Paleo-ecosystems: Early Toarcian environmental crisis

The Early Toarcian environmental crisis and oceanic anoxic event

(Early Jurassic; 183 Ma BP)
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Oceanic anoxic events (OAE):

OAEs represent periods in Earth’s history that were highlighted by widespread organic matter burial, associated with anoxia and/or euxinia at a global scale.

The Early Toarcian OAE represent the first of series of OAEs documented throughout the Jurassic and Cretaceous (Jenkyns, 2010).

OAEs were often accompanied by (global) climate perturbations and extinction events.
In the sedimentary record the Early Toarcian event is expressed by the widespread accumulation of organic matter-rich sediments. Those have been intensively studied throughout Europe (Germany: Posidonia Shale; France: Schistes Carton; UK: Jet Rock). Early Toarcian bituminous sediments have a thickness of 10 to 40 m and have been deposited within 1 to 1.5 Myr. At some locations black shale deposition lasted longer than 2 Myr. Due to high concentrations of organic matter and the wide spatial and stratigraphic extent, Early Toarcian black shales can be important sources rocks (e.g. North Sea, Central Paris Basin).
Toarcian bituminous sediments are famous for their excellent fossil preservation. Remains of mainly nektonic organisms can be extremely enriched in distinct horizons, suggesting slow sediment accumulation rates in combination with a low-energetic depositional environment.
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- Global warming (icehouse-greenhouse transition?)
- Carbon cycle perturbation
- Sea level rise
- OAE

Epoch: Early Jurassic
Stage: Early Toarcian
Biozone: H. serpentinum/H. falciiferum
- Karoo volcanism
- Ferrar volcanism

- K-F LIP
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δ\(^{18}\)O (‰ VPDB) vs. pCO\(_2\) (p.p.m.v.)

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δ\(^{13}\)C\(_{org}\) (‰ VPDB)

- 

δ\(^{13}\)C\(_{carb}\) (‰ VPDB)

- 

Sea level rise

Extinction level

Glacial deposits?
Global paleogeographic reconstruction of the Earth during the Early Toarcian (approx. 183 Ma BP) (Blakey, “Global Paleogeography and Techtonics in Deep Time © 2016 Colorado Plateau Geosystems Inc.”). Shelf areas where bituminous sediments have been accumulated were marked in yellow. The Toarcian CIE has been documented from locations around the globe attesting to a global perturbation of the carbon cycle.
Jurassic climate conditions
The Jurassic as well as the Cretaceous have been commonly associated with overall warm climate conditions during a long-lasting greenhouse mode (Frakes et al., 1992). A low equator-pole temperature gradient has been associated with ice-free polar regions.
The assumption of an overall ice-free Jurassic world was mainly based on floral and faunal distribution patterns. The occurrence of vegetation adopted to warm temperate climates at high latitudes has been used as evidence for warm (subtropical) climates at polar regions.

Analysis of floral provinces provides only a superficial view on climate conditions, summarizing warm and cold climate conditions over a period of several tenth of millions of years.

e.g. Early Jurassic: 201 – 174 Ma BP (GTS 2012)
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Jurassic climate ups and downs – cold (ice-house) – green (hot-house) cycles?
Glacial-derived deposits of Early Jurassic (Pliensbachian) age have been reported from Siberia as well as from Europe (e.g. Suan et al., 2011; Teichert & Luppold, 2013).

A) glendonites: calcite pseudomorphs (CaCO₃ x 6H₂O), formation requires temperatures below 4°C, but might also be associated with methane seeps

B) boulder rocks: large blocks in a fine-grained sediment matrix, typically associated with ice-related transport.
Climate evolution across the Pliensbachian-Toarcian boundary and throughout the Early Toarcian, inferred from belemnite oxygen isotope data, stomata-indices, floral-characteristics, GDGT-based air temperature reconstructions and sedimentological features (glacial-derived deposits, glendonites). Data are from numerous sources.
Timing of the Karoo-Ferrar volcanism
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Correlation of peak activity phases of Karoo-Ferrar volcanism with the Early Toarcian climate change. Data are from numerous sources.
Early Toarcian extinction event(s)
The Early Toarcian extinction event in a wider context. The Early Toarcian environmental crisis was associated with profound environmental changes as well as with drastic climate perturbations ($p\text{CO}_2 \times 3$; 4-6°C rise in SST). However, high extinction rates were mainly documented for benthic taxa, while nektonic organisms experienced high turnover rates.
The Early Toarcian environmental crisis is associated with multiple extinction events that affected invertebrates and primary producers.
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Changes in the species diversity of ammonites from sections from Europe and N-America. A diversity loss has been documented in the *kanense* zone (time-equal to the *D. tenuicostatum* and *H. serpentinum* zones). Also shown extinction and origination rates for ammonites and foraminifera. Data from Caruthers et al. (2013) and references therein.
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High extinction rates were documented for benthic communities that suffered from declining oxygen levels in bottom waters across the shelf seas. Benthic island (e.g. paleo-swells above the chemocline) allowed benthic organisms to survive. During phases of enhanced bottom water oxygenation benthic taxa resettled previous death zones.
The Early Toarcian Carbon Isotope Excursion
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The Pliensbachian to Early Toarcian carbon isotope stratigraphy recorded a negative carbon isotope excursion (Toa-CIE) that has been recorded in coeval sediments around the globe. Local depositional-related processes, however, impacted on the expression of the Toa-CIE. The Toa-CIE was preceded by a CIE at the Pl-Toa-boundary.
The Toa-CIE has been documented in marine and terrestrial organic matter as well as in marine carbonates attesting to a perturbation of the entire exchangeable carbon reservoir (data from Hesselbo et al., 2000).
A negative shift has also been documented in biomolecules originated in marine taxa and in land plant-derived long-chain n-alkanes (Schouten et al., 2000; Xu et al., 2017). Data support a global carbon cycle perturbation affecting the marine as well as the atmospheric carbon reservoirs.
Impact of local depositional conditions on the expression of the Toa-CIE in the sedimentary record.

Changes in sedimentation were related to the local depositional setting and to (global?) sea level changes.

Transgressive phases resulted in stratigraphic condensation, while regressive phase in erosive events.

(see Pittet et al., 2014; Ruebsam et al., 2014; 2015)
MTM power spectra for stacked organic carbon isotope record (Luxembourg + Yorkshire) and for the inorganic carbon isotope record from Peniche. Similar spectral peaks have been documented for both records attesting to a similar periodicity. Based on their frequency ratios spectral peaks can be linked to Milankovitch frequencies (LF bpf: low frequency band-pass filter).

The presence of an orbitally-forced periodicity in both carbon isotope records indicated that changes in global carbon cycle were potentially associated with climate-sensitive carbon reservoirs.
Statistical analysis (spectral analysis) confirmed the presence of a periodicity in carbon isotope data that can be associated with astronomical cycles (Milankovitch).
Magnitude of the Toa-CIE: The Toa-CIE is associated with a decline in carbon isotope values that range from -3 to -7‰. Changes in organo-facies (source/preservation of the sedimentary organic matter) can impact on carbon isotope values. Thus, a good correlation is seen for HI and carbon isotope values (Suan et al., 2015).
Corrected for organic matter changes the Toa-CIE can be associated with a decline of about -3 to -4‰ (Suan et al., 2015).
Mechanism proposed to explain the Toarcian CIE:

- Recycling of $^{12}$C-enriched carbon in a stratified water column (Küspert, 1976). Toa-CIE not only evident in anoxic/euxinic sediments.

- Volcanic outgassing associated with the emplacement of the K-F-LIP (e.g. Brazier et al., 2016). Isotopic composition of volcanic CO$_2$ similar to atmospheric CO$_2$, thus huge amounts of carbon would be required to explain a -3‰ negative CIE.

- Intrusion of magmatic dykes into Gondwana coals (Svensen et al., 2007). Orbitally-forced periodicity cannot be explained by carbon emission related to volcanism.

- Increased rates of wetland methanogenesis (Them II et al., 2017). Fail to explain the recovery of the Toa-CIE as well as the shift from eccentricity to obliquity dominated forcing.

- Methane and CO$_2$-release from cryosphere reservoirs (Ruebsam et al., in review). Requires the formation of a (expanded) cryosphere during the Late Pliensbachian.
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Effect of releasing different amounts of carbon with distinct source-specific isotopic composition. A negative CIE can only be produced by emission of $^{13}$C-depleted carbon, e.g. from aerobe organic matter (OM) degradation, thermogenic methane, or biogenic methane release. A mixture of these sources is possible as well. On the contrary, unrealistic huge amounts of volcanogenic CO$_2$ would be required to affect the isotopic composition of the exchangeable carbon reservoir.
Early Toarcian black shales
(The Toarcian Oceanic Anoxic Event)
Timing of black shale deposition throughout the Western Tethyan Shelf. The onset of black shale deposition occurred at a similar but at the same stratigraphic interval. Differences in onset and stratigraphic extent of bituminous sediments can be associated with local depositional conditions.
Comparison of Lower Toarcian sections from the Aquitaine Basin and SW German Basin illustrates facies variations. In basin-margin areas and areas of shoals and swells the Pliensbachian–Toarcian boundary is marked by an unconformity (lower sequence boundary). By contrast, sections from the basin centers are characterized by regressive black shales representing the correlative conformity (Röhl & Schmidt-Röhl, 2005).
Black shale deposition throughout the Western Tethyan shelf was linked to the sea level evolution. Here shown a sea level reconstruction that was based on $C_{27}/C_{29}$ sterane ratios (Frimmel, 2002).
A similar sea level evolution has been inferred from grain-size analysis of terrigenous-derived sediment constituents that was carried out for a core from the central Paris Basin (Hermoso et al., 2013).
Changes in the depositional conditions were controlled by 1) the long-term sea level evolution and 2) environmental instabilities potentially controlled by astronomical cycles (Ruebsam, unpublished).
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Geochemical profiles of TOC and Mo abundances and of carbon and molybdenum isotopes for Early Toarcian sediments from the Cleveland Basin (UK) (Dickson et al., 2017).
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Geochemical profiles of TOC and Mo abundances and of carbon and molybdenum isotopes for Early Toarcian sediments from the Dotternhausen Quarry (S-Germany). In the Cleveland and the S-German Basin TOC-rich intervals showed low Mo-abundances, attesting to depletion of the aqueous Mo-reservoir. Differences in the isotopic composition of the Mo are explained by the degree of Mo-drawdown that was controlled by the redox state (H$_2$S concentration) (Dickson et al., 2017).
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Geochemical profiles of TOC and Mo abundances and of carbon and molybdenum isotopes for Early Toarcian sediments from the Belluno Basin (Italy) (Dickson et al., 2017). In contrast to the Cleveland Basin and the S-German Basin that were, both, part of the European Epicontinental Basin System, the Belluno Basin was a small depression, situated in the Alpine-Mediterranean sector. Lower TOC and Mo abundances in combination with lower Mo-isotope values were characteristic for preferentially suboxic/anoxic conditions.
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Evolution of Mo-abundances and Mo-isotope data during the Toarcian Oceanic Anoxic Event in different sub-basins across the European Epicontinental Basin System. Similar long-term trend reflect secular changes in the isotope composition of the sea water, controlled by the relative size of oxic versus euxinic Mo-sinks. Differences can be linked to local redox and hydrological conditions.
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Stratigraphic evolution of Mo/TOC ratios and cross-plot of TOC with Mo for Early Toarcian sediments from the Cleveland Basin indicated changes in hydrology and sea water chemistry. Lowest Mo/TOC-ratios can be associated with a severe Mo-depletion to the widespread euxinia and a strong hydrogeographic restriction of the Western Tethyan shelf. The degree of restriction was controlled by the sea level evolution. Moreover, deepwater renewal times, controlled by the persistence of water column stratification, might also impacted on Mo/Toc-ratios (McArthur et al., 2008).
The presence of aromatic carotenoids (isorenieratane, chlorobactane, okenane), originated in green sulfur bacteria, attested to the presence of H₂S-rich waters that have expanded into the photic zone (Jet Rock, Cleveland Basin UK). Also shown indicators of water column stratification and the redox state. Data from French et al. (2014).
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Paleogeographic map of the Western Tethyan Shelf with focus on the epicontinental basin system and the Alpine-Mediterranean Sector showing the spatial distribution of bituminous sediments and the occurrence of aromatic carotenoids, diagnostic for photic zone euxinia (PZE) (data from Schouten et al., 2000; van Breugel et al., 2006; French et al., 2014).

PZE was a common feature of European epicontinental sub-basins, but has been also reported for a setting in the Alpine-Mediterranean sector of the Eastern Tethyan Shelf (Ruebsam et al., submitted).
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Freshwater-driven salinity stratification as driver of shelf sea anoxia and organic matter accumulation. Lower oxygen isotope values at high latitudes reflect lowered sea surface salinities.

Red numbers indicate MTTC-indices (methylated chromanes) that confirmed lower salinities in the epicontinental basins of the Western Tethyan shelf (higher values).

Brackish conditions at the NW shelf sea either resulted from riverine freshwater discharge or from the inflow of Arctic freshwater.

Lower MTTC-indices were documented in areas influenced by saline Tethyan currents.
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Freshening of the Arctic Ocean due to melting ice caps?
Organo-facies of Early Toarcian black shales
(West Tethys Shelf)
Organo-facies evolution of the Posidonia Shale from southern Germany. High TOC- and HI-values confirmed the presence of well-preserved algae/bacteria-derived organic matter. Based on Rock Eval data organic matter can be attributed to kerogen types II and I/II. (Frimmel, 2002, PhD Thesis; Röhl & Schmidt-Röhl, 2005).
Organo-facies evolution of the Posidonia Shale from northern Switzerland. Trends observed match those from the Posidonia Shale of southern Germany (Montero-Serrano et al., 2015).
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Organic matter of preferentially marine origin has also been documented for the Schistes Carton (Posidonia Shale equivalent) from the Paris Basin. The distribution of n-alkanes, expressed by the TAR (terrestrial-aquatic ratio) supported a marine organic matter dominance. (Ruebsam, PhD thesis).
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n-alkane distribution in different facies intervals of the Schistes Carton from the Paris Basin. Laminated, TOC-rich sediments showed a clear dominance of short-chain n-alkanes that were derived from aquatic organisms (algae, bacteria).
Microphotographs of polished block sections confirmed that in the laminated sediments of the Schistes Carton Fm organic matter is represented by alginites that were enriched in distinct horizons. The presence of Tasmanales remains might be characteristic for the presence freshwater-tolerant algae taxa.
Sediments of the Schistes Carton Fm as well as of the Posidonia shale showed high sterol/hopanoid-ratios, indicating a dominance of eukaryotic primary producers.
Distribution of C$_{27}$ to C$_{29}$ steroids representing changes in Early Toarcian sediments from S-Germany (Posidonia Shale, left figure) and from the Paris Basin (Schistes Carton Fm, right figure). High concentration of C$_{29}$-steranes, mainly seen in sediments corresponding to the *spinatum* and *tenuicostatum* zones, represent land plant input. Increased abundances of long-chain n-alkanes (nC$_{27-31}$) supported terrigenous-derived organic matter contributions.

In the Posidonia Shale and the Schistes Caron Fm high abundances of C$_{27}$ and C$_{28}$ steroids can be associated with variable contributions of marine and freshwater-tolerant algae, respectively. Sediments associated with more brackish conditions showed high abundances of C$_{28}$ steroids, derived from Prasinophyte algae.
Paleo-ecosystems: upper Permian Kupferschiefer

Literature (some recommendations)

OAEs in general:
Jenkyns, H.C., Geochemistry of oceanic anoxic events G3 11, no. 3, Q03004, doi:10.1029/2009GC002788

The Toarcian Oceanic Anoxic Event (black shale deposition):

The Toarcian extinction event:
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The Toarcian Carbon Cycle perturbation:


Karoo-Ferrar Volcanism:


Toarcian (Jurassic) climate:


!!!Papers providing a nice overview and a good introduction (for a first reading) were highlighted red.