Regional coalification curves corrected for net exhumation

Due to Late Cretaceous – Early Cenozoic inversion of fault blocks in the Sorgenfrei–Tornquist Zone and Neogene–Pleistocene regional uplift of the Norwegian–Danish Basin (e.g. Michelsen & Nielsen 1991, 1993; Jensen & Schmidt 1993; Japsen 1993, 1998; Petersen *et al.* 2003a), present-day burial depths must be corrected for post-Early Cretaceous net exhumation (Fig. 18). Petersen *et al.* (2003a) presented a regional coalification curve for the Norwegian–Danish Basin based on 249 measurements from 15 wells (onshore wells and the Hans-1 well in the Kattegat). That study did not include offshore wells from the Skagerrak area. The well-sections were corrected for net-exhumation values obtained from the analysis of sonic velocities of shales by Japsen (1993). The accuracy of this method is dependent on a uniform shale unit covering the entire study area and a valid sonic velocity reference curve. Net exhumations for wells not included in Japsen's (1993) study were estimated by comparison to nearby wells and interpolation.

In the present study, new regional coalification curves for the Norwegian–Danish Basin have been constructed in order to evaluate the depth to the oil window. The depths of the samples have been corrected for net exhumation, the magnitudes of which have been derived from both shale and chalk velocities. A total of 560 vitrinite reflectance (VR) measurements from 26 wells in the Norwegian–Danish Basin were available for construction of the coalification curves (Fig. 18). The VR values are from Thomsen (1980, 1983), Schmidt (1985, 1988, 1989) and GEUS unpublished data. All VR values are random measurements performed on core samples, sidewall cores or cuttings, and as many particles as possible were measured in each sample. Untreated rock samples (whole rock) were used, as such samples – compared to kerogen concentrates – have the advantage that it is easier to identify the primary vitrinite particles and thus avoid oxidised and bituminous organic matter (e.g. Barker 1996). Identification of the primary, i.e. indigenous or autochthonous, vitrinite is essential for obtaining reliable VR values as this vitrinite reflects the actual ther-

Table 1. Net exhumation magnitudes*

Well	Shale†	Chalk†	Mean§	VR	Comments
Anholt-1	*1400*	*1400*	-	-	Comparison to Hans-1, Terne-1 and Frederikshavn-1 (very uncertain)
Års-1	442	461	-	-	
Børglum-1	1185	600	-	-	
C-1	*300*	306	-	-	Comparison to Inez-1 and Vemb-1 (264 m)
D-1	*50*	50	-	-	Comparison to L-1
F-1	481	357	419	1200	
Farsø-1	377	530	-	-	
Felicia-1/1A	1020	712	866	800	
Fjerritslev-2	1443	802	-	-	
Frederikshavn-1	*1000*	702	-	-	Comparison to Sæby-1 (1051 m)
Gassum-1	*1090*	579	-	-	Comparison to Voldum-1 (845 m) + 250 m deeper chalk truncation
Haldager-1	*1400*	486	-	-	Comparison to Børglum-1 and Fjerritslev-2
Hans-1	1735	-	-	-	
Hobro-1	*450*	543	-	-	Comparison to Års-1 and Kvols-1
Hyllebjerg-1	470	552	-	-	
Inez-1	344	445	395	850	
K-1	624	414	519	1300	
Kvols-1	361	420	-	-	
L-1	0	0	-	-	
Mors-1	690	602	-	-	
R-1	*150*	176	-	-	Comparison to C-1, L-1, S-1 (0 m) and Vemb-1 (238 m)
Rønde-1	394	447	-	-	
Skagen-2	*1000*	*1000*	-	-	Comparison to Børglum-1, Frederikshavn-1 and Sæby-1 (1051 m)
Terne-1	1373	-	-	-	
Vedsted-1	*1300*	*500*	-	-	Comparison to Børglum-1, Fjerritslev-2 and Haldager-1
Vinding-1	*175*	*250*	-	-	Comparison to Mejrup-1 (sh: 231 m; ch: 253 m) and Vemb-1 (sh: 264 m; ch: 238 m)

* Net exhumation magnitudes based on shale and chalk sonic velocity data (Japsen *et al.* 2007)
† Magnitudes in italics are estimated; see comments column
§ Mean of shale (sh) and chalk (ch)

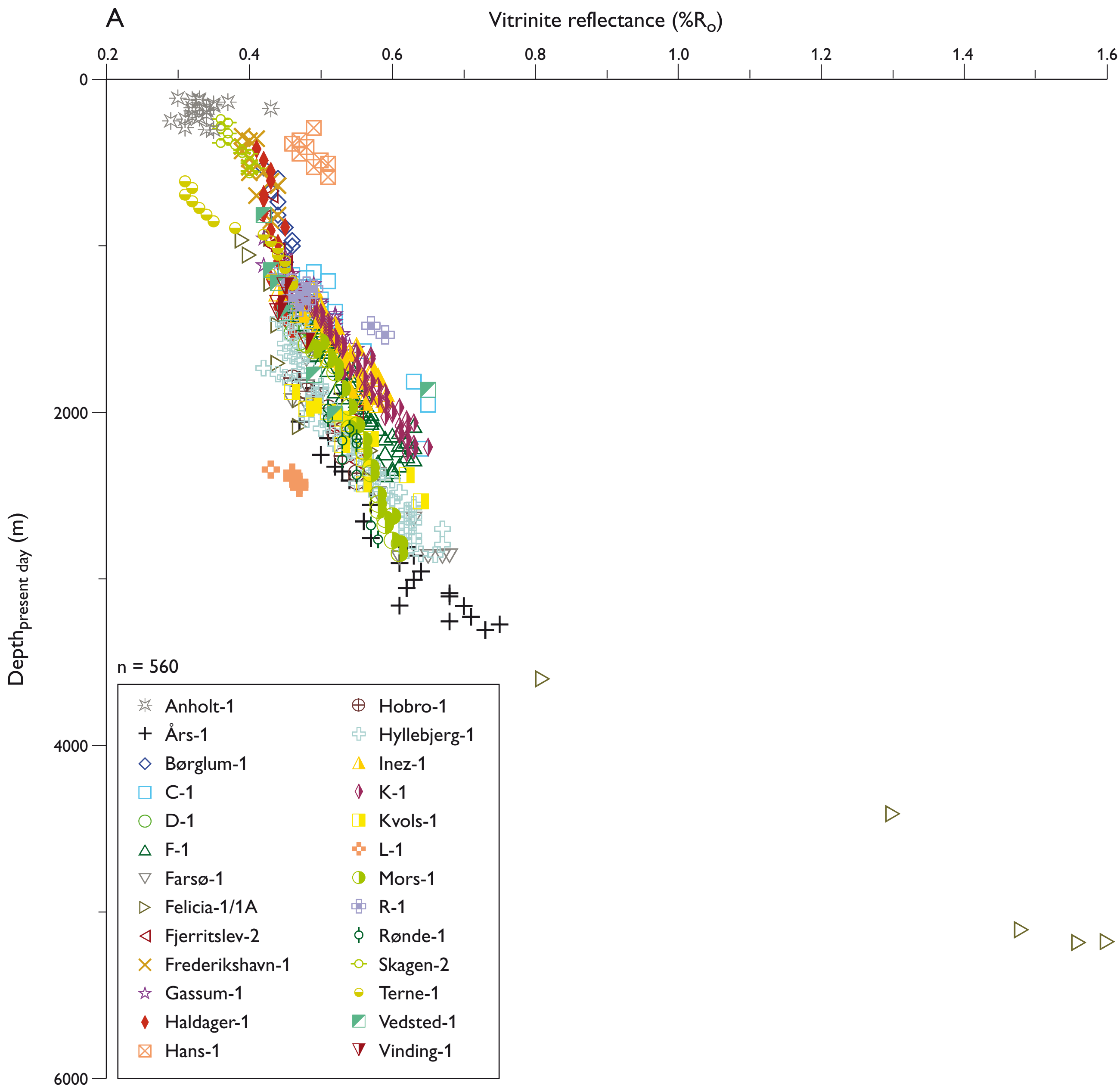

Fig. 18. **A**: Vitrinite reflectance values plotted against present-day depths for 26 onshore and offshore wells.

mal maturity of the organic matter at the sampled depth. Higher reflecting vitrinite particles may represent recycled organic matter that attained higher maturity from the temperature history of its former host rock (e.g. Bostick 1979; Hunt 1996; Taylor *et al.* 1998). In contrast, vitrinite that yields anomalously low reflectance values may be suppressed (Buiskool Toxopeus 1983; Carr 2000a, b). A more detailed description of the prerequisites for construction of a regional coalification curve is presented in Petersen *et al.* (2003a).

Shale velocity-based curve

The shale sonic velocity reference curve of Japsen (1993) has recently been refined and new, modified net-exhumation values based on shale velocities have been proposed (Table 1; Japsen *et al.* 2007). The revised magnitudes of net exhumation are reduced by about 100 m compared to the values used by Petersen *et al.* (2003a). The new net-exhumation values have been used to revise the coalification curve

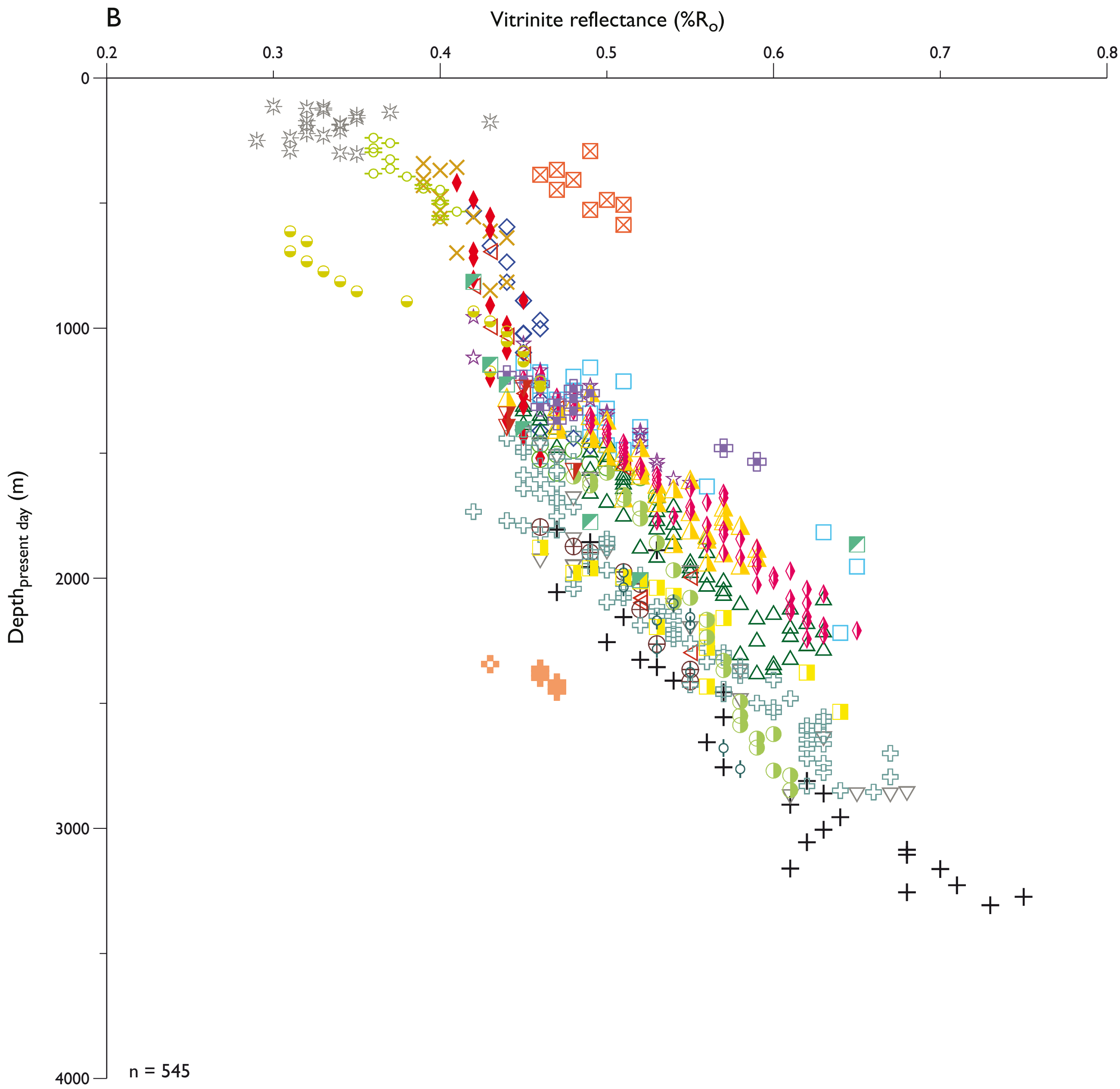

Fig. 18. **B:** As in 18A, but excluding the Felicia-1/1A deep well; for legend, see Fig. 18A.

for the study area. In Fig. 19, the present depths of samples from 25 wells have been corrected for the magnitudes of net exhumation obtained from shale velocities. For some wells, net-exhumation values based on shale velocities are not available, and the amount of net exhumation for these wells has been estimated by comparison to nearby wells and stratigraphic evaluation (Table 1). Despite the VR data showing considerable scatter, 13 of the wells define a well-constrained VR trend (Fig. 20A). Following Petersen *et al.* (2003a), the Fjerritslev-2, Haldager-1 and Vedsted-1 wells from the Fjerritslev Trough are not included as they define an atypically steep maturation gradient. This was explained by a probable overestimation of shale velocities in this area due to an increased coarse-grained component within the lowermost Fjerritslev Formation. The Anholt-1 and Terne-1 wells show unusually low VR values and are thus not included. Compared to the curve in Petersen *et al.* (2003a), the Horsens-1, Lavø-1 and Ullerslev-1 wells have been

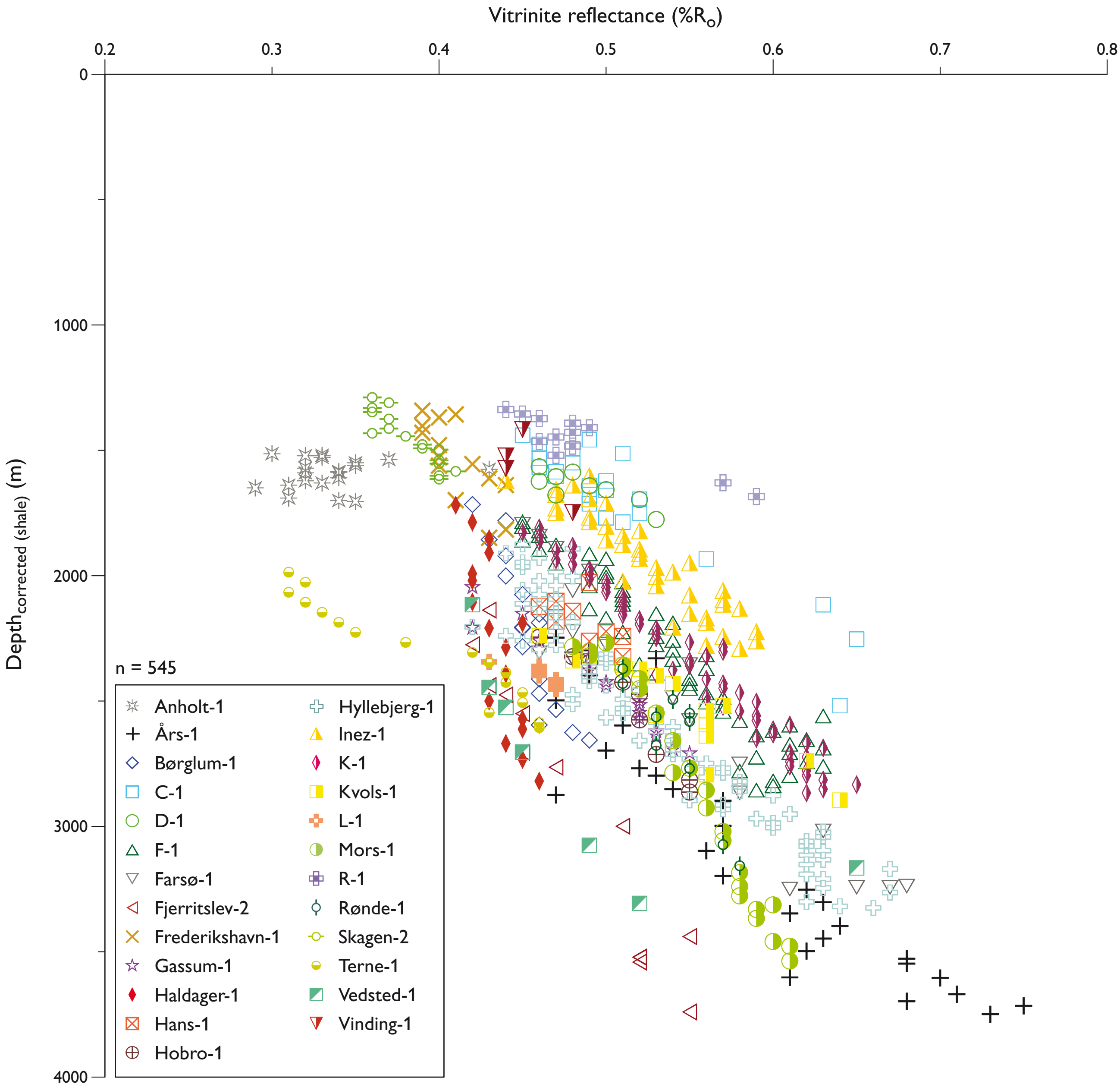

Fig. 19. Vitrinite reflectance values from 25 wells plotted against depths corrected for post-Early Cretaceous uplift on the basis of shale sonic velocity data.

omitted, as only one VR measurement is available from each well. The VR data from the Børglum-1 well are, however, included in the new coalification profile. Accurately determined VR values will define a straight line in a semi-log plot (Dow 1977), and the established VR profile yields a correlation coefficient of 0.89 (Fig. 20A). The linear regression line intercepts the surface at a VR of *c.* 0.26%R_o which is at the upper end of the reflectance values recorded for peaty organic matter at the surface (*c.* 0.10–0.25%R_o; Cohen *et al.* 1987). If the start of the oil window is set at a VR of *c.* 0.6%R_o, the 'shale curve' suggests that the top of the oil window occurs at a burial depth of *c.* 3050 m.

VR data from offshore wells in the Skagerrak are not included in the coalification curve (Fig. 20A). Generally, the VR values from these wells lie above the maturity curve (Fig. 19), and data from four of the wells (D-1, F-1, Inez-1 and K-1) provide a relatively well-defined VR trend (Fig. 20B). The regression line yields a correlation coefficient of 0.80 and intercepts the surface at a VR of *c.* 0.28%R_o. This alternative maturity gradient may be applied for the off-

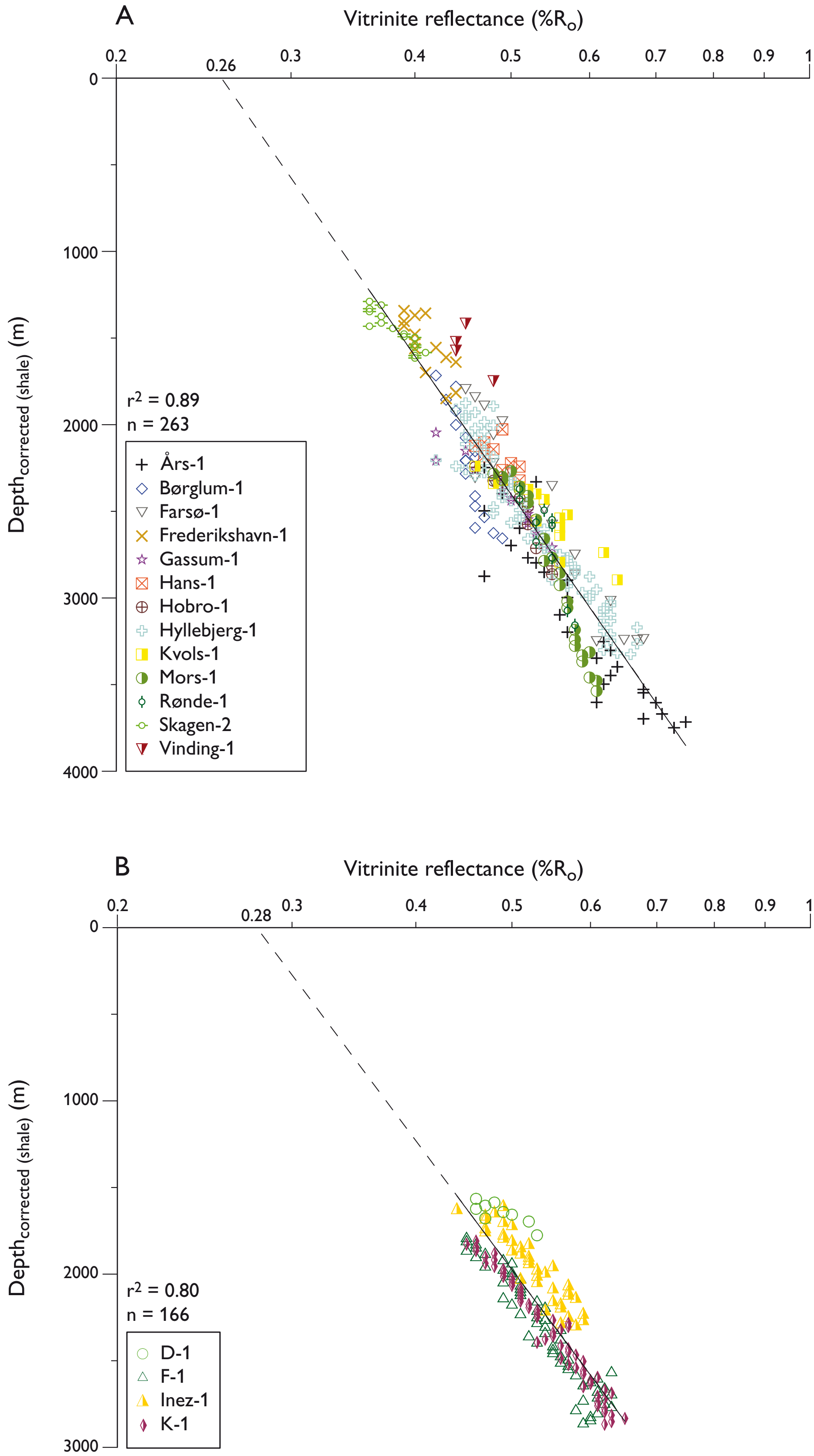

Fig. 20. **A:** Regional coalification curve for the Norwegian–Danish Basin based on 12 onshore wells and the Hans-1 well, selected from the wells in Fig. 19 (see text). A total of 263 vitrinite reflectance values have been used. The regression line has a correlation coefficient of r^2 = 0.89 and the line intercepts the surface at 0.26%R_o. The depth to the top of the oil window at 0.6%R_o is *c.* 3050 m. **B:** Coalification curve based on four wells from the Skagerrak area. The regression line yields a correlation coefficient of 0.80 and the line intercepts the surface at a VR of *c.* 0.28%R_o. The top of the oil window (VR *c.* 0.6%R_o) occurs at a burial depth of *c.* 2600 m according to this curve.

shore part of the study area. According to this curve, however, the top of the oil window (VR *c.* 0.6%R_o) occurs at a burial depth of *c.* 2600 m which, given the absence of petroleum discoveries in this part of the basin, is probably too shallow. Underestimation of the magnitude of exhumation in the area may provide an explanation for the apparently erroneous curve.

Chalk velocity-based curve

Chalk velocities have – like shale velocities – been used to estimate the magnitude of net exhumation by Japsen (1998). Considerable uncertainty in the estimated exhumation may be introduced if the chalk section is <300 m thick. Net-exhumation magnitudes based on new chalk velocities (Japsen *et al.* 2007) have been used to correct the present-day sample depths in this study (Table 1). Compared to the net-exhumation magnitudes in Japsen (1998), the adjusted values presented here are reduced by about 200 m. In Fig. 21, the present depths of samples from 25 wells have been corrected for the magnitudes of net exhumation obtained from chalk velocities. The VR data show a relatively large scatter, although the data seem to group into two elongate populations with the upper population principally formed by offshore wells in the Skagerrak. The linear regression line for a regional VR curve based on 15 onshore wells and the Hans-1 well has a correlation coefficient of 0.87 (Fig. 22A), which is slightly poorer than the 'shale curve'. The linear regression line is, however, based on more data (n = 282) as VR data from the Fjerritslev-2 and Vedsted-1 wells are included in the coalification profile. Like the 'shale curve', the Haldager-1 well yields an abnormally steep maturity gradient, while the Anholt-1 and Terne-1 wells display much too low VR values compared to the overall trend defined by the majority of wells (Fig. 21). The curve intercepts the surface at a VR of *c.* 0.28%R_o, which is at the upper end of the VR values of peaty organic matter (Fig. 22A). Compared to the 'shale curve', the slightly lower gradient of the 'chalk curve' yields a burial depth of *c.* 3100 m for the top of the oil window using a VR of 0.6%R_o.

As with the shale velocity-corrected samples, the chalk velocity-corrected samples from offshore wells in the Skagerrak yield VR values that generally lie above the established maturity profile (Fig. 21). Three of these wells (F-1, Inez-1, K-1) provide a well-constrained VR gradient (correlation coefficient of 0.90) that intercepts the surface at *c.* 0.26%R_o (Fig. 22B). According to this curve, the top of the oil window is located at about 2450 m depth, which is considered an unrealistically shallow burial depth probably due to underestimation of the magnitude of exhumation.

Depth to the top of the oil window

If the top of the oil window is set at a maturity level corresponding to *c.* 0.6%R_o, the two depth-corrected maturity gradients, derived from the onshore wells, yield similar depths to the top of the oil window (*c.* 3050–3100 m). According to the relationship between VR and burial peak temperature of Barker & Pawlewicz (1994), *c.* 0.6%R_o corresponds to *c.* 95°C. This fits reasonably well with the present-day thermal gradient of 31.4°C/km in Felicia-1/1A, as estimated from corrected bottom-hole temperature measurements. In contrast, depth-corrected maturity gradients based on offshore wells from the Skagerrak yield unrealistically shallow burial depths to the top of the oil window. Burial depths of only 2450–2600 m would imply the presence of mature source rocks in the area, which is inconsistent with the lack of direct evidence of generated petroleum.

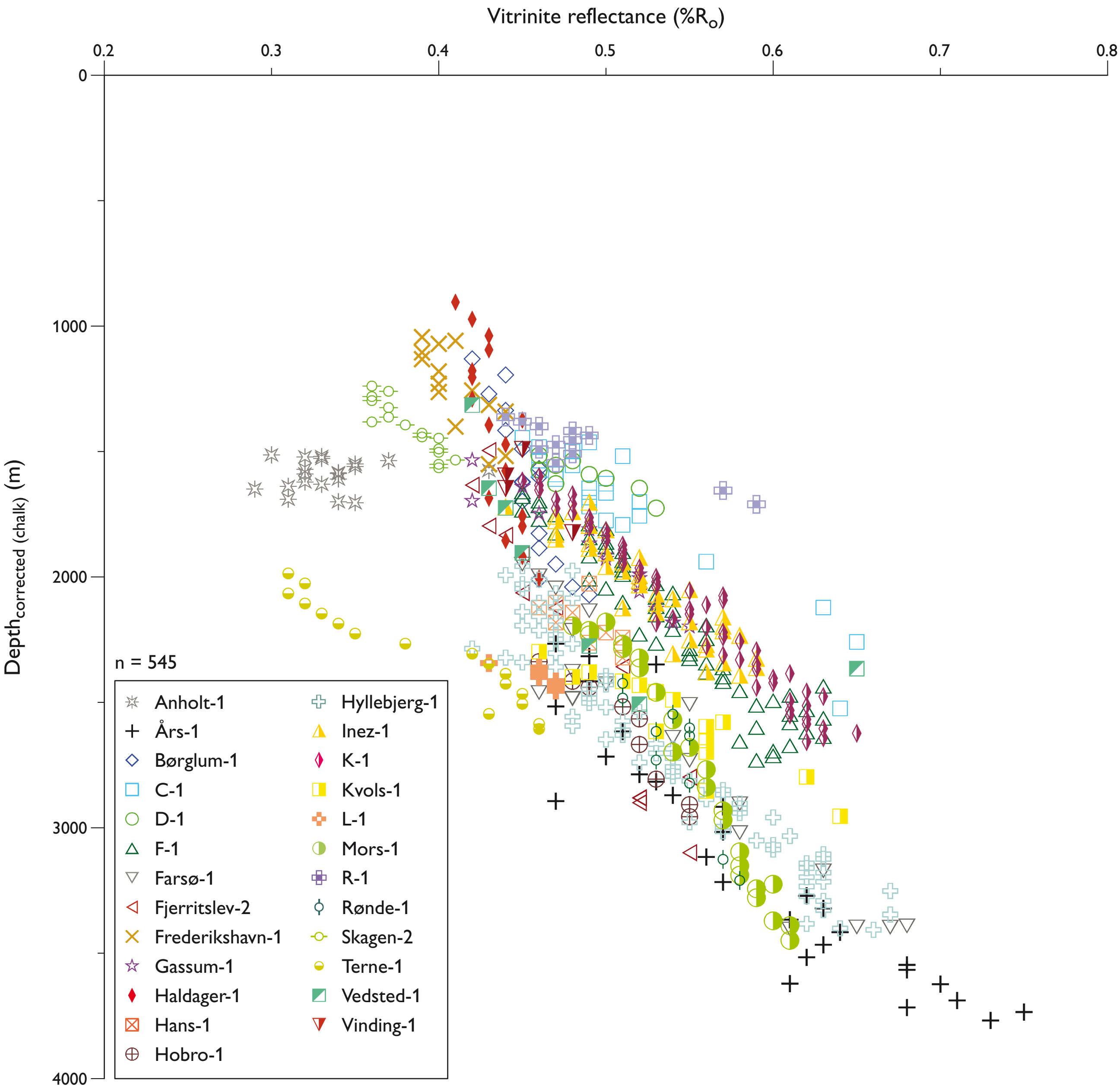

Fig. 21. Vitrinite reflectance values from 25 wells plotted against depths corrected for post-Early Cretaceous uplift on the basis of chalk sonic velocity data.

Fig. 22. **A**: Regional coalification curve for the Norwegian–Danish Basin based on 14 onshore wells and the Hans-1 well, selected from the wells in Fig. 21 (see text). A total of 282 vitrinite reflectance values have been used. The regression line has a correlation coefficient of $r^2 = 0.87$ and the line intercepts the surface at 0.28%R_o. The depth to the top of the oil window at 0.6%R_o is *c.* 3100 m. **B**: Coalification curve based on three offshore wells from the Skagerrak area. The VR data form a very well-constrained VR gradient (correlation coefficient of 0.90) that intercepts the surface at *c.* 0.26%R_o. According to this curve, the top of the oil window is located at only *c.* 2450 m depth.