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Discussions**

# Phanerozoic black shales and the Wilson Cycle

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**Abstract**

The spatial and temporal distribution of black shales is related to the development of the environments in which they accumulate and to a propitious combination of environmental variables. Whereas much has been done in recent years to improve our understanding of the mechanisms behind the temporal distribution of black shales in the Phanerozoic, the interpretation of the palaeogeographical distribution of black shales is still dominated by an oversimplistic set of three uniformitarian depositional models that do not capture the complexity and dynamics of environments of black shale accumulation. These three models, the restricted circulation, the (open) ocean oxygen minimum and the continental shelf models, are in fact a uniformitarian simplification of the variety of depositional environments that arise and coexist throughout the course of a basin's Wilson Cycle, i.e. the dynamic sequence of events and stages that characterise the evolution of an ocean basin, from the opening continental rift to the closing orogeny. We examine the spatial distribution of black shales in the context of the Wilson Cycle using examples from the Phanerozoic. It is shown that the geographical distribution of black shales, their position in the basin infill sequence and their nature (e.g. type of organic matter, lithology) depend on basin evolution because the latter controls the development of sedimentary environments where black shales may be deposited.

## 1 Introduction

"Black shale" is commonly used in the geological literature as a moniker for a variety of fine-grained organic matter-rich lithologies deposited in a broad swathe of sedimentary environments from lakes to deep sea (Arthur, 1979; Jenkyns, 1980; Waples, 1983; Bohacs et al., 2000; Tyson, 2005). Black shales can be deposited by any one or combination of processes that control fine-grained sedimentation: pelagic settling, hemipelagic deposition, hemiturbiditic and contouritic sedimentation, turbidity currents, hyperpycnal and debris flows, slides and slumps (Stow et al., 2001). Even though fine-grained sedimentary rocks are the most ubiquitous component of the geological

J. Trabucho-Alexandre
et al.

record (Potter et al., 1980), the distribution of black shales in the Phanerozoic is mainly limited to six stratigraphic intervals (Fig. 1), which together represent about one-third of Phanerozoic time (Klemme and Ulmishek, 1991). The petroleum source rocks in these intervals have provided more than 90 % of the world's known reserves of hydrocarbons (Tissot, 1979; Klemme and Ulmishek, 1991). The spatial and temporal distribution of black shales, a key factor controlling the occurrence of petroleum (White, 1993; Otis and Schneidermann, 1997), is related to the development of environments in which black shales may accumulate and to a propitious combination of environmental variables: organic productivity, subsequent preservation of organic matter and appropriate sedimentation rates (Katz, 2005; Tyson, 2005). The preservation of organic matter is, in turn, dependent on several (partly) independent and interacting variables such as organic matter type, sea water oxygenation, burial rates, natural vulcanisation processes and sediment grain size (Stow et al., 2001).

The interpretation of ancient environments in which black shales were deposited is commonly made in terms of uniformitarian depositional models. Traditionally, three models are used to summarise the range of environments in which black shales can accumulate: the restricted circulation, the open ocean (oxygen minimum), and the continental shelf models (Didyk et al., 1978; Tourtelot, 1979). These depositional models, it will be argued, are a simplification of specific intervals of the Wilson Cycle, i.e. the plate tectonic process of ocean formation and closure (Dewey and Burke, 1974). J. Tuzo Wilson's concept that ocean basins are dynamic entities provides a framework upon which the tendency of certain sediment types to be clustered in geological time, i.e. associated with specific stages in basin development, can be interpreted. Furthermore, it provides a comprehensive model for the development in time of environments of black shale deposition from lacustrine environments in a continental rift through large continental shelves of an expanding ocean basin and upwelling zones along convergent continental margins to the seafloor of foreland basins. It includes and builds upon the three traditional depositional models and places them in a dynamic plate tectonic context.

We apply Wilson's remarkable idea that ocean basins have a life cycle and that "each stage has its own characteristic rock types and structures" (Wilson, 1968) to Phanerozoic black shales. The existing depositional models for black shales are expanded to include environments at all stages of the Wilson Cycle. Whilst each basin has its
5   own tectonic history, that may be more or less complex, the evolution of their depositional environments is mostly similar. Examples from different time intervals in the Phanerozoic (Klemme and Ulmishek, 1991) illustrate how basin development controls the distribution of black shales in time and space, and their characteristics. The resulting models represent a comprehensive and dynamic view of ancient environments of
10  black shale accumulation; therefore, they are probably more useful in the interpretation of black shales than the existing three models in isolation.

## 2   The Wilson Cycle as a comprehensive depositional model for Phanerozoic black shales

Prior to the 1960s plate tectonics revolution, the Earth was mainly regarded as a "rigid,
15  stable body whose surface features ha[d] evolved slowly by processes [one could] see in action [at present]" (Wilson, 1968). Nowadays, it is amply acknowledged that the transition from intracontinental rift to ocean basin (Fig. 2a–f) occurred repeatedly since at least the Late Archaean (Kearey et al., 2009). The former existence of ancient oceans is implied by continental reconstructions and by fragments of ancient oceanic
20  crust preserved as ophiolites in orogenic belts.

Wilson described the life cycle of ocean basins (Fig. 2a–f) and noted that each stage is associated with particular rock types and structures (Wilson, 1966, 1968). However, he did not mention black shales. Black shales, the product of an optimal combination of production, concentration and preservation of organic matter (Bohacs et al.,
25  2000; Tyson, 2005), have been deposited in a variety of subaqueous environments, including, but not limited to: (i) lakes and shallow epicontinental seas in continental rift settings (Fig. 2a, b), (ii) shallow epicontinental seas on flooded landmasses during

**Phanerozoic black shales and the Wilson Cycle**

J. Trabucho-Alexandre et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

transgressions and eustatic highstands (Fig. 2c), (iii) shallow pericontinental seas, particularly on the outer shelf, in association with transgressions and upwelling (Fig. 2c), (iv) the mesopelagic to upper bathyal portion of the continental slope and seamounts associated with the impingement of the oxygen minimum layer (cf. Wyrtki, 1962) on the seafloor often in association with upwelling of nutrient-rich waters and (v) deep seafloor of basins as a result of transport by turbidity currents.

Three uniformitarian depositional models, based on modern analogues, are traditionally used to summarise the range of environments in which black shales can accumulate: the restricted circulation model, the open ocean model and the continental shelf model (Didyk et al., 1978; Tourtelot, 1979). The "restricted circulation model" is the oldest conception of how black shales are formed and arose from early study of the Black Sea by authors who envisaged it as a modern analogue for ancient environments of black shale deposition (Pompeckj, 1901). It has greatly influenced geological thinking on the subject of organic matter-rich sedimentation. Ironically, it is probably the least useful of the three because it imposes such extreme requirements on the deposition of black shales that the Black Sea is probably only a good analogue for the Black Sea (cf. Tyson, 2005). It is more useful to adapt this model and rename it "restricted *basin* model". This derivation of the traditional "restricted *circulation* model" retains the restricted physiography of the basin and its large depth-to-width ratio, but sheds the *requirement* that circulation be sluggish. Thus, basins that share such physical characteristics, but are not necessarily characterised by stably stratified water masses or by a euxinic water column, fall within this model. As a consequence, the Mediterranean falls within the "restricted *basin* model". The open ocean model includes many different environments the only point in common being the location in an ocean. Therefore, this model is an oversimplification of the variety of environments and processes that lead to an enrichment of organic matter in marine sediments. Furthermore, some ancient environments of black shale deposition in the open ocean, e.g. submarine seamounts under upwelling zones (Tourtelot, 1979; White, 1979), are absent in the modern ocean. Modern shelves are fairly unique in geological history, being the product of the fast sea

**Phanerozoic black shales and the Wilson Cycle**

J. Trabucho-Alexandre et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Phanerozoic black shales and the Wilson Cycle**

J. Trabucho-Alexandre et al.

Printer-friendly Version

Interactive Discussion

level rise after the last ice age. The continental shelf model, which is the least uniformitarian of the three, is commonly interpreted invoking nonuniformitarian shelf processes (e.g. permanent stable stratification of the water column over the shelf and the absence of bottom currents). However, whereas many depositional environments are nonuni-
5   formitarian simply because they are absent in the present-day tectonic configuration, exogenic processes – at least in the Phanerozoic – are in all likelihood uniformitarian. Moreover, marine environments on continental crust are not limited to ancient pericontinental shelf and extensive epicontinental seas, but have included flooded continental rifts and pericontinental shelves of varying areal extent (Bradley, 2008).
10   The problem of a uniformitarian interpretation of black shale deposition is that it limits the choice of analogue environments of black shale deposition to those available in the present-day tectono-geographical configuration. The realisation of this "no-analogue" problem is not new (Arthur and Sageman, 1994), and it is widely acknowledged that the extensive ancient epicontinental seas have no equivalent in the modern world. In spite
15   of this realisation, the interpretation of ancient black shale depositional environments has not been subject to critical reevaluation, and the three traditional depositional models are still commonly invoked to explain black shale successions.

Correlations have been proposed between the supercontinent cycle, superplume events, black shale deposition and other geological anomalies (e.g. Sheridan, 1987;
20   Larson, 1991; Sinton and Duncan, 1997; Kerr, 1998; Condie, 2004; Katz et al., 2005). These studies represent major leaps forward in our understanding of the temporal distribution of Phanerozoic black shales. They provide possible answers to the stratigraphic clustering of black shales in specific stratigraphic intervals of the Phanerozoic (Klemme and Ulmishek, 1991). Here, we describe a relation between ocean basin
25   development and black shale deposition, i.e. between the Wilson Cycle and organic matter-rich sedimentation (Table 1), contributing to an improved understanding of the temporal and geographical distribution of black shales and the variety of environments in which they form.

## 2.1 Continental rift

Continental rifting is the earliest stage in ocean basin formation (Fig. 2a). During the continental rift phase sedimentation in the basin is mostly terrestrial. Lakes may be created in depressions along the rift axis, and such lakes can be very deep and al-
⁵ kaline (e.g. East African Rift lakes). Sedimentation in lacustrine systems is extremely sensitive to climate (Bohacs et al., 2000). If winter temperatures do not reach freezing, the bottoms of these lakes are typically oxygen deficient, and, on their bottom, organic matter-rich, anoxic mud can accumulate. The Lower Permian Whitehill Formation (South Africa) contains lacustrine black shales with oil-prone kerogens that are
¹⁰ believed to originate from the accumulation of freshwater algae under anoxic, fresh to brackish water conditions in a protorift basin in southwestern Gondwana (Faure and Cole, 1999). Occasional marine incursions allowed sulphate reduction and pyrite deposition in these environments (Peters et al., 2005). Carboniferous lacustrine shales have also been deposited in the final stages of a synrift sequence of East Greenland
¹⁵ (Ziegler, 1988; Stemmerik et al., 1990). The oldest Mesozoic source rocks in the South Atlantic are probably those in the North Falkland Basin (Richards and Hillier, 2000): early synrift fluvial and lacustrine rocks (cf. Caroll and Bohacs, 1999), which are relatively organic matter-rich even though the organic matter is poorly preserved, and late synrift lacustrine deposits, which are more organic matter-rich and reflect the transition
²⁰ from marginal marine to fully open-marine conditions (Peters et al., 2005).

As the rift matures, intrusion of seawater into the fracture system may occur (Fig. 2b), and, depending on regional climate, evaporitic or restricted marine sedimentation takes place in the flooded continental rift (Hay, 1981; Hay et al., 1981). Even though emphasis is given here to first-order tectonic controls on sedimentation, the role of regional
²⁵ climate must not be downplayed. Regional climate is primarily defined by zonal climate belts, and, in the course of Earth's history, basins migrated through these belts leading to changes in their sedimentation patterns (Brongersma-Sanders, 1971; Wilde et al., 1997; Berry, 2010). Together with eustasy and tectonics, climate is a major allocyclic control on sediment supply and sedimentation (Cecil, 2003).

**Phanerozoic black shales and the Wilson Cycle**

J. Trabucho-Alexandre et al.

Marine deposits in flooded continental rift settings may alternate with marginal terrigenous material transported by turbidity currents towards the basin centre. In proximal settings of the graben, where fan deltas build out, black shale formation will in general be suppressed as dilution inhibits organic enrichment of the sediments. However, in sediment-starved settings associated with rapid differential subsidence and arid or geomorphologically subdued hinterlands (Ravnås and Steel, 1998), or associated with rift shoulder morphologies conducive to sediment transport away from the basin, the deposition of source rocks with type I/II kerogens may occur if water depth, connectivity with the open ocean and regional climate favour estuarine circulation (Fig. 2b), which brings nutrients into the epicontinental basin. Examples of black shale accumulation due to invasion of a continental rift by marine waters are abundant, and these black shales are commonly excellent source rocks. The Permian Kupferschiefer of northern Europe, for instance, was deposited during active block faulting and the initial stages of marine transgression in relatively shallow water depth (Brongersma-Sanders, 1965), after which salt was deposited. The Toarcian and the Kimmeridgian of the North Sea area, an aulacogen where no oceanic crust was generated, are good examples of unusually organic matter-rich marine black shales deposited in a continental rift setting. Toarcian and Kimmeridgian black shales are found in onshore, gentle sags, e.g. the Cleveland Basin (Powell, 2010), and offshore in deeper (ca. 100 m) grabens, e.g. the Central Graben and the Dutch Central Graben. These grabens are subbasins created by crustal extension within the epicontinental shelf sea wherein the preservation of organic material was favoured. In the Far East, after widespread Palaeogene rifting with corresponding terrestrial sedimentation, an Early Miocene transgressive pulse flooded the rift basins: Oligocene black shales were mainly deposited in lacustrine and fluviolacustrine environments within the rift basins and contain oil-prone kerogens (e.g. offshore Vietnam), whereas Miocene black shales are gas-prone and were deposited in deltaic facies built out over continental margins (Petersen et al., 2001; Peters et al., 2005).

Lakes in continental rift settings may be regarded as a special case of the "restricted basin model" of black shale deposition. However, as Bohacs et al. (2000) noted, lakes differ from marine basins in several important ways therefore making it inappropriate to apply one unmodified model to all restricted basin systems. Shallow epicontinental seas in continental rift settings may be regarded as a "restricted basin" and also as a "continental shelf". Both depositional models may contain processes capable of explaining a number of characteristics of black shales deposited in these settings. However, they are probably best interpreted as a specific type of environmental setting separate of other also shallow and restricted settings.

## 2.2 Juvenile spreading centre and expanding ocean

Continued extension results in juvenile oceanic spreading centres. During the early, sediment-starved stages of this phase, shelves are underdeveloped as some time is required for the development of drainage networks and the accumulation of marginal strata (Ravnås and Steel, 1998; Bradley, 2008). Offshore, the shallow, young basin will experience black shale deposition if environmental conditions are favourable (a positive water balance, for instance), while, if the conditions are warm and arid, evaporite and carbonate deposition dominate the facies association (Hay, 1981). This black shale accumulation setting is similar to that previously described for a flooded continental rift. Marine black shales deposited under conditions of restricted water circulation (Zimmerman et al., 1987) were formed when Gondwana pulled apart during the Late Jurassic and accommodation increased episodically along the rift axis. A series of lakes (Fig. 2a) formed that gave rise to source rocks in both West Africa and Brazil (Peters et al., 2005). Clastic deposition became dominant during the Cenomanian as the basins between the South Atlantic continental masses deepened with increasing plate separation. The conditions that favoured black shale deposition were maintained until the Late Cretaceous when continued spreading led to the establishment of a deep connection with the North Atlantic allowing meridional circulation of ocean water and

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

the ventilation of bottom waters in both basins (van Andel et al., 1977; Topper et al., 2011).

As seafloor spreading results in an expanding ocean, the basin changes from a narrow, landlocked state to a more open ocean state (Fig. 2c). In general, landlocked basins have a more terrigenous character than more open basins and hence neritic black shales deposited during the early stages of this phase are typically land-sourced and hence more gas-prone, whereas black shales deposited during later stages are more pelagic algal sourced and oil-prone. Palaeogeography and regional climate impose a second order control on the nature of the sediments deposited in a basin. The two end-members may occur concomitantly in a single basin such as, for instance, in the mid-Cretaceous North Atlantic (Tissot et al., 1980; Summerhayes, 1981), with gas-prone western and oil-prone southern and eastern margins.

As the basin deepens, black shale deposition transits from the bottom of the basin, previously relatively shallow, onto the seafloor of the growing continental shelves. The reason behind this relocation of black shale formation is related to the increasing transit paths to the seafloor as water depths increase in the expanding and subsiding basin as well as to the increasing volume of subthermocline water. Anoxia in the open ocean is unlikely due to the large mass of subthermocline water (Wignall and Newton, 2001). Overturning circulation, largely driven by extremes of surface temperature and salinity, and stirring by wind and tides (e.g. Ledwell et al., 2000), promotes an effective ventilation of the entire water column, and, in combination with the long settling times of particulate material from the euphotic zone to the seafloor, preservation of organic matter is very low. Nevertheless, slope instability processes, especially in organic matter-rich successions where diagenetic gas generation within slope sediments is an additional factor, may promote the transfer of part of the organic matter-rich sediments towards deeper, more distal settings where they are preserved as fine-grained, organic matter-rich turbidites (Degens et al., 1986; Stow et al., 2001). Examples of such turbidites may be found as deep sea Cretaceous black shales in the northern North Atlantic (e.g. ODP Site 1276) (Trabucho Alexandre et al., 2011) and in the Mariana Basin in the Pacific

**Phanerozoic black shales and the Wilson Cycle**

J. Trabucho-Alexandre et al.

Ocean (DSDP Site 585) (Whitman et al., 1985; Premoli Silva and Sliter, 1986).

Rapid sinking of the margins and the drowning of topography generally follow the early, sediment-starved stage. As the rift margins cool and subside, a large volume of sediment is eroded from areas peripheral to the rift. These sediments are deposited on the margins forming a buildup of thick seaward-prograding sediment wedges resulting in the shelf, slope and rise submarine topography characteristic of mature passive margins. As terrigenous sediment input increases, dilution overrides black shale development until the shelves have become more mature and a decrease in sediment supply occurs or, alternatively, until a rise in base level occurs. In the latter case, the base of the transgressive systems tract will typically be organic matter-rich above the transgressive ravinement surface in more offshore shelf settings and, with continued sea level rise, the maximum flooding surface may also be typified by black shale deposition (cf. Wignall, 1994). Gas-prone black shales may be deposited during the prograding stage of passive margins in paralic environments of siliciclastic coasts – such as deltas – without the requirements presented above for oil-prone, neritic black shales. It should be noted that sediment supply to the shelf is not evenly distributed but consists rather of a series of point sources (i.e. the river mouths) which can fill in a local area of the shelf whilst most of the shelf remains sediment starved (Hay and Southam, 1977; Hay, 1981). Once the local area is filled in, or if base level is lowered, discharge may occur over the shelf break, as is the case of the present-day Mississippi.

Sea level oscillations, which are also related to climate, exert an important control on marine sedimentation because the presence, size and distribution of marine subenvironments depends on sea level and also because the distribution of sedimentary facies in the marine realm is partly controlled by sea level stand, especially at shallow water depths where sea level oscillations have the greatest effect. At present, most export production is concentrated along the continental margins (Walsh, 1991; Laws et al., 2000), where up to 90 % of organic carbon burial takes place (Hedges and Keil, 1995). Black shale deposition is thus expected to be favoured when extensive shelves surround and extend into the (Fig. 2c) continental masses (Potter et al., 1980; Mann et al.,

**Phanerozoic black shales and the Wilson Cycle**

J. Trabucho-Alexandre et al.

Title Page

| Abstract | Introduction |
| Conclusions | References |
| Tables | Figures |

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Phanerozoic black shales and the Wilson Cycle**

J. Trabucho-Alexandre et al.

2003). Such a scenario is associated with supercontinent breakup and the onset of the Wilson Cycle because newly formed oceanic crust is thermally buoyant and hence the global ocean basin volume decreases leading to transgressive pulses (e.g. Hays and Pitman, 1973; Pitman, 1978; Cogné et al., 2006).

Widespread black shale deposition in the Cretaceous is a reflection of the opening of modern ocean basins and the maturation of their passive margins as well as a consequence of the mid-Cretaceous superplume and eustatic sea level high (e.g. Larson, 1991). In the mid-Cretaceous, extensive epicontinental seas along the Tethyan seaway and the pericontinental seas on the young continental shelves of the North and South Atlantic experienced significant organic matter-rich sedimentation (van Andel et al., 1977; Kuhnt and Wiedmann, 1995; Lüning et al., 2004; Emeis and Weissert, 2009). The nature of the organic matter depended on palaeogeographical setting. In general, marine organic matter is restricted to sequences of the southern North Atlantic and the margins of the adjacent Western Tethys and becomes more widespread in the uppermost Cenomanian/Turonian (Tissot et al., 1980; Summerhayes, 1981; Kuhnt and Wiedmann, 1995). In the North Atlantic, pre-Cenomanian rocks typically have low TOC (<1 %) dominated by terrigenous plant debris. During the Cenomanian, organic matter richness increased and reached a maximum near the Cenomanian/Turonian boundary (Oceanic Anoxic Event 2) with TOC up to 40 %. These organic matter-rich rocks commonly represent three different depositional settings: shelf shales and marls, continental margin marls and deep water shales and organic matter-rich silt- and sand-stones (turbidites). Organic matter-rich sedimentation persisted beyond the Cenomanian/Turonian at certain shelf localities, e.g. northern South America, due to the estuarine circulation and upwelling (Trabucho Alexandre et al., 2010). Black shale deposition in the rest of the basin was discontinued after the opening of the Equatorial Atlantic Seaway to deep water circulation (Topper et al., 2011).

Several environments of black shale accumulation are associated with an expanding ocean. The most important are those located on epi- and pericontinental shelves. Even though both may be summarised by the traditional "continental shelf model",

the processes that lead to black shale formation in these environments and the geo-graphical extent of organic matter-rich facies and their marine or terrigenous character, amongst other characteristics, (partly) depend on tectonic setting. Accumulation of organic matter-rich sediments on the deep seafloor, commonly related to resedimen-tation processes transporting shelf and slope material to the deep sea (Degens et al., 1986; Stow et al., 2001), is related to the early stages of ocean basin opening and does not fall under any of the three existing depositional models – lthough the presence of these resedimented materials is sometimes erroneously interpreted in the light of the "restricted circulation model".

## 2.3 Mature ocean basin and closure

Widespread black shale deposition is not favoured in mature ocean basins because their thermally subsided seafloor is very deep and their active continental margins (shelves) very narrow (Fig. 2d). Furthermore, during agglomeration of continental masses, i.e. the late stages of the Wilson Cycle, less submarine volcanism occurs and sea level falls; consequently, fewer nutrients are added to the system. Moreover, due to a reduced surface area of shelf seas, the dissipation of tidal energy in the open ocean increases with consequent improved vertical mixing (de Boer and Trabucho Alexan-dre, 2011). Therefore, the development of organic matter-rich sediments is inhibited. Nevertheless, black shales may still be deposited under regions of enhanced upwelling, such as the eastern margins of the basin (e.g. present-day Peru), or in silled marginal basins (e.g. Gulf of California). Coastlines with upwelling tend to be arid (Brongersma-Sanders, 1971); the lack of vegetation on land reinforces the oil-prone character of black shales deposited on continental shelves under zones of intense upwelling. Arid-ity limits the dilution of the organic matter by terrigenous material while at the same time stimulating productivity by aeolian fertilisation of the euphotic zone (e.g. Jickells et al., 2005). Silurian black shales deposited on the southern passive margin of the Rheic Ocean (North Africa and Middle East) consist of graptolitic shales with abundant or-ganic matter related to blooms of marine prasinophytes (Tyson, 1994). The deposition

of these shales took place during a high sea level stand in a mature ocean basin with wide shelves located at 45–55° S under an upwelling zone (Parrish, 1982; Tissot et al., 1984; Klemme and Ulmishek, 1991; Lüning et al., 2000; Peters et al., 2005; Cramer and Saltzman, 2007). Late Devonian algal-rich black shales, which were deposited at
5 high southern latitudes along the western margin of Gondwana (Brazil and Bolivia) under an upwelling zone, are a further example of black shale deposition on the margins of a mature ocean basin.

The terminal stages of the Wilson Cycle are characterised by significant constriction of the basin, which becomes a landlocked marginal basin (Fig. 2d). During this phase,
10 black shales may be deposited as a consequence of estuarine circulation patterns (Brongersma-Sanders, 1971) which, in turn, depend on the location of the basin with respect to zonal climate belts. Examples of this type of black shale development are the Neogene Mediterranean sapropels and the Holocene Black Sea. Examples of black shales deposited in marginal basins include the San Joaquin and offshore California
15 and Caspian basins. These basins contain thick, dominantly marine diatomaceous source rocks of Miocene age, which was the last Phanerozoic interval of major source rock deposition (Peters et al., 2005). Black shale deposition on the margins of the narrow, closing Iapetus Ocean (Europe; Fig. 2e) took place at tropical latitudes on a drowned carbonate shelf (Leggett, 1978; Klemme and Ulmishek, 1991).
20 The final stages in the Wilson Cycle, i.e. subduction, closure of an ocean basin and orogeny, lead to the creation of foreland basins. When mountains are built through the closure of an ocean basin, tectonic loading of the crust during incremental growth of the orogen leads to the creation of accommodation space on both sides of the orogen (Ettensohn, 2008). Accommodation space creation is initially very rapid, and shal-
25 low transgressive seas move across the basin. However, because no major subaerial source of sediment is available to fill the basin, sediment starvation characterises the initial stages of foreland basins. Mud and organic matter in the water column comprise the main sediment input and accumulate as black shales on the basin floor. This situation is typical of retroarc foreland basins (e.g. Appalachian Basin), which are floored by

**Phanerozoic black shales and the Wilson Cycle**

J. Trabucho-Alexandre et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◀ | ▶|

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

J. Trabucho-Alexandre et al.

continental crust. Black shales deposited during the Devonian and Permian in basins west of the Appalachian Mountains (Ettensohn, 2008) reflect deposition in a foreland basin (Fig. 2e) during the closure of the Iapetus and Rheic oceans. As subaerial relief is formed, however, black shales are no longer developed due to increased dilution by coarse siliciclastic sediments. Peripheral foreland basins, which are located on the plate margin being consumed, have a different situation and receive large volumes of clastic sediment that form thick, flysch-like sequences.

## 3 Conclusions

Sedimentation is intimately associated with basin development. Wilson, a pioneer in the development of the Theory of Plate Tectonics, noted that each stage in ocean basin development has its own characteristic rock types. Ancient black shales, which are the source rocks for most of the world's known oil reserves, were deposited at various stages of the Wilson Cycle. Even though black shales may be deposited in different environments at any stage of the Wilson Cycle, their petrological characteristics and the processes that have led to their formation vary considerably. Indeed, the term "black shale" is useful when referring to organic matter-rich sedimentary rocks in general, but it should not be forgotten that it is a collective noun grouping rocks with very different origins. The spatial distribution of black shales is controlled by climate, oceanography and basin evolution, the latter controlling the development of sedimentary environments in which black shales may accumulate. Furthermore, tectonic setting (partly) controls the type of black shale, their stratigraphic and geographical extent and their position in the basin infill sequence. Correlation of coeval "black shales" without taking into account their sedimentological characteristics and the local processes that led to their formation is likely to lead to unsound palaeoenvironmental interpretations.

Conceptual models and modern analogues help make the interpretation of ancient black shale successions possible. However, uniformitarian, oversimplified models actually present a barrier to the interpretation of the environments of black shale

accumulation because they are commonly simple, static, oceanographical models that do not take into account two very important variables: (i) the tectonic setting and evolution of a basin and (ii) changing regional climate due to lithospheric plate migration. A successful interpretation of ancient environments of black shale accumulation must have its foundations on these two variables upon which oceanographical interpretations can then be superimposed. Understanding why black shales were more widespread during specific time intervals in the Phanerozoic is very important. However, the fact that black shales are coeval does not mean that similar processes produced them or that depositional environments were similar; rather, each black shale should be interpreted individually after which a meaningful correlation in terms of processes may be achieved.

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**Phanerozoic black shales and the Wilson Cycle**

J. Trabucho-Alexandre et al.

Title Page

| Abstract | Introduction |
| Conclusions | References |
| Tables | Figures |

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Phanerozoic black shales and the Wilson Cycle

J. Trabucho-Alexandre et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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**Phanerozoic black shales and the Wilson Cycle**

J. Trabucho-Alexandre et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Mineral deposits: research and exploration, where do they meet?, edited by: Papunen, H. and Balkema, A. A., Rotterdam, 125–128, 1997.

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**Phanerozoic black shales and the Wilson Cycle**

J. Trabucho-Alexandre et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄◄ | ►►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Phanerozoic black shales and the Wilson Cycle**

J. Trabucho-Alexandre et al.

**Table 1.** Summary of black shale occurrence with respect to Wilson Cycle stages and their respective depositional environments.

| Wilson stage | | Example | Processes | Environments | Black shales |
|---|---|---|---|---|---|
| Continental rift | Terrestrial | East African rift | Crustal thinning, uplift | Alluvial, lakes | Lacustrine |
| | Flooded | Aegean Sea | As above, seawater intrusion | Restricted shallow marine, fan deltas | Shallow marine |
| Juvenile basin | | Red Sea | Spreading, uplift | Small shelves, shallow seafloor | If estuarine |
| Mature ocean | Opening | Atlantic Ocean | Spreading | Extensive shelves, deep seafloor | Shelf |
| | Closing | Pacific Ocean | Spreading, subduction | Narrow shelves, very deep seafloor | Upwelling zones |
| Volcanic arc | | Western Pacific Ocean | Subduction, volcanism | Backarc basin, abyssal seafloor | No |
| Terminal | | Mediterranean Sea | Compression, uplift | Marginal basin | If estuarine |
| Foreland basin | Peripheral | Persian Gulf | Lithospheric flexure, subsidence | Marginal basin | Fluvio-deltaic, shallow marine |
| | Retroarc | Andean Basins | | Marginal basin | Fluvio-deltaic, shallow marine |
| Orogen | | Himalaya | Compression, uplift | Alluvial | No |
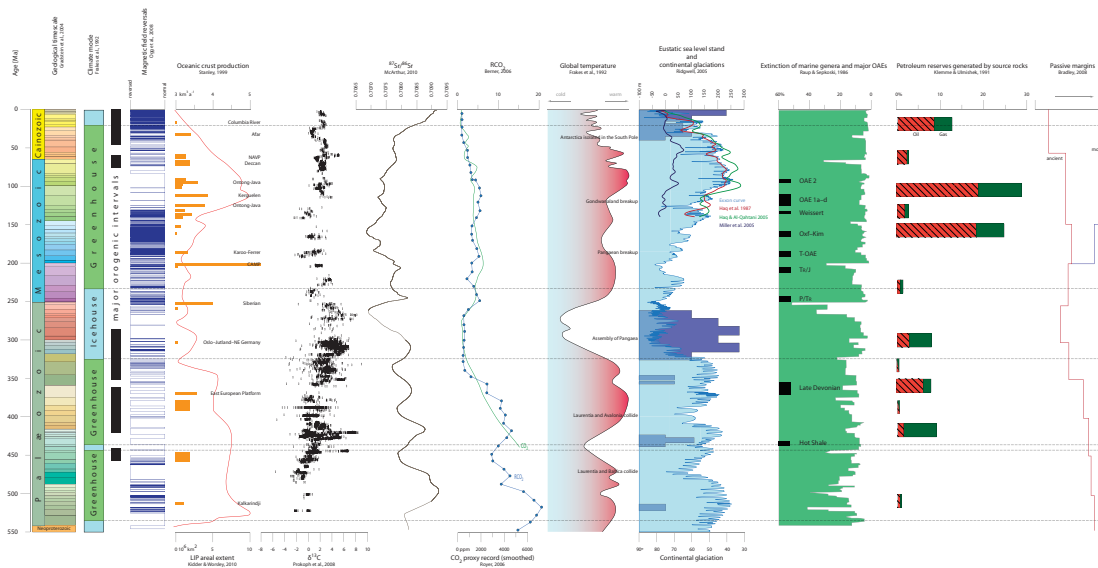
**Fig. 1.** Phanerozoic patterns of various indicators of global change. From left to right: Phanerozoic geological timescale (Gradstein et al., 2004), climate mode (Frakes et al., 1992), major orogenic intervals, magnetic field reversals (Ogg et al., 2008), oceanic crust production (Stanley, 1999) and LIP aereal extent (Kidder and Worsley, 2010), carbon isotope curve (Prokoph et al., 2008), strontium isotope curve (McArthur, 2010), $RCO_2$ and $CO_2$ proxy record (Berner, 2006; Royer, 2006), global temperature (Frakes et al., 1992), eustatic sea level stand (Exxon curve; Haq et al., 1987; Haq and Al-Qahtani, 2005; Miller et al., 2005), continental glaciations (Ridgwell, 2005), extinction of marine genera and major oceanic anoxic events (OAEs) (Raup and Sepkoski, 1986), petroleum reserves generated by source rocks (Klemme and Ulmishek, 1991), and passive margin extension (Bradley, 2008).
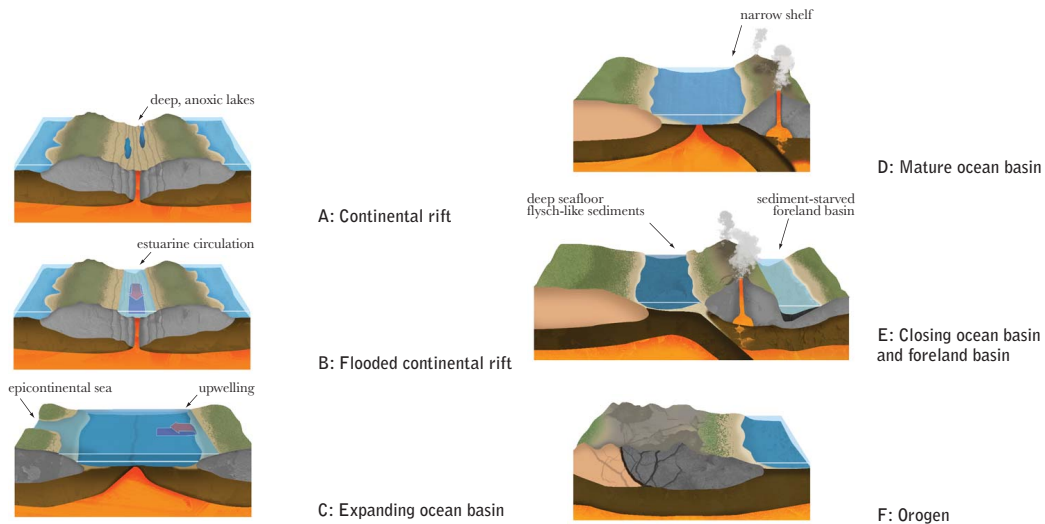
**Fig. 2.** Schematic overview of the Wilson Cycle. The different blocks show a schematic overview of the development and closure of an ocean basin. Annotations refer to environments where black shales may accumulate and to processes that intervene in the formation of black shales.