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Porosity and sonic velocity depth trends of Eocene chalk in Atlantic Ocean: Influence of effective stress and temperature

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A B S T R A C T

We aimed to relate changes in porosity and sonic velocity data, measured on water-saturated Eocene chalks from 36 Ocean Drilling Program drill sites in the Atlantic Ocean, to vertical effective stress and thermal maturity. We considered only chalk of Eocene age to avoid possible influence of geological age on chalk compaction trends. For each depth, vertical effective stresses as defined by Terzaghi and by Biot were calculated. We used bottom-hole temperature data to calculate the time–temperature index of thermal maturity (TTI) as defined by Lopatin. Porosity and compressional wave velocity data were correlated to vertical effective stresses and to TTI.

Our porosity data showed a broader porosity trend in the mechanical compaction zone, and the onset of the formation of limestone at a shallower burial depth than the porosity data of the Ontong Java Plateau chalk show. Our porosity data do not show or at least it is difficult to define a clear pore-stiffening contact cementation trend as the Ontong Java Plateau chalk. Mechanical compaction is the principal cause of porosity reduction (at shallow depths) in the studied Eocene chalk, at least down to about 5 MPa Terzaghi's effective stress corresponding to a porosity of about 35%. This indicates that mechanical compaction is the principal agent of porosity reduction. Conversely, at deeper levels, porosity reduction is accompanied by a large increase in sonic velocity indicating pore-filling cementation. These deep changes are correlated with TTI. This indicates pore-filling cementation via an activation energy mechanism. We proposed a predictive equation for porosity reduction with burial stress. This equation is relevant for basin analysis and hydrocarbon exploration to predict porosity if sonic velocity data for subsurface chalk is available.

1. Introduction

It is known that both the *in-situ* stresses and thermal maturity acting on subsurface sediments increase with increasing burial depth (Wetzel, 1989; Fabricius et al., 2008). This causes changes in physical and mechanical properties of sediments. Consequently, as burial depth increases, a link between vertical effective stress and physical properties such as porosity and sonic velocity of chalk could be established. Additionally, an indirect temperature control on cementation in deep-sea chalk is advocated (Fabricius et al., 2008), and thus it may be possible to establish a relationship between thermal maturity and porosity of deep-sea chalk. In this paper, we first aimed to compare the deep-sea Eocene chalk porosity data from the Atlantic Ocean with those of Fabricius et al. (2008) from the Pacific Ocean. We then focused on establishing porosity and compressional wave (P-wave) velocity depth trends for the Atlantic Ocean Eocene chalks, which we then related to vertical effective stress and thermal maturity (Fabricius et al., 2008). The relationship of P-wave velocity to vertical effective stress, taking into account the influence of cementation (Biot, 1941), can be used to estimate Biot's effective stress if seismic velocity data is available. The predicted Biot's effective stress could then be used to find the corresponding porosity for any given depth. Hence, a meaningful prediction of porosity of inaccessible subsurface layers of chalk could be made if the vertical effective stress and thermal maturity of chalk is known. This study is relevant for basin analysis modelling and hydrocarbon exploration in chalk sediments especially in deepwater basins where drilling is expensive.

Porosity reduction as a result of pore-filling calcite cementation may also be linked to the thermal maturity of the chalk, possibly as a result of increasing burial. Although vitrinite reflection (VR) data is a well accepted method (e.g. using the kinetics Burnham and Sweeney, 1989) to directly determine the thermal maturity of sediments, vitrinite are generally not prevalent in chalks. In this study, we therefore expressed the thermal maturity of the studied

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Eocene chalk by the TTI as defined by Lopatin (Waples, 1980) and assume that heating is solely caused by burial as there is no reported evidence of non-burial related thermal processes such as hot fluid flows or proximal igneous activity to the studied sites. TTI describes the cumulative effect of the time a sedimentary rock experiences in each 10 °C temperature interval during burial (Waples, 1980).

Here, we used porosity and P-wave velocity data measured on water-saturated Eocene chalk from the Atlantic Ocean to address depth trends for porosity and P-wave velocity. To establish depth trends, the porosity and P-wave velocity data were correlated with the vertical effective stresses as defined by Terzaghi (1923) and Biot (1941). The same data were also correlated with the time–temperature index of thermal maturity (TTI) as defined by Lopatin (Waples, 1980). Finally, the present results were compared with the results obtained by Grützner and Mienert (1999) on the Atlantic sediments, by Mallon and Swarbrick (2002) on non-reservoir North Sea Chalk, and by Fabricius et al. (2008) on deep-sea chalk from the Ontong Java Plateau of the western Pacific Ocean.

Grützner and Mienert (1999), Mallon and Swarbrick (2002), and Fabricius et al. (2008) included data of pelagic carbonate sediments from different geological ages in their studies. However, we focused only on Eocene chalk to avoid possible influence of chalk age (i.e. fossil assemblage) in diagenesis of chalk. Therefore, we restricted our dataset to chalk samples of the same age that represent only an Eocene time interval. In this way, time is also nearly constant since the deposition of the studied Eocene chalk , and thus the Eocene chalks primarily differ with respect to stress, pressure, temperature, and texture.

2. The litholoy of the Atlantic Eocene carbonates

During the Eocene, pelagic carbonate oozes were deposited in the Atlantic basins. As a result of diagenesis, pelagic carbonate oozes (unconsolidated) transformed to chalk (consolidated) or even further to limestone (indurated). Here, we used the term chalk to refer to all three types of calcareous pelagic sediments: unconsolidated, consolidated, and indurated. The studied Eocene chalk is not purely calcitic as indicated by the variations in carbonate content (Table 2). The presence of fine clay content may reduce the calcite-to-calcite grain contacts and occupy some of the pore space in the chalk and thus reduce porosity. This may also make the frame of the chalk sediment weaker (i.e. more compressible), which in turn becomes more susceptible to mechanical deformation (Fabricius, 2000). Clay can also form locations for initiation of pressure dissolution. Apart from burial diagenesis, there must also be some impact of mineralogy and texture on the physical properties of chalk.

Porosity of newly deposited carbonate ooze sediments near the seafloor is very high, but it decreases with increasing burial depth, whereas sonic velocity and bulk density increases (e.g. Hamilton, 1980; Japsen, 1993). Porosity reduction with increasing burial depth is due to mechanisms such as mechanical compaction and thermo-chemical cementation of sediments (Giles et al., 1998). The porosity reduction with burial depth has been described by several authors not least because of the implications of this in hydrocarbon exploration (e.g. Hamilton, 1976; Scholle, 1977; Wetzel, 1989; Borre and Fabricius, 1998; Grützner and Mienert, 1999; Mallon and Swarbrick, 2002; Fabricius et al., 2008; Alam et al., 2010).

3. Previous related studies

Hamilton (1974) and several later authors have addressed mechanical compaction of carbonate ooze sediments. Mechanical compaction begins immediately after deposition of the calcareous ooze. It reduces porosity primarily through a more efficient packing of particles, but fossils and grain sizes of other particles may remain constant (e.g. Lind, 1993; Grützner and Mienert, 1999). This depends on chalk depositional texture, however, textural information of the studied chalk are not available, thus we assumed the same texture as in those deep-sea chalks studied by Lind (1993).

The geological age of the sediments in Grützner and Mienert (1999) study was not taken into account, and also the physical effect of “depth below seafloor” was not addressed. Similarly, Mallon and Swarbrick (2002) described two linear trends for porosity loss with burial depth for non-reservoir chalk of the Central North Sea. But, depth is only an approximation for thermal maturity and vertical effective stress (σ') in uniaxial strain condition described by Biot's effective stress (Biot, 1941). Static and dynamic β of chalk from the North Sea was studied by Alam et al. (2012). They found that static and dynamic β values are not significantly different and below one. In this study, the laboratory measured sonic velocity and bulk density data of the studied Eocene chalk were used to estimate dynamic β as by Alam et al. (2012).

Fabricius et al. (2008) defined mechanical compaction, pore-stiffening contact cementation and pore-filling cementation as

Table 1
A list of the 36 ODP sites, included in this study, with their geographical coordinates and the Eocene chalks depth intervals. The geographical coordinates are found at the following website: http://iodp.tamu.edu/janusweb/coring_summaries/sitedetails.cgi.

ODP site	Geographical coordinates		Water depth	Depth interval
	Latitude	Longitude	(m)	(mbsf)
101-627B[a]	27°38.1000′ N	78°17.6520′ W	1036	181-220
101-628A[a]	27°31.8480′ N	78°18.9480′ W	976	260-289
101-634A[a]	25°23.0220′ N	77°18.8820′ W	2835	144-163
113-689B[a]	64°31.0200′ S	3°5.9940′ E	2080	130-204
113-690B[a]	65° 9.6288′ S	1°12.2958′ E	2914	97-133?
114-698A	51°27.5400′ S	33°5.9580′ W	2138	0-61
114-699A[a]	51°32.5200′ S	30°40.6200′ W	3706	316-497
114-700B[a]	51°31.9800′ S	30°16.6860′ W	3601	26-229
114-701C[a]	51°59.1000′ S	23°12.7020′ W	4637	424-471.8
114-702B[a]	50°56.7600′ S	26°22.1160′ W	3084	40-247
114-703A[a]	47°03.0600′ S	07°53.6820′ E	1796	120-364
150-902D	38°56.0790′ N	72°46.3752′ W	808	680-740
150-903C[a]	72°46.3752′ W	72°49.0236′ W	446	1070-1150
150-904A[a]	38°51.8058′ N	72°46.0842′ W	1123	341-577
150-906A[a]	38°57.8958′ N	72°45.9972′ W	913	555-602
154-925A[a]	4°12.2490′ N	43°29.3340′ W	3042	773-930
154-929E[a]	5°58.5678′ N	43°44.4000′ W	4356	491-770
160-967E	34°4.1060′ N	32°43.5250′ E	2553	130-167
165-998B	19°29.3870′ N	82°56.1600′ W	3180	590-905
165-999B[a]	12°44.5970′ N	78°44.4180′ W	2828	727-960
165-1001A[a]	15°45.4270′ N	74°54.6270′ W	3260	165-232
171B-1049A[a]	30°08.5436′ N	76°06.7312′ W	2656	19-93
171B-1050A[a]	30°05.9977′ N	76°14.1011′ W	2300	0 - 224
171B-1051A[a]	30°03.1740′ N	76°21.4580′ W	1983	3-508
171B-1052E[a]	29°57.0906′ N	76°37.5966′ W	1345	0-165
171B-1053A[a]	29°59.5385′ N	76°31.4135′ W	1630	11-183
174A-1073A[a]	39°13.5214′ N	72°16.5461′ W	639	654-663
207-1257A	9°27.2302′ N	54°20.5184′ W	2951	42-150
207-1258A[a]	9°26.0003′ N	54°43.9994′ W	3192	8-253
207-1259A	9°17.9989′ N	54°11.9984′ W	2354	125-445
207-1260A	9°15.9485′ N	54°32.6327′ W	2549	35-335
207-1261A	9°2.9168′ N	54°19.0384′ W	1900	367-391
208-1262A	27°11.1601′ S	1°34.6200′ E	4759	80-182
208-1263A	28°31.9702′ S	2°46.7690′ E	*2717*	92-335
208-1265A	28°50.1010′ S	2°38.3602′ E	3060	192-318
208-1267A	28°5.8805′ S	1°42.6586′ E	4355	145-232

[a] These are the 24 ODP sites with bottom-hole temperature data used in the TTI calculations, see Table 4.