	0.88	21/1-16	4.78	1.91
15/7-1	3.88	1.55	21/2-7	2.10	0.84
15/8-1	3.63	1.45	21/2-8	3.23	1.29
15/11-2	5.55	2.22	21/3-3	4.15	1.66
15/11-3	5.40	2.16	21/4-4	4.93	1.97
15/13-4	4.35	1.73	21/9-10	5.38	2.15
15/14-3	4.10	1.64	21/10-7	3.10	1.24
15/15-1	14.10	5.63	21/15-2	5.30	2.12
15/17-3	4.85	1.94	21/18-2	10.93	4.37
15/17-8	5.45	2.18	22/1-7	3.50	1.40
15/18-2	7.15	2.86	22/2-1	4.05	1.62
15/20-1	18.03	7.21	22/2-2	6.13	2.45
15/20-3	11.95	4.78	22/2-3	7.23	2.89
15/21-15	4.40	1.76	22/3-1	3.93	1.57
15/22-6	3.85	1.54	22/4-1	2.58	1.03
15/23-2	5.15	2.26	22/4-3	3.83	1.53
15/23-3	5.00	2.00	22/6-13	3.45	1.38
15/23-6	4.73	1.89	22/7/-1	6.83	2.73
15/24-1	6.45	2.58	22/7-2	6.90	2.76
15/24-2	4.95	1.98	22/8-2	5.55	2.22
15/27-1	3.65	1.46	22/8-3	5.80	2.32
15/28-2	12.00	4.80	22/9-3	14.98	5.99
15/29-4	3.95	1.58	22/9-4	4.68	1.87
15/30-6	5.25	2.10	22/10-5	16.40	6.56
16/6-1	4.48	1.79	22/11-9	5.38	2.15
16/11-1	5.80	2.32	22/12-3	5.00	2.00
16/11-4	3.48	1.39	22/12-4	4.45	1.78
16/12-4	3.15	1.26	22/13-4	9.43	3.77
16/12-9	6.23	2.49	22/14-1	10.65	4.26
16/12-10	5.85	2.34	22/15-2	6.33	2.53
16/13-2	4.93	1.97	22/16/2	2.90	1.16
16/13-3	5.38	2.15	22/18-3	2.45	0.98
16/16-2	2.63	1.05	22/18-4	3.85	1.54
16/17-5	3.9	1.56	22/19-1	6.15	2.46
16/17-7	3.85	1.54	22/20-1	7.70	3.08
16/17-12	5.23	2.09	22/20-3	9.35	3.75
16/18-1	10.95	4.38	22/21-3	6.53	2.61
16/18-2	4.48	1.79	22/22-1	9.08	3.63
16/21-5	12.90	5.16	22/26-2	7.20	2.88
16/22-3	6.10	2.44	22/30-1	4.30	1.72
16/22-5	6.05	2.42	23/11-2	9.78	3.91
16/23-3	8.43	3.37			

TABLE 2. Stable isotope data measured on calcite concretionary cements.

Borehole	Mineral blank=cal	Cored depth (m)	$\delta^{13}C_{PDB}$	$\delta^{18}O_{PDB}$	$\delta^{18}O_{SMOW}$
14/13-3		825.43	−13.5	2.6	8.2
		825.44	−13.6	−3.2	27.6
		825.45	−14.2	−3.1	27.7
		825.58	−4.0	−7.7	23.0
		825.59	−4.0	−7.3	23.4
		830.35	−9.9	−5.6	25.2
		830.36	−8.7	−5.3	25.4
		830.37	−7.5	−6.2	24.5
		830.38	−3.7	−4.2	26.6
		830.31	−3.2	−4.3	26.5
	vein	830.32	−3.4	−4.4	26.3
		830.33	−5.1	−4.6	26.2
		830.70	−5.5	−6.7	24.0
		830.71	−9.0	−5.5	25.3
		830.72	−10.5	−5.7	25.0
		830.73	−9.3	−5.2	25.6
		830.82	−10.8	−4.9	25.8
		830.83	−9.8	−4.5	26.3
		830.84	−8.3	−5.4	25.3
		830.85	−5.6	−7.3	23.4
15/20-4		2012.5	−29.0	−10.5	20.5
		2012.5	−26.7	−10.5	20.5
		2012.5	−26.0	−10.4	20.2
		2012.5	−25.2	−10.6	20.0
		2012.6	−24.1	−10.4	20.2
		2012.6	−23.3	−10.3	20.3
15/26-3	ankerite	1874.3	12.7	−10.3	20.3
	ankerite	1875.2	−18.9	−9.5	21.2
	ankerite	1877.9	1O.3	−7.9	22.8
	ankerite	1878.0	11.0	−8.0	22.7
	ankerite	1878.3	9. 8	−7.9	22.8
		1894.5	12. 6	−10.3	20.3
		1894.8	13.5	−10.2	20.4
		1925.9	−6.7	−12.5	18.0
		1929.8	−1.3	−5.9	24.8
15/26-4		2272.9	−18.5	−9.2	21.4
		2274.0	11.1	−9.8	20.9
		2274.3	11.0	−8.0	22.7
		2274.5	11.7	−9.7	20.9
		2274.6	11.5	−9.4	21.2
		2274.7	11.0	−9.7	20.9
		2467.7	0.4	−1.5	29.4
		2468.5	−1.8	−12.6	17.9
		2469.9	−3.6	−15.3	15.2
		2469.9	2.6	−2.7	28.2
		2300.3	−14.0	0.6	31.6
		2300.5	9.0	−9.7	21.0
16/28-6		2681.5	−24.8	−8.5	22.2
		2681.6	−21.9	−8.9	21.7
		2681.7	−20.3	−9.3	21.3
		2682.0	−17. 3	−10.6	20.0
		2682.3	−17.0	−10.7	20.0
		2683.0	−18.7	−11.7	18.8
		2683.3	−22.5	−9.0	21.1
16/29-2		2638.0	−4.1	−11.1	23.6
		2638.0	−5.0	−12.5	18.0

TABLE 2. (*contd.*)

Borehole	Mineral blank=cal	Cored depth (m)	$\delta^{13}C_{PDB}$	$\delta^{18}O_{PDB}$	$\delta^{18}O_{SMOW}$
		2642.6	−5.4	−12.5	18.1
		2643.5	2.7	−7.1	23.6
		2643.8	−2.3	−12.5	18.5
		2664.9	−1.1	−12.3	18.0
		2666.9	−3.2	−12.5	17.9
		2666.9	−2.9	−12.1	19.5
		2666.9	−3.2	−12.4	18.3
		2666.9	−2.7	−11.4	18.0
	vein	2682.8	−0.7	−13.1	17.5
		2683.5	−0.4	−12.6	18.2
		2683.S	−0.7	−12.5	18.0
21/10-1		2155.7	−0.4	−6.3	24.4
	siderite	2156.8	2.3	−3.8	27.0
	siderite	2156.8	1.7	−3.9	26.9
	siderite	2156.8	1.8	−4.6	26.2
	siderite	2156.8	−0.5	−3.7	27.1
		2170.2	0.1	−8.6	22.1
		2242.4	−7.4	−11.4	19.2
		2242.4	−15.9	−11.0	19.6
	chalk	2242.7	−10.6	−10.6	20.0
22/17-4		3106.8	−11.1	−11.0	19.2
		3107.4	−10.7	−11.2	19.4
		3107.7	−3.7	−10.8	19.8
22/20-3		2689.4	−4.3	−7.7	23.0
		2689.7	−4.7	−8.0	22.6
23/16-4		2150.2	−2.9	−18.8	11.5
		2156.4	−0.1	−13. 0	17.5
		2156.5	−0.3	−12. 6	17.9
		2156.8	0.8	−12. 9	17.63
		2162.3	−6.3	−9.6	21.1

may have contained detrital carbonate fauna (Bjørlykke *et al.*, 1992; Harris, 1992). However $^{87}Sr/^{86}Sr$ ratios of deltaic Ness Formation concretions indicate that cross-formational flow has occurred, and this may have transported Ca into the sandstones (Haszeldine *et al.*, 1992).

This study examines Palaeocene sandstones of the Montrose Group. Here the precipitation of concretions is noted as the most volumetrically important diagenetic reaction (Cutts, 1991; O'Connor & Walker, 1993). In this study, the percentage of concretions within sandstones has been calculated from 1:500 completion logs (Fig. 1). We find that the distribution of concretions within 101 boreholes is not uniform, but concretions are more abundant in certain areas (Table 1), and the distribution of cement may sometimes be controlled by deeper structures. Where core is available, it has sometimes been possible to analyse isotopic compositions of concretions (Table 2), to provide further insights into the processes controlling concretion distribution (Stewart, 1995).

GEOLOGICAL SETTING

The Montrose Group is a composite body composed of three lithostratigraphically similar units. Several stratigraphic classifications have been erected (Deegan & Scull, 1977; Stewart, 1987; Knox *et al.*, 1993), a modified classification was not the focus of this study, the classification of Stewart (1987) was used here, as this provided uniformity across the study area when our work commenced, and a link to sequence stratigraphic concepts. His terms, as used here are: basal Maureen Formation, up to 100 m thick (Stewart's (1987) Maureen Formation equivalent Sequence 2B); the dominant

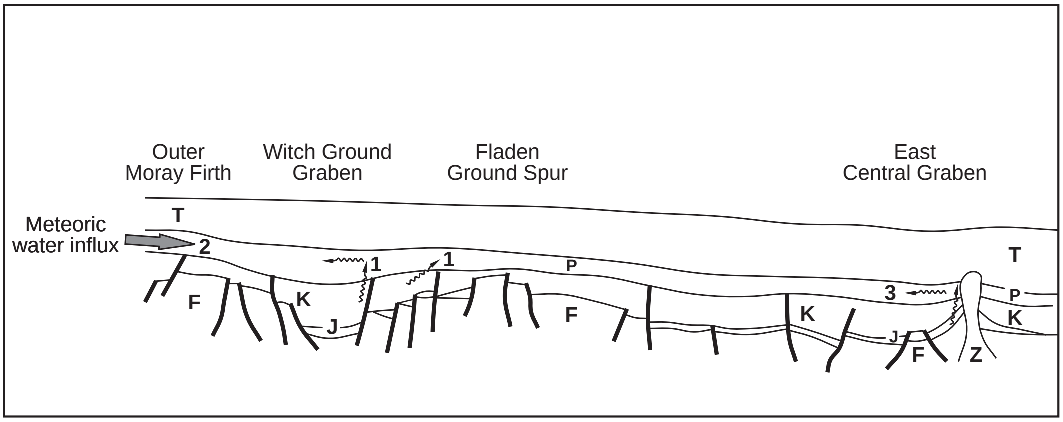


FIG. 2. Cartoon cross-section west–east across the Central North Sea.

sand-rich Andrew Formation, up to 450 m thick (Stewart's (1987) Andrew Formation Equivalent Sequence 3); and the uppermost Forties Formation, up to 250 m thick (Stewart (1987) Forties Formation equivalent sequence 7). Sandstones are little affected by structure, and were shed rapidly during a fall of relative sea level, driven by igneous plume uplift of the sediment source (White & Lovell, 1997). Burial depths are 100s of m within the Moray Firth and up to 3000 m within the Fisher Bank Basin in the Central North Sea (Fig. 2).

Underlying the Montrose Group is a sequence of Upper Cretaceous marls and chalks up to 1000 m thick, which thin over Mesozoic highs (Fig. 2). Underlying the Cretaceous are Upper Jurassic sandstones and the Kimmeridge Clay source rock. Within the Central Graben, along the east edge of UK Quadrant 22, Zechstein salt domes puncture the overlying sediment (Fig. 2) and in some cases may penetrate to become adjacent to the Montrose Group sandstones (Foster & Rattey, 1993). Overlying the Montrose Group in the Outer Moray Firth is the Upper Palaeocene Moray Group, a deltaic complex which prograded eastwards in response to relative sea-level fall.

The Montrose Group sandstones in this study were deposited by high-density turbidity flows (Stewart, 1987; Knox *et al.*, 1993). Sedimentological descriptions of core samples from the Montrose Group indicate that these consist predominantly of massively-bedded sandstones with sparse de-watering structures. The depositional facies of these sandstones are similar on a regional scale (Thomas *et al.*, 1974; Stewart, 1987; Crawford *et al.*, 1991; Cutts, 1991; Tonkin & Fraser, 1991; Den Hartog Jager *et al.*, 1993; Jones & Milton, 1994). Petrographically, these sandstones are predominantly sub-arkosic to sub-litharenites (Crawford *et al.*, 1991; Cutts *et al.*, 1991).

Concretions are present within virtually all cores. Concretions are normally on the scale of 10s of cm but can be up to 2 m thick (Tonkin & Fraser, 1991). The large thickness and 1-D sampling of concretions makes it impossible to determine whether concretions are laterally extensive or spherical. As part of our study, some concretions were small enough in core to be seen as oblate spheroids. Where resistivity wireline logs are available, a lateral extent of metres (similar shallow and deep resistivity), or a lateral termination (different shallow and deep resistivity) can be inferred (Fig. 3). However due to variability of information, this was not systematically recorded. It has been suggested that concretions act as permeability baffles, locally within the Balmoral Field 16/21 (Tonkin & Fraser, 1991).

The sandstones of the Andrew Formation are believed to be vertically and laterally stacked channels (Anderton, 1993). These have a high connectivity, particularly within the Witch Ground Graben, which would facilitate any pore-fluid movement. The formation of levee banks during deposition of Andrew Formation sands was hindered due to very high sand:mud ratios. It is thought that the Andrew Formation is derived from shallow buried sandstones on the East Shetland Platform (Den Hartog Jager *et al.*, 1993). The Andrew Formation is regionally hydrostatically

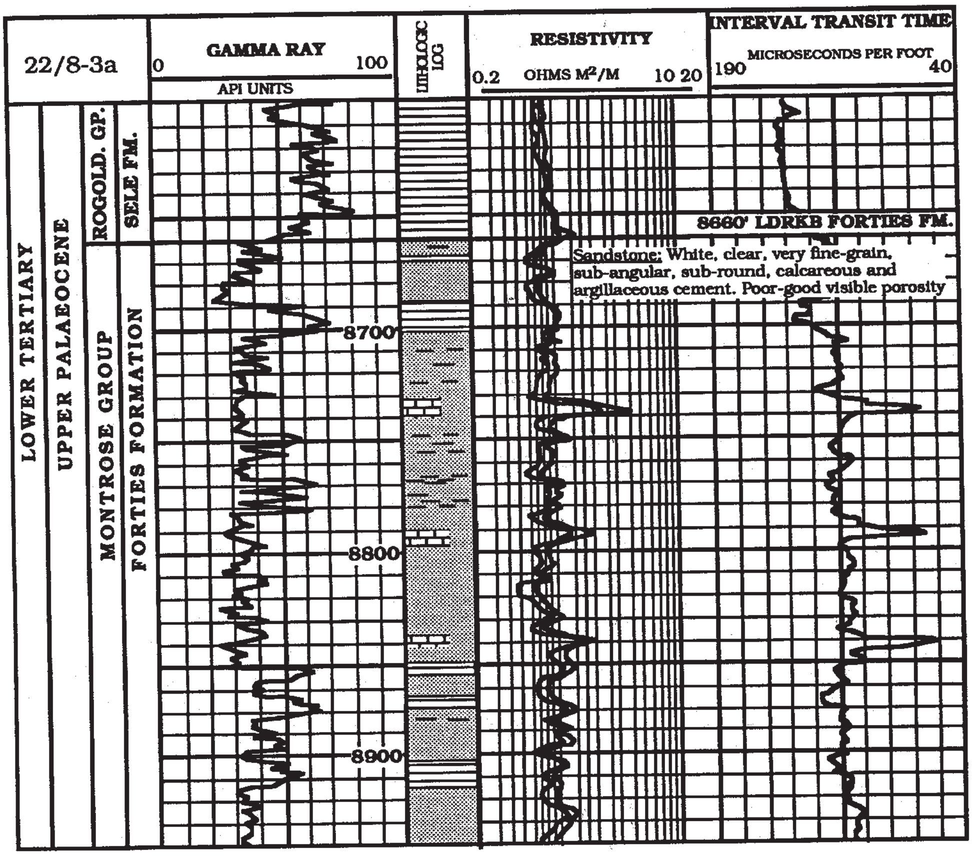


FIG. 3. Composite log of well 22/8-3. An example of distinct concretions within monotonous Montrose Group sandstones. In wells similar to this, concretion thicknesses are simple to measure. Concretion thickness is measured at half peak height width of sonic kick. Resistivity log enables estimation of lateral continuity of concretions. For example, at 8,737 and 8,792 the shallow and deep traces differ, interpreted to indicate discontinuous cement. At 8,840 the traces are similar, interpreted to indicate laterally continuous cementation.

pressured, but completion log records suggest that mild overpressure can be encountered at its distal extent in Quadrants 29 and 30. During deposition of the Forties Formation the supply of clastic sediment waned and sand:mud ratios declined. Deposition of the Forties Formation was centred south of the Halibut Horst and in the East Central Graben. Stable levee banks evolved. Sand-rich channel systems became enclosed in mud levee banks. These sand channels are of the scale of several to tens of km across. Connectivity within these areas is reduced (Den Hartog Jager *et al.*, 1993). Burial of the sediments has been constant with particularly rapid burial within the Witch Ground Graben during the early Eocene (Barnard & Bastow, 1992).

METHODOLOGY

Composite logs record physical properties of rocks *in situ*; these include transit times, natural gamma-ray radioactivity and density. The main litho-facies within the Montrose Group is a massively-bedded channel sandstone, where amalgamated units can be 10s of m thick. The log traces of the sandstones are therefore consistently stable. Concretions are identified by an anomalous combination of kicks on the sonic log (fast transit time) and resistivity log (high resistivity) in simple channel sandstones (Fig. 3).

Composite logs were examined from boreholes spread across the study area. To gauge what was recognizable on the composite logs, cored concretions of known thickness were compared with the composite logs available from those particular wells. For example, in well 15/20-4, concretions as small as 25 cm diameter seen in core were accurately identified on the composite log. Consequently, the errors associated with such measurements are considered to be minimal.

For individual wells, gross concretion thickness was recorded. The thickness of individual concretions was measured from the composite logs at the half peak-height width. This was then converted to metres. Peaks within electric logs record physical differences in rocks. Kicks or changes in steady traces can be due to a variety of changes in the lithologies. Carbonate concretions are relatively simple to identify within the thick-bedded and relatively homogeneous sandstones which make up the bulk of the Montrose Group. Marls or chalk-rich beds were not recorded. Only cements within sandstone units were recorded, not those within mudrocks.

Away from depositional axes and in distal deposits, mud:sand ratios rise, and sandstone bed thickness decreases. These 'ratty' log traces are harder to measure, because depositional complexity may mimic concretions (Fig. 4). In such boreholes, additional information was used including: mudloggers' reports, sedimentological reports, and notes from the composite log. This assisted determination of carbonate cements by such terms as 'calciferous', 'calcareous', 'carbonate-cemented', or 'hard-cemented'.

To minimize recording errors, the composite logs were sampled in a random selection. Some logs were deliberately analysed twice, to estimate the errors of reproducibility in estimating log 'kicks'. Most errors were ±10–20%, some up to ±30% of the initial measurement. This is the largest error in the study. Maximum errors within massive sandstones were generally ~10%. Although larger errors are possible in 'ratty' sediments, these may give readings greater than, or less than, the true thickness of carbonate. Thus these potential errors of measurement do not systematically bias the thickness of carbonate on an areal basis between different boreholes. Thus the recorded increase of carbonate cement in 'ratty' sands is considered to be real.

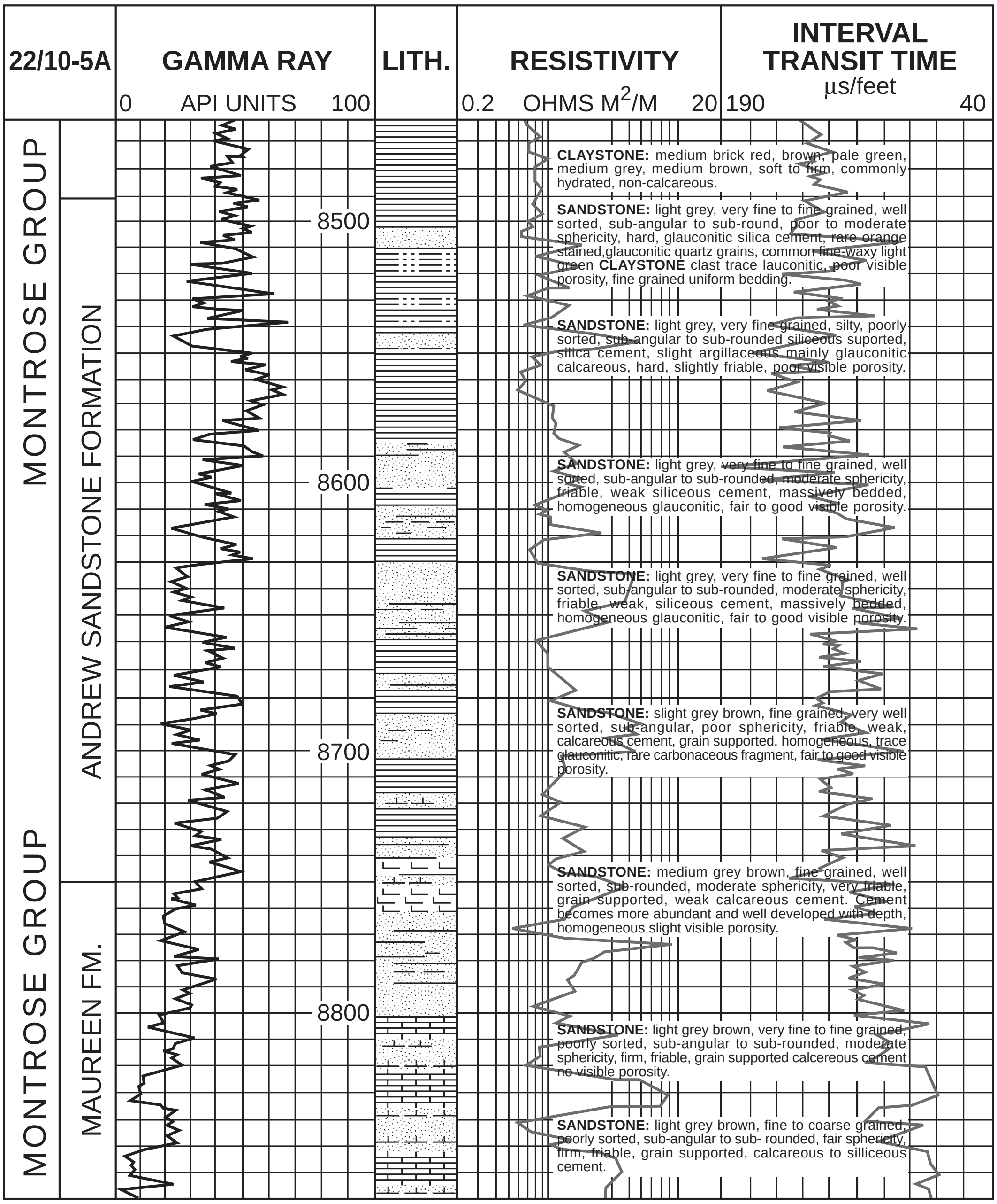
Concretions from core were examined by thin-section petrography. This showed that concretionary carbonate cements were poikilotopic calcites, with minimal other cementing minerals. A range of calcite mineralogies exists including manganiferous, ferroan and calciferous. These are interpreted to be a consequence of cementation depths, ranging from sea-bed to 100s of m burial (Stewart, 1995). A corresponding range of minus-cement porosities also occurs, with a total range of 30–67%. However most minus-cement porosity values are in the range 35–45%, so that a single value of 40% for the minus-cement porosity was chosen, as insufficient data are available to justify individual values for different regions. Consequently, a potential 10% error at maximum exists due to this effect in calculated carbonate volumes. Concretions from the East Central Graben have lower minus-cement porosities than those from the Witch Ground Graben; this is interpreted to indicate precipitation at deeper burial, rather than a systematic variation in original depositional porosity.

Measurements of concretion thickness were recorded (Table 1) as was the total thickness of the Montrose Group. This permitted calculation of carbonate thickness as a percentage of the Group, and enabled preparation of a map summarizing regional results. Where core was available, isotopic analyses were made of carbonate cements, and these permit interpretation of differing processes operating in different areas.

RESULTS AND DISCUSSION

The map of concretion percentage for Quadrants 14, 15, 16, 21, 22 and 23 is shown in Fig. 5, based on data in Table 1. Proportions of concretions generally vary between 1.6% and 18% of core length. If the assumption is made that minus-cement porosities average 40% (see above) then this represents 0.6% to 7.4% of rock volumes. The range of concretion percentage thickness is remarkably similar over most of the study area, some 70% of boreholes are cemented over 3–7% of group thickness.

The amount of original detrital carbonate is unknown within these sandstones, as detrital carbonate is rarely seen outwith cemented horizons. This is an important parameter which could



CLAYSTONE: medium brick red, brown, pale green, medium grey, medium brown, soft to firm, commonly hydrated, non-calcareous.

SANDSTONE: light grey, very fine to fine grained, well sorted, sub-angular to sub-round, poor to moderate sphericity, hard, glauconitic silica cement, rare orange stained,glauconitic quartz grains, common fine-waxy light green **CLAYSTONE** clast trace lauconitic, poor visible porosity, fine grained uniform bedding.

SANDSTONE: light grey, very fine grained, silty, poorly sorted, sub-angular to sub-rounded siliceous suported, silica cement, slight argillaceous mainly glauconitic calcareous, hard, slightly friable, poor visible porosity.

SANDSTONE: light grey, very fine to fine grained, well sorted, sub-angular to sub-rounded, moderate sphericity, friable, weak siliceous cement, massively bedded, homogeneous glauconitic, fair to good visible porosity.

SANDSTONE: light grey, very fine to fine grained, well sorted, sub-angular to sub-rounded, moderate sphericity, friable, weak, siliceous cement, massively bedded, homogeneous glauconitic, fair to good visible porosity.

SANDSTONE: slight grey brown, fine grained, very well sorted, sub-angular, poor sphericity, friable, weak, calcareous cement, grain supported, homogeneous, trace glauconitic, rare carbonaceous fragment, fair to good visible porosity.

SANDSTONE: medium grey brown, fine grained, well sorted, sub-rounded, moderate sphericity, very friable, grain supported, weak calcareous cement. Cement becomes more abundant and well developed with depth, homogeneous slight visible porosity.

SANDSTONE: light grey brown, very fine to fine grained, poorly sorted, sub-angular to sub-rounded, moderate sphericity, firm, friable, grain supported calcereous cement no visible porosity.

SANDSTONE: light grey brown, fine to coarse grained, poorly sorted, sub-angular to sub- rounded, fair sphericity, firm, friable, grain supported, calcareous to silliceous cement.

FIG. 4. Composite log of 22/10-5. This well illustrates the nature of Montrose Group lateral to depositional axes. Measuring concretions within wells like this requires mudloggers' reports and geological reports to aid identification of cemented horizons.

influence the volume and distribution of carbonate concretions. Unaltered detrital carbonate is only rarely found in the Montrose Group, and is restricted to Danian age horizons at its base. It is known that erosion of chalks situated at the west Central North Sea basin margins contributed to the

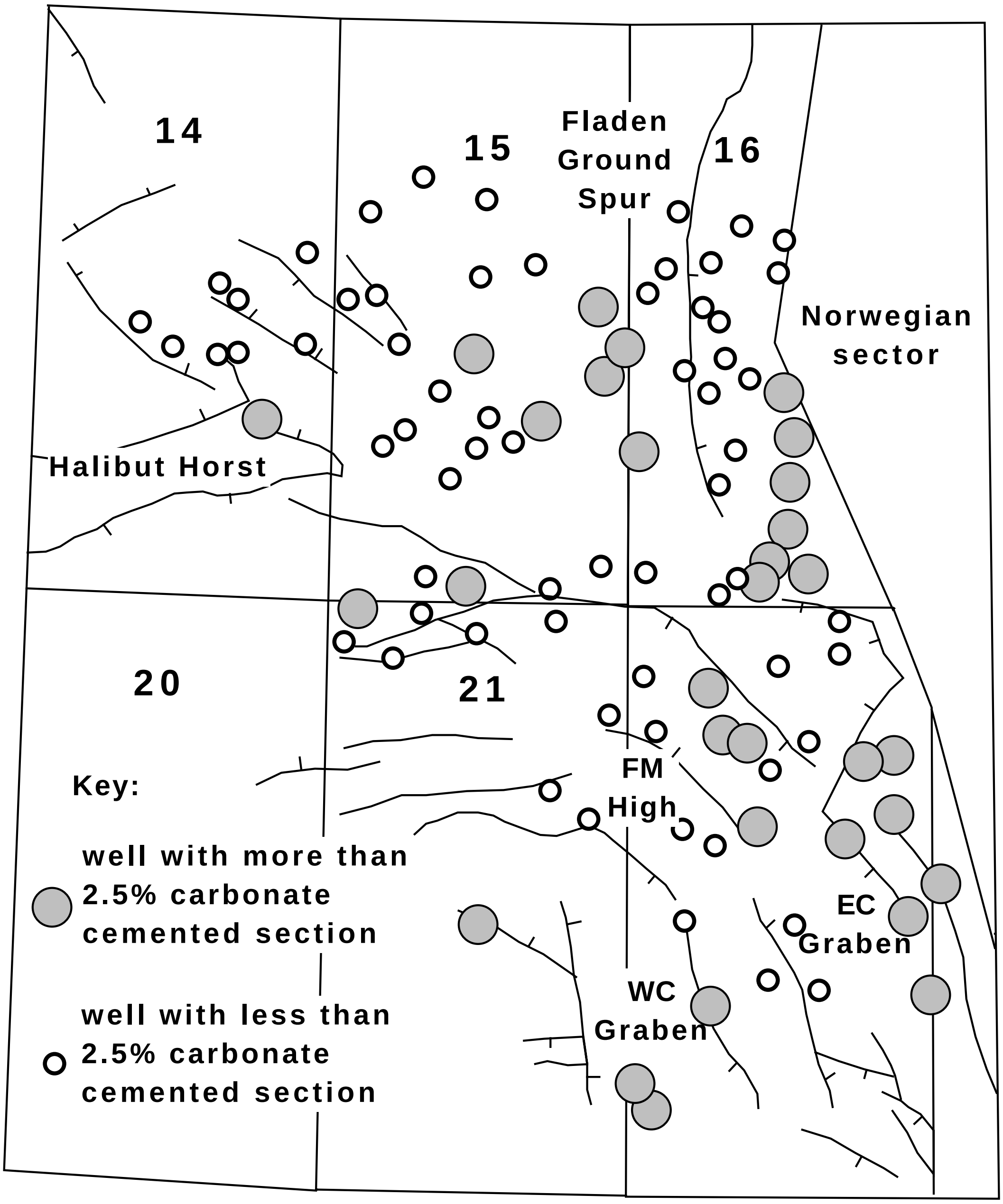


FIG. 5. Map of concretion percentage for Montrose Group sandstones. For most sandstones, concretions generally comprise 3–7% of the thickness of the Montrose Group. There are areas which have anomalously high amounts of concretions. These are: (1) axis of Witch Ground Graben, north flank of Witch Ground Graben and around the southern tip of the Fladen Ground Spur; (2) along the axis of the East Central Graben; (3) around the east side of Quadrant 22; and (4) within blocks 16/28 and 16/29. Values >2.5% are shaded, and are tabulated in detail in Table 1.

sediments at the base of the Maureen Formation (Stewart, 1987) in the initial stages of Montrose Group deposition. Most Maureen Formation sediments have a marly base of Danian age. Isotopic analyses indicate that some of this reworked chalk has contributed to concretions near the base (Table 2, Stewart, 1995); higher within the Montrose Group, chalk has no detectable effect. A detailed study, which is better quantified, within the Everest field shows identical features of an elegant isotopic mixing trend within carbonate cements from a chalky base upwards within the Montrose Group.

There are distinct areas where concretion percentage increases to volumes above this background level. These are generally along the north flank of the Witch Ground Graben, along the axes of the Witch Ground Graben and East Central Graben, and at points deeper into the graben system.

Witch Ground Graben concretions

The Montrose Group is dominated by the Andrew Formation in this area. Composite logs and cores indicate that the sequence is dominated by massive thick-bedded sandstone channel deposits. Log 'kicks' are easy to define, and represent precipitation of concretions.

Concretions from wells 15/20-4 and 16/28-6, within the Witch Ground Graben and Fisher Bank Basin, have been analysed isotopically (Stewart *et al*., 1993; Stewart, 1995). They have $\delta^{13}C_{PDB}$ compositions with characteristically negative values (-25 to -30) similar to values measured from carbonates which are known to have precipitated as a result of degradation of hydrocarbons (Dimitrakopolous & Muehlenbachs, 1987; O'Brien & Woods, 1994, Macaulay *et al*., 1999). Dead oil stain was seen within concretions from wells 16/28-6 and 15/20-4. Oxygen isotopic compositions of the concretions indicate that because the concretions are texturally early, then concretions precipitated within meteoric influenced waters with negative $\delta^{18}O_{SMOW}$ compositions.

The predominance of diagenetic carbonate in this area may therefore be due to the bacterial oxidation of migrating hydrocarbons within meteoric water (Fig. 6). Meteoric water is only likely to have flowed through the Montrose Group during the late Palaeocene during a period of extreme sea level fall. This was likely to have taken place during the progradation of the Moray Group when an 800 m relative sea level fall occurred (Jones & Milton, 1994). This has implications for oil migration into the Palaeocene. The Witch Ground Graben underwent particularly rapid burial during the Palaeocene, accommodating up to 600 m of clastic sediments. Maturation of Kimmeridge Clays began during the Maastrichtian (Barnard & Bastow, 1992), and migration of this oil began during the Lower Eocene or Oligocene according to Mason *et al*. (1995). It is inferred that source rock sediments were also overpressured at this time, similar to the situation at the present day in the SW Central Graben. Consequently, vertical oil migration may have been focused at structurally-controlled leak-off points (Darby *et al*., 1996, 1997). If the diagenetic carbonate marks out palaeo-migration paths in this area, then the timing of migration can be given a minimum date. Watson *et al*. (1995) also found concretions with unusually negative $\delta^{13}C_{PDB}$ compositions within the Montrose Group in the Balmoral Field 16/21. Oil-staining, however, was not reported.

East Central Graben and South Viking Graben

Montrose Group sediments here are thin bedded, and can form 'ratty' traces on the composite logs. Consequently, the individual values of carbonate cements may be subject to error, although the regional pattern of relative differences is considered to be secure. Concretions within these sandstones have C isotopic values which indicate that they formed during decarboxylation reactions. Compositions of calcite, measured by SEM/EDS, in these concretions also indicate that they are Mn-calcites. Manganese enrichment has also been noted to occur during diagenesis within the underlying chalk sequence (Taylor & Lapre, 1987). Therefore it is possible that these Mn-cements are related to import of ions by movement of pore-fluids from the underlying Jurassic. Strontium isotope ratios from concretions formed diagenetically, late in the Montrose Group, are also slightly more radiogenic than depositional calcite. This indicates that ^{87}Sr had entered the porewaters during precipitation. Such an increase in ^{87}Sr is usually considered to result from dissolution of silicate minerals such as feldspar (Emery & Robinson, 1993). Calcite cements within the underlying chalks are also noted to be slightly more radiogenic than matrix chalk and these cements become more radiogenic in

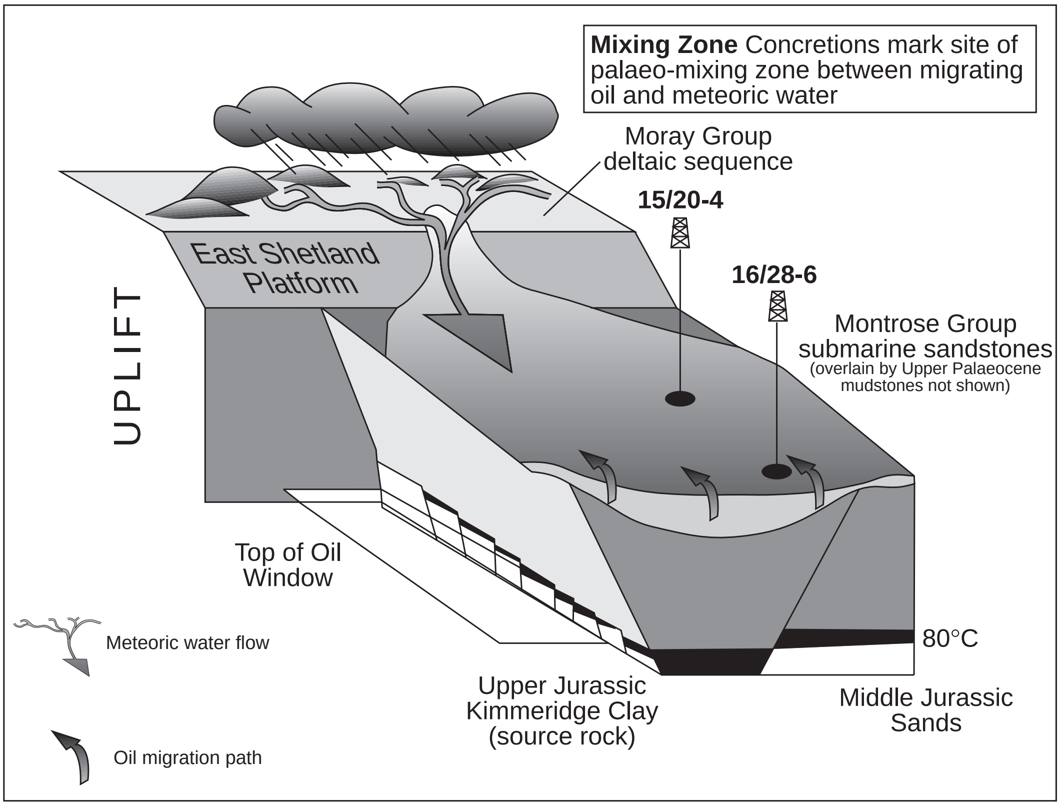


FIG. 6. Cartoon illustrating possible scenario within the Witch Ground Graben during the late Palaeocene. Meteoric water entered into the Montrose Group sandstones from the Outer Moray Firth. Hydrocarbons migrated upwards from the Jurassic Kimmeridge Clay and laterally westwards through the Montrose Group aquifers. In this zone of mixing, the hydrocarbons were biodegraded and concretions were precipitated.

^{87}Sr with depth (Taylor & Lapre, 1987; Smalley *et al*., 1992). This was interpreted by Smalley *et al*. (1992) to have resulted from waters derived from underlying Jurassic sediments (and Zechstein salt) moving upwards into the Cretaceous (Fig. 7). It is therefore probable that such waters also rose into the Montrose Group, producing unusually radiogenic ^{87}Sr in cements formed at relatively shallow burial. The effects of such vertical movements of pore-water can also be deduced from present-day salinity values which are unusually high in these areas (Smalley & Warren, 1994). Blocks 22/9 and 23/11 appear to have abundant and ^{87}Sr-rich diagenetic carbonates in depositionally distal areas (Fig. 5, Stewart, 1995). These are areas where salt tectonics are important (Fig. 7), and may identify fluid leak-points resulting from salt diapirism, associated faulting and vertical fluid movement.

CONCLUSIONS

(1) Regional mapping of concretions by composite wireline log analysis indicates that concretions comprise between 1.6% and 18% of sandstone length. The majority of boreholes have 3–7% length. If sandstones had 40% initial porosity, then there is 0.6–7.4% carbonate within the Montrose Group. Some 70% of boreholes have 1.2–2.8% carbonate.

(2) Mapping of concretions from wireline logs has identified areas which have high concentrations of carbonate concretions. These are located structurally, along the axis and north flank of the Witch Ground Graben, along the axis of the East Central Graben and the flank of the Jaeren High.

(3) Unusually negative −25 to −30‰ $\delta^{13}C_{PDB}$ compositions of calcites in the Witch Ground

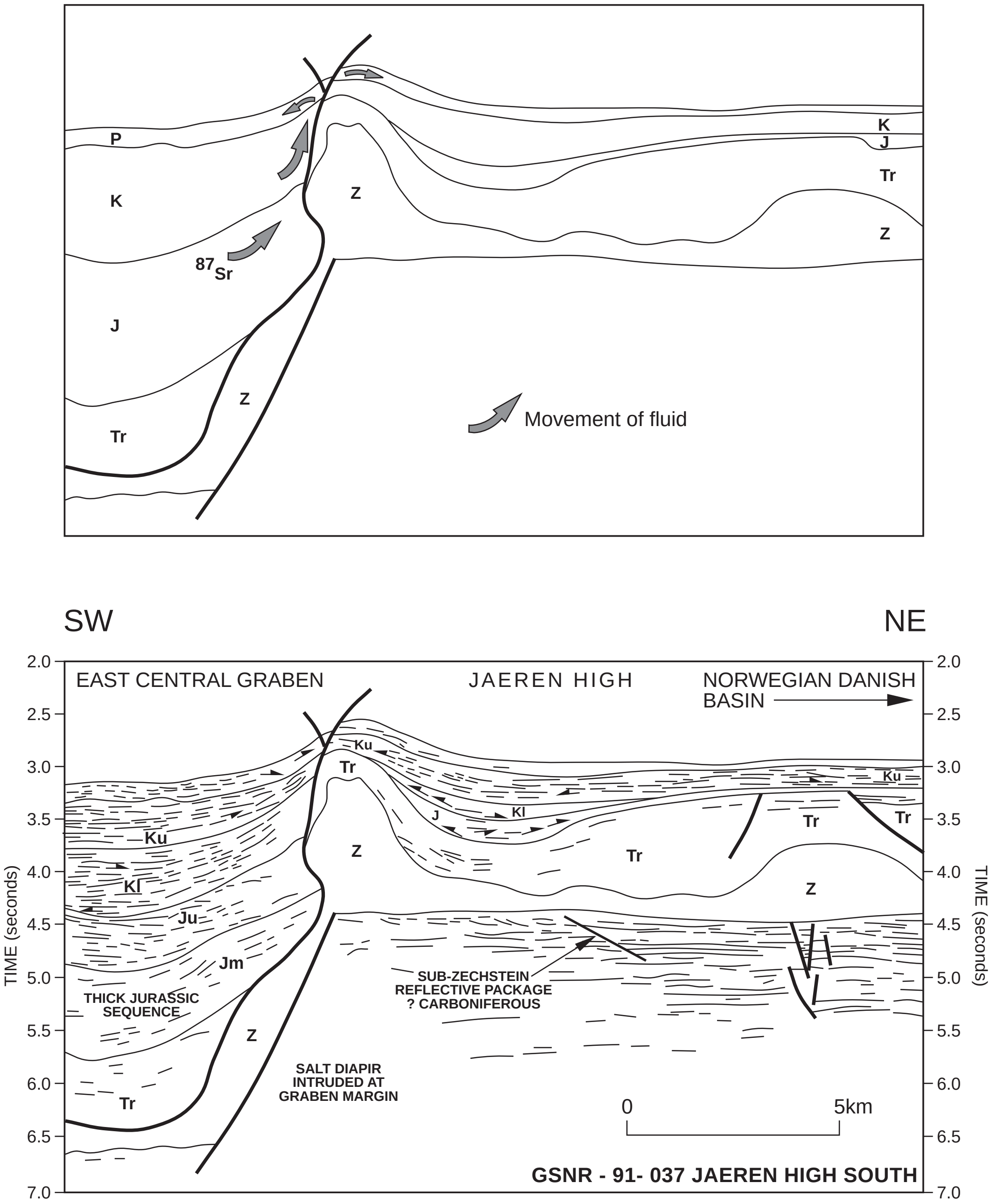


FIG. 7. Seismic section illustrating the effect of salt diapirism on overlying sediments. Late-grown concretions in the Montrose Group have Sr ratios which indicate introduction of radiogenic ^{87}Sr from deeper pore-waters into these sandstones. Diagenetic calcite from the underlying Cretaceous chalks, also has a radiogenic component introduced into the cements, and this also increases downwards (Smalley *et al*., 1992). Anomalously large volumes of concretion cements may be related to vertical fluid transfer from overpressured Jurassic sediments into the shallow basin. Thus shallow cementation can act as an exploration guide to deeper structural controls.

Graben indicates that those concretions precipitated during early subsidence when early migrating oil from deep leak-off points mixed with meteoric water. The meteoric water entered the Montrose Group during a period of relative sea level fall. Locations of isotopically characteristic concretions can be used as exploration guides in shallow sediment to leak-off from overpressured structures deeper in the basin.

(4) In the Viking Graben and East Central Graben, C isotopic compositions of -10 to $+2‰$ $\delta^{13}C_{PDB}$ are interpreted to indicate derivation from detrital chalk, and from deeper decarboxylation. Radiogenic ^{87}Sr was advected from deeper pore-waters by cross-formational flow, spatially associated with Zechstein salt diapirism.

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