Plate-wide stress relaxation explains European Palaeocene basin inversions

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During Late Cretaceous and Cenozoic times, many Palaeozoic and Mesozoic rifts and basin structures in the interior of the European continent underwent several phases of inversion (the process of shortening a previously extensional basin)[1]. The main phases occurred during the Late Cretaceous and Middle Palaeocene, and have been previously explained by pulses of compression, mainly from the Alpine orogen[2–5]. Here we show that the main phases differed both in structural style and cause. The Cretaceous phase was characterized by narrow uplift zones, reverse activation of faults, crustal shortening, and the formation of asymmetric marginal troughs. In contrast, the Middle Palaeocene phase was characterized by dome-like uplift of a wider area with only mild fault movements, and formation of more distal and shallow marginal troughs. A simple flexural model explains how domal, secondary inversion follows inevitably from primary, convergence-related inversion on relaxation of the in-plane tectonic stress. The onset of relaxation inversions was plate-wide and simultaneous, and may have been triggered by stress changes caused by elevation of the North Atlantic lithosphere by the Iceland plume[6] or the drop in the north–south convergence rate between Africa and Europe[7].

The sedimentary succession southwest of the Sorgenfrei-Tornquist Zone in the central part of the Danish Basin has recorded the two phases of inversion (Fig. 1). The Late Cretaceous phase occurred during a general increase of relative sea level, which provided space for a background thickness of chalk sediments. The inversion is visible in thinning of the sedimentary sequences onto the inversion ridge and the presence of internal unconformities and embedded sandstone bodies[8], which show that the main

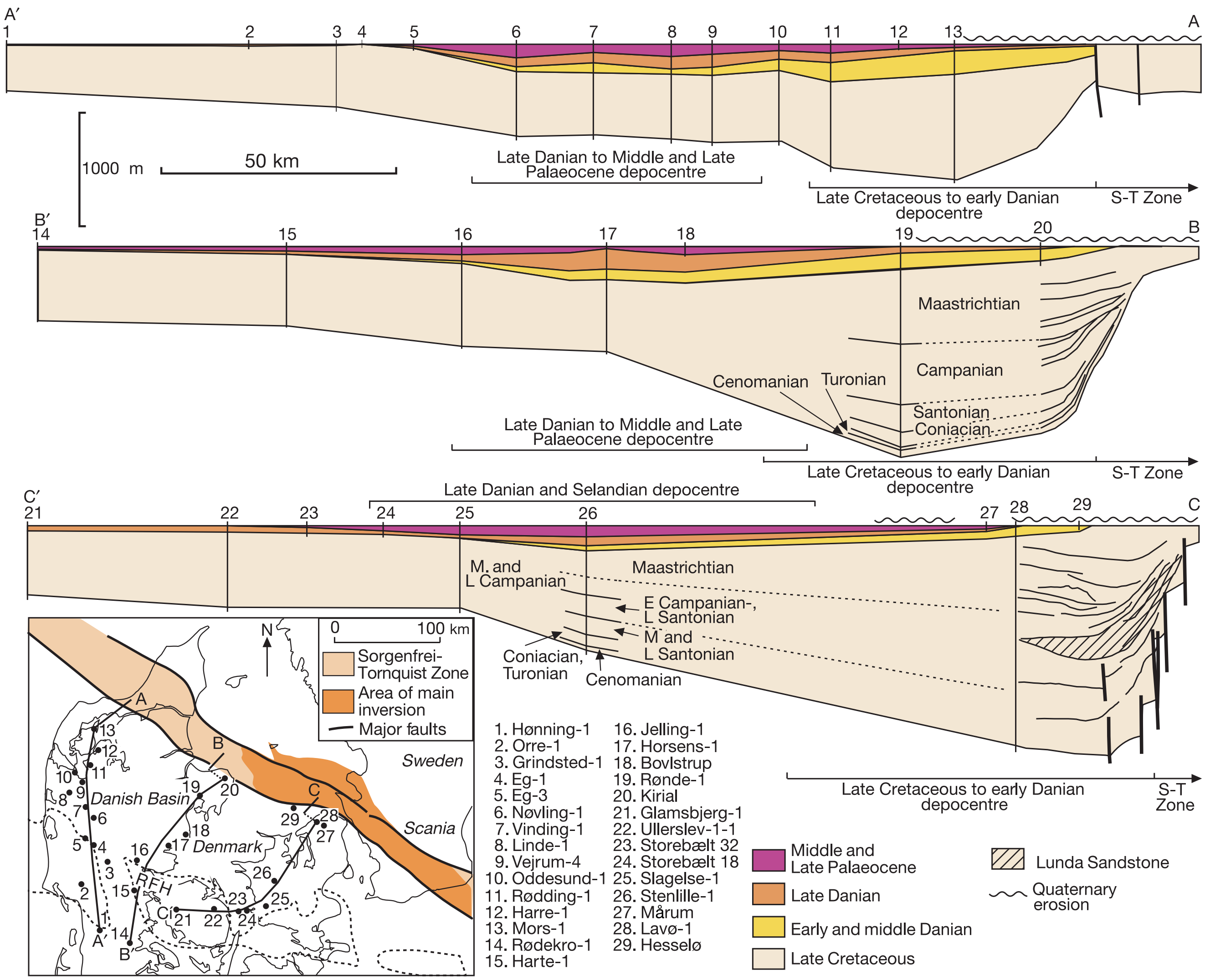

Figure 1 Geological profiles. Geosections across the marginal troughs of the Sorgenfrei-Tornquist Zone (STZ) representing the mildly inverted northwestern part (A–A′ and B–B′) and the strongly inverted southeastern part (C–C′). The Late Cretaceous marginal trough was formed during primary inversion, culminating during the Santonian and Campanian[8,12]. The secondary, more distal, Palaeocene trough is shallower and more symmetric than the Cretaceous trough. For section B–B′ simple calculations based on the slope of the basal Upper Cretaceous and Palaeocene beds indicate that the Palaeocene uplift was only 10–15% of the total primary and secondary uplift. The datum level is the top of the Upper Palaeocene deposits in sections A–A′ and B–B′ and the top of the Middle Palaeocene deposits in section C–C′. R-FH, Ringkøbing-Fyn High; E, Early; M, Middle; L, Late.

uplift occurred during the Campanian and lower Maastrichtian. Simultaneously, the chalk basin southwest of the Sorgenfrei-Tornquist Zone developed a marked, asymmetric deepening towards the inversion axis (Fig. 1). This development conforms closely to the Late Cretaceous inversion history of other structures across the European continent[3].

The structural style and compressional cause[2,3] of the Late Cretaceous inversion phase agree with the results of model experiments[9–11]. Compression and shortening (for example, 5–10%) of a model rift squeezes sediments out of the rift along the inversion axis because the crust thickens. The order of magnitude of erosion depth along the inversion axis is 10^3 m. Simultaneously, a positive lithospheric load develops along the central inversion axis (relative to the pre-compression state) because the eroded lighter material is replaced by underlying, denser material (crust and compacted sediments). The primary marginal troughs form as a consequence of flexural isostatic compensation of this load, enhanced by sediment loading from the troughs themselves[9–11] (Figs 1, 2). The internal lithospheric load along the inversion axis prevails after erosion of all topography because rift inversion starts with an attenuated crystalline crust and a (thick) sedimentary cover. Thus, the flexural foredeeps of inversion zones and the loads that keep them in place are very resistant features.

The Middle Palaeocene inversion of the Sorgenfrei-Tornquist Zone, however, was entirely different. During the Danian, the depocentre southwest of the zone shifted away from the inversion zone, and at the beginning of the late Danian more distal, shallow and symmetric depocentres developed (Fig. 1). Slightly later ($\sim 10^5$ yr), during the early Selandian, the composition of the chalk component, constituting 50–70% of the sediment, changed from primarily biogenic to reworked Late Cretaceous chalk[12], marking the onset of the Middle Palaeocene inversion.

The more distal position and symmetric shape of the associated shallow, marginal troughs show that the Palaeocene inversion phase was more gentle and dome-like than the Late Cretaceous phase. We suggest that the cause was also different, as additional tectonic compression would simply continue the deepening of the Late Cretaceous asymmetric marginal troughs[11]. In fact, our model experiments (Fig. 2) indicate that the Middle Palaeocene inversion of the Sorgenfrei-Tornquist Zone is best explained by relaxation of the in-plane tectonic stress rather than by compression.

The mechanism is well known[13] and occurs because the equilibrium depth of the lithosphere flexure caused by the loads of the central inversion zone and the fill of the primary marginal troughs is sensitive to the level of in-plane stress. Thus, the Late Cretaceous compressional state of the lithosphere over-deepened the flexure slightly, and secondary relaxation inversion followed as an inevitable consequence of a relaxation of the in-plane compression in the Middle Palaeocene (Figs 1, 2). The surface expression of the relaxation inversion is a low-amplitude (order of magnitude 10^2 m), smooth, domal uplift of the central inversion zone and the proximal areas of the primary marginal troughs, and subsidence of more distal, shallow and symmetric secondary marginal troughs (Fig. 2). At the southern end of the Sorgenfrei-Tornquist Zone around Scania, the Middle Palaeocene inversion apparently was relatively narrow and partly detached from the marginal troughs[8]. We attribute this to a major discontinuity in the lithospheric structure in the area[14].

The Middle Palaeocene inversion phase in northwest Europe has invariably been linked to additional compression[2–5]. Relaxation inversion in the aftermath of compression was never considered. In the light of our findings for the Sorgenfrei-Tornquist Zone, we have examined the inversion history of several key European structures. It appears that the Palaeocene phase possesses all the characteristics of relaxation inversion: (1) the uplifts were domal, generally non-ruptural and mostly affected a wider area than the Late Cretaceous phases. (2) The marginal troughs were shallower and developed in a more distal position. (3) Where erosion depths of the secondary phase are available, they are about 10% of the total erosion. Furthermore, the Middle Palaeocene inversions were simultaneous within the resolution of the stratigraphic data (a few Myr), in contrast to the ~20 Myr duration of the Late Cretaceous phase, indicating that they were triggered

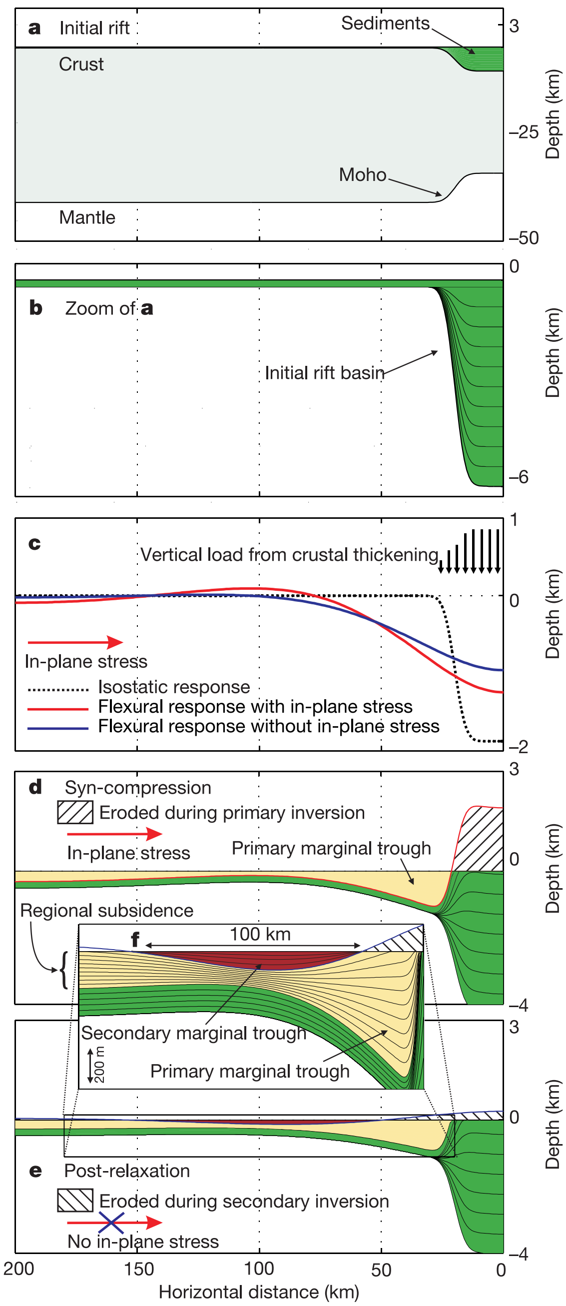

Figure 2 Mechanisms of primary and secondary inversion. **a**, **b**, Geometry of initial rift basin (rifting has ceased). **c**, Deflection of upper mantle caused by (blue) load of central inversion zone and (red) loading together with in-plane compression. **d**, Geometry of basin fill after primary inversion (in-plane compression). **e**, Geometry after secondary inversion (no in-plane compression). **f**, Enlarged view of the marginal troughs after secondary inversion. The amplitude and wavelength of secondary inversion depends on the flexural rigidity of the lithosphere, the magnitude of the load, density contrasts in the lithosphere and the size of stress change involved. Loading across the structure by differentially compacting sediments and ductile stress relaxation may enhance the amplitudes of vertical displacements. Typically, the erosion depth of the secondary phase amounts to about 10% of the total erosion. Model densities are 2,400 kg m^{-3} for sediments, 2,900 kg m^{-3} for crust, and 3,300 kg m^{-3} for lithospheric mantle. The bending stiffness of the elastic plate is 2×10^{21} N m^{-1}. The magnitude of in-plane stress is 5×10^{12} N m^{-1}.

by a single event causing a plate-wide stress change.

The Tornquist-Teisseyre Zone across Poland experienced a strong Late Cretaceous compressional inversion, with an estimated 2–3 km of erosion[15]. In analogy with the Sorgenfrei-Tornquist Zone, we interpret the narrow Cretaceous depocentres as the remains of the primary marginal troughs, and the wider and more distal Palaeocene depocentre as the secondary marginal troughs (Fig. 3a). The elongate area of uplift separating the depocentres is, in accordance with model experiments (Fig. 2), wider than the ridge formed during the primary inversion[16].

The Danish Central Graben saw episodic and relatively weak Late Cretaceous, fault-controlled inversion of Late Jurassic–Early Cretaceous depocentres[17]. Post-Danian[17], possibly during the Middle Palaeocene[18], the structural style changed to gentle folding and doming of a wider area[17,18]. The Dutch Central Graben[19] experienced a stronger Late Cretaceous inversion with patchy removal of the chalk sequence (Fig. 3a), followed by differential post-Danian subsidence across the inverted graben[19]. In both cases, the Middle Palaeocene change of structural style and the influence of the gentle differential vertical movements on the post-Danian Palaeocene sediments (Fig. 3a) can be explained by relaxation inversion.

The Lower Saxony Basin (Fig. 3a) experienced strong Late Cretaceous inversion with several kilometres of erosion and formation of pronounced marginal troughs[20], which signal the existence of a loading-induced lithosphere flexure. This primary inversion mode was followed by domal, non-ruptural uplift during the Palaeocene[20,21], which we identify with secondary relaxation inversion. Evidence of the change in inversion style comprises deep truncation of the deposits of the primary marginal troughs along the margins of the inversion zone and relaxation movements along former Late Cretaceous reverse faults dated by Palaeocene sediments[21]. The proximal part of the post-Danian Palaeocene depocentre to the north (Fig. 3a) is in the right position to be a secondary marginal trough, but detailed thickness information is not available to us.

The inverted[22] Weald-Boulonnais area (Fig. 3a) is flanked by shallow, symmetric depocentres of early Thanetian (NP6) age[23], which have all the characteristics of secondary marginal troughs. Detection of a preceding Late Cretaceous inversion is complicated by the absence of sediments of this age. However, the Late Cretaceous deposits at the southern margin of the Weald contain gravity flows of allochthonous chalks and lateral changes in thickness and lithology, which are controlled by en-echelon folds of transpressional origin[24], indicating a Late Cretaceous uplift. The maximum uplift occurred where the thickest chalks had previously been deposited[24], yielding total erosion depths of approximately 1,500 m towards the east.

In the southern North Sea, several Palaeozoic and Mesozoic rift structures (the West Netherlands Basin[3,19,25], the Broad Fourteens[3,19,26], the Central Netherlands Basin[3] and the Sole Pit Trough[27]) experienced strong fault-controlled Late Cretaceous[3,25] primary inversion resulting in uplift and 2,000–3,000-m-deep erosion of narrow ridges, and formation of associated primary marginal troughs (Fig. 3b). The onset of the Middle Palaeocene inversion phase is, as in the Danish Basin[12], marked by an extremely high percentage of reworked Late Cretaceous nannofossils in the Middle Palaeocene deposits[28]. The distribution of the post-Danian Palaeocene sediments in the Netherlands and offshore reveals a broad, domal uplift and subsidence pattern distinctly different from the narrower, ridge-like structural style of the Late Cretaceous compressional inversion phase (Fig. 3b). Rather than additional compression, a Middle Palaeocene relaxation of in-plane tectonic stress excited the longer wavelength of vertical surface movements involved in flexural isostasy of the lithosphere, and averaged the loading effect of individual narrow inversion ridges into one broad flexural response. Continued regional subsidence in the area with differential loading of the crest and flanking marginal troughs by

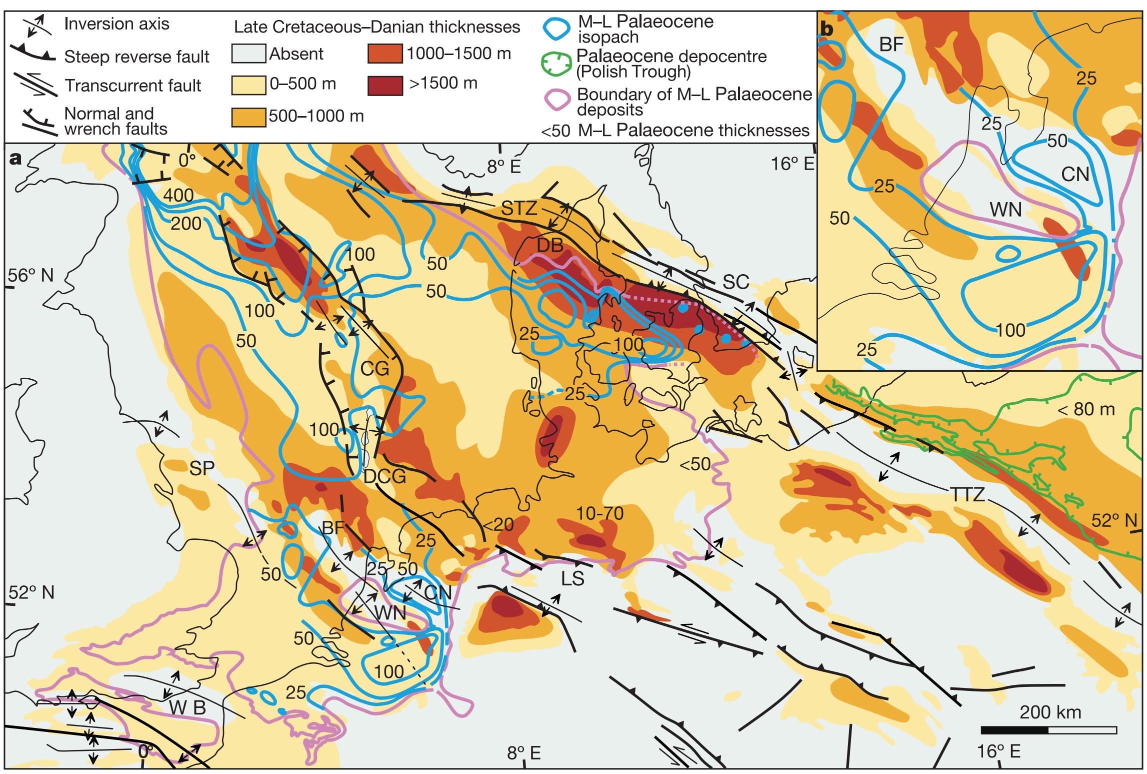

Figure 3 Isopach signature of inversion movements. **a**, Late Cretaceous–Danian isopach[3] (primary inversions) with superimposed Middle–Late (M–L) Palaeocene depocentres[30] (secondary inversions) and inversion structures[3,17–19]. BF, Broad Fourteens Basin; CN, Central Netherlands Basin; CG, Danish Central Graben; DB, Danish Basin; DCG, Dutch Central Graben; LS, Lower Saxony Basin; SC, Scania; SP, Sole Pit High; STZ, Sorgenfrei-Tornquist Zone; TTZ, Tornquist-Teisseyre Zone; WB, Weald-Boulonnais area; WN, West Netherlands Basin. The northwestern end of the STZ appears asymmetric because of deep Quaternary erosion to the north. Around Scania the STZ inversion is asymmetric. The depocentre east of the TTZ represents Palaeocene deposits[31]. <50: M–L Palaeocene thickness less than 50 m. **b**, Enlarged view of southern North Sea.

the overlying sediment packages led to the apparent evolution of the domal inversion through the Eocene[19,25]. The estimated 200–300 m of crestal erosion during this phase[25] agrees well with the predicted relative magnitudes of erosion for the primary and secondary inversion (Fig. 2). Relaxation of compressional induced stresses by ductile flow processes in the softer parts of the lithosphere may have contributed to the Palaeogene evolution[9–11]. However, the plate-wide synchroneity of the Middle Palaeocene inversions indicates a sudden plate-wide release of inversion potential, a significant fraction of which must therefore have been maintained in compressionally over-deepened elastic flexures.

An erosional phase in the southern North Sea around the Eocene–Oligocene boundary has been explained by a Pyrenean phase of compression[3,19,25–27], but may not be easy to distinguish from the erosional effects of the global sea level fall at that time[29].

It is widely accepted that flexural isostasy provides a causal relation between in-plane stress variations, differential vertical movements of the surface of the lithosphere and changes in the depositional patterns of the sedimentary sequences[13]. Application of this concept requires knowledge about the initial lithospheric deflection, which generally is not available away from topographic loads in the interior of continents. The central regions of rift basins, however, tend to become positively loaded during the rifting and thermal sag phase and therefore develop an intrinsic downward flexure, which in some cases has been revealed by accelerated subsidence[15] in the incipient stage of compressional inversion. This pre-loading of rift basins promotes the formation of the asymmetric, primary marginal troughs during compressional inversion, and contributes positively to the over-deepening of the flexure that drives the relaxation inversion.

The existence of a positive load of the lithosphere along inversion ridges allows for prediction of the flexural response of the lithosphere to in-plane stress variations. Application of this concept to key European inversion structures allows us to explain the Middle Palaeocene change of inversion style, the synchroneity of the event across the European plate, the relative magnitude of the Late Cretaceous and Palaeocene erosion phases (when estimates exist) and the control exerted by the inversion movements on the post-Danian Palaeocene deposits.

The surprising conclusion that relaxation of in-plane tectonic stress, rather than increased Alpine compression, explains the European Middle Palaeocene inversions calls for reconsideration of the sources of the stresses affecting the interior of the European plate. Candidates for producing a plate-scale change of tectonic setting at this time involving forces in the range of 10^{12} N m^{-1} include uplift of the North Atlantic lithosphere by the Iceland plume[6] and the drop in north–south convergence rate between Africa and Europe[7]. □

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Palaeomagnetism of the Vredefort meteorite crater and implications for craters on Mars

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Magnetic surveys of the martian surface have revealed significantly lower magnetic field intensities over the gigantic impact craters Hellas and Argyre than over surrounding regions[1]. The reduced fields are commonly attributed to pressure demagnetization caused by shock waves generated during meteorite impact[2,3], in the absence of a significant ambient magnetic