The Accumulation of Organic-Matter-Rich Rocks within an Earth Systems Framework: the integrated roles of Plate Tectonics, Atmosphere, Ocean, and Biota through the Phanerozoic

Kevin M. Bohacs, Ian O. Norton
ExxonMobil Upstream Research Company
3120 Buffalo Speedway
Houston, Texas 77096, U.S.A.

Debbie Gilbert, Jack E. Neal, Martin Kennedy*, Walter Borkowski, Marcia Rottman, and Tracy Burke
ExxonMobil Exploration Company
233 Benmar Street
Houston, Texas 77060, U.S.A.

(* presently at: Department of Earth Science, University of California, Riverside, 900 University Avenue, Riverside, CA 92521)

Summary

Fundamental concepts of plate tectonics, paleogeography, ecology, and atmospheric and oceanic circulation can be used in conjunction with models of source-rock deposition to understand the location and character of organic-matter-rich rocks (ORR) at global to regional scales. Ocean and atmosphere circulation patterns directly impact processes governing organic-carbon production and preservation. One can convolve these patterns with paleogeographic reconstructions and make predictions of ORR occurrence and character at global to regional scales.

The accumulation and character of organic material in sedimentary strata results from complex interactions among physical, chemical, and biological processes (e.g., Tyson, 1995; Bohacs et al., 2005). In the modern ocean, organic carbon arrives in continental margin settings via three main pathways: 1) particulate organic material derived from biological production in surface waters, 2) advection of land-derived detrital organic material, and 3) adsorbed organic compounds on clay mineral surfaces. Modern oceanic production (Figure 1a) and total organic carbon (TOC) distribution (Figure 1b) maps indicate that organic material (OM) is not randomly distributed across the ocean floor, but varies as a function of continental configuration and marine depositional setting relative to global wind and ocean circulation patterns. The systematics of the distribution of organic-matter-rich sediments in the modern ocean provides a basis for prediction of analogous strata in the past. One must, however, exercise caution in these predictions and clearly differentiate essential processes that function throughout geological history from accidental combinations in modern environments.

Summaries of ORR occurrence through time (e.g., Katz, 1990; Ulmishek and Klemme, 1990; Neruchev, 1995) indicate the influence of various scales of factors on ORR accumulation. Typical factors cited include geologic age, paleolatitude, tectonic setting, and biotic evolution (e.g., Ulmishek and Klemme, 1990). We here illustrate an approach, integrated across global to sub-basin scales, to understanding and predicting the occurrence, distribution, and character of ORRs.

At the global scale, the three ultimate controls are plate tectonics, solar input, and biological activity. These controls are not completely independent, especially in how they interact at the scale of derivative intermediate controls, such as climate distribution, circulation of atmosphere and oceans, accommodation change, global sea level, and evolution of landscapes and bathymetry (see Figure 2). It is these derivative controls that combine at the local scale to influence directly the proximate controls of production, destruction, dilution, and accommodation on significant accumulation of ORRs. The ultimate accumulation of a particular ORR is, however, always the result of a contingent combination of various scales of factors because of the fundamentally non-linear nature of the

system— sensitively dependant on global and extrabasinal boundary conditions and teleconnections through the atmosphere and ocean as well as the particular local biota. For example, the large-scale accumulations of diatomaceous ORRs around the Pacific Ocean in the Miocene (Monterey Fm, California; Opoka, Russian Far East; Onnagawa Fm, Japan) were influenced by the evolution of diatoms as a dominant planktonic producer, the large-scale oceanic circulation patterns that resulted from the interaction of developing ice sheets and the closing Tethyan Ocean and opening Southern Ocean, water mass evolution and silica budget, and by local basin bathymetry and topography interacting with oceanic and atmospheric circulation to control nutrient and clastic fluxes (e.g., White et al, 1992; Isaacs, 2001; Bohacs et al., 2005).

  We start our discussion with plate tectonic evolution through the Phanerozoic, then address proximate causes of production, destruction, and dilution of organic matter, and finally examine how the larger scale controls affect the local scene.

PLATE RECONSTRUCTIONS

  This chapter presents a series of plate reconstructions for eight Phanerozoic times to demonstrate the occurrence of organic-matter-rich rocks within a paleo-environmental framework. Times were selected based on important tectonic or paleogeographic events. These reconstructions were developed at ExxonMobil over a period of years as part of a series of regional studies that covered most of the globe. They represent our 'global plate model'. Plate reconstructions are constrained by several forms of data. These data, in order of decreasing accuracy, are:

  1) Constraints from plate boundaries. The most useful set of data comes from sea-floor magnetic lineations and fracture zones. These features are produced when new sea floor is generated by sea floor spreading; see, for example, Kearey and Vine (1990), chapter 4. For plate reconstructions, magnetic lineations are used to constrain the age of sea floor. Matching identical age anomalies formed on either side of a spreading ridge, with motion direction constrained by fracture zones, provides the most accurate plate reconstruction possible. This technique also lends itself to statistical analysis so that this is one area of geology that can be very accurately quantified with error estimates (Hellinger, 1981; Kirkwood et al., 1999). There is no direct quantitative method for restoration of plate motion across subduction zones, so plate reconstructions that include subduction zone boundaries must rely on indirect methods. The azimuthal information available from earthquake fault-plane-solution techniques can be used to constrain present-day relative motion directions, at least (DeMets et al., 1990), but this cannot, of course, be used for anything but motions in the recent past. A more indirect approach for testing plate reconstructions is to use seismic tomography to infer locations of subducted plates. From these, it is possible to compare the amount of subducted plate implied by the plate model against the length of plate inferred from tomography. This has been successfully demonstrated for motion between the Farallon and North-American plates (Bunge and Grand, 2000) and for Tethyan regions (Hafkenscheid, 2004).

  2) Paleomagnetic data. For plate reconstructions involving plates without sea floor spreading magnetic lineations, paleomagnetic data provides the next-best quantitative constraint. The assumption here is that the Earth's field can be approximated by an axial dipole that has been stable with respect to the spin axis for all time. There have been many studies of this assumption and, although there is room for doubt, the balance of data favors a stable long-term dipole field. Another assumption is that paleomagnetic directions measured from a rock sample or samples gathered from a small area and covering a short interval of geologic time do actually record poles applicable to the whole plate from which the sample came. Only local geologic control can answer this question, but even with good control questions can remain. An example is ongoing debate about the polar wander path for North America in the Jurassic. This arises because Jurassic data comes from two areas, the Jurassic rifts of the eastern USA and from sedimentary basins in the southwestern US. Paleomagnetic poles from the two areas for similar ages do not agree. This is thought to be caused by local strain in the rift setting of the eastern samples and also by rotation of the Colorado Plateau in the southwestern USA relative to the rest of North America (Steiner, 2003). The paleomagnetic method is, however, the best constraint available for all reconstructions where no seafloor spreading data is

available, i.e. all reconstructions for times older than the Early Jurassic (age of the oldest ocean crust preserved today).

3) Without quantitative constraints provided by ocean spreading or paleomagnetic data, quantitative plate reconstructions become much worse. Climate bands provide more qualitative information on plate positions, with large error bars. For most Paleozoic reconstructions the method used is to constrain plate positions as far as possible with paleomagnetic data and then to make sure that the sequence of plate motions implied by the model makes geologic sense when compared with local data. This mostly consists of keeping track of relative plate motions—making sure there is convergence where subduction is known, divergence where there is rifting and quiescence where demanded.

All of the approaches above assume that one of the fundamental assumptions of plate tectonics, that of plate rigidity, is valid. For many plates, especially those under compression, the assumption is obviously not valid, as evidenced by ongoing deformation of Asia associated with the India collision (for more, see Gordon, this volume). For many large plates, however, the rigid-plate assumption has proved to be valid, especially for those that include oceanic crust. Any intraplate deformation is likely to produce mappable structures. The North Sea grabens, for instance, which record several Mesozoic rifting events in Baltica, are the result of about 25 kilometers of extension. This amount of internal strain is not detectable at the thousand-kilometer scale of the entire plate. On the other hand, it does show that even small amounts of strain produce large structures, so the lack of structures for many large plates implies that the rigid plate assumption is usually valid.

Some of the major deformation episodes for which there is a quantitative way to estimate regional strain are taken into account in this paper. These are:

a) Asian deformation implied by an Eocene India collision: The approach used here is to locate India relative to Asia at 48 Ma, the time of collision, using sea floor spreading data around a plate circuit from India-Madagascar to Africa-North America-Europe to Asia. The space left between India and Asia is then filled with retrodeformed India (600 km in the Himalaya) and the rest assigned to Asia. It is noteworthy that the huge amount of deformation implied for Asia is difficult to reconcile with observed deformation within Asia (Replumaz and Tapponnier, 2003). This question needs further research.

b) Deformation of the Mediterranean to Iran region impacted by the Miocene collision of Arabia: This includes the Caspian area, Turkey, and the Aegean, where compression between Arabia and Europe is accommodated by westward escape of Turkey into a southward-expanding Aegean.

c) Deformation of eastern Russia where the north end of the Atlantic-Arctic Ocean spreading system comes onshore. In this area, the Arctic ridge spreading is accommodated by extension in the Moma Rift area of Siberia then, further to the southeast, motion is accommodated by compression all the way to the Aleutian subduction zone.

d) Tertiary strike slip in the western USA and Canada is accomplished by large coast-parallel strike-slip faults. The southern end of these faults is a zone of extension that does not lend itself to rigid-body analysis. We end the strike-slip motion in a zone of distributed extension in Alaska.

e) Variscan deformation of Europe: Late Paleozoic amalgamation of Pangea was accommodated by extensive deformation. Accurate restoration of this deformation is not possible, but we can make estimates based on the work of Matte (1986). We have not attempted restoration of deformation between Africa and North America (the Appalachians) even though this probably amounted to several tens of kilometers of shortening.

Key Aspects of Individual Plate Reconstructions

Cambrian (500 Ma): This map portrays the oldest time for which we have some confidence in both the positions of the major plates and their basic outlines. Before this time, the Pan-African orogeny, the major orogeny that resulted from the assembly of Gondwana, was still active. We have little data to constrain how the blocks making up Gondwana were assembled.

Ordovician (450 Ma): Our interpretation of the location of Baltica, in the southern hemisphere in the Early Paleozoic, is derived from paleomagnetic data (Cocks and Torsvik, 2002). Siberia is located west of North America and moves around present-day Arctic Canada during the

rest of the Paleozoic before colliding with Baltica in the Carboniferous-Permian. This track of Siberia is consistent with paleomagnetic data from Didenko and Pechersky (1993). Placement of Siberia to the west of North America is an example of the paleolongitude uncertainty when constraining past plate positions with paleomagnetism. An equally valid location of Siberia would be to the east of North America, as used in many published reconstruction, e.g. Van der Voo, (1993). We chose the position to the west of North America so that, as Siberia moves past Arctic Canada through the Paleozoic, it can interact with Arctic Canada to produce the Paleozoic orogenies like the Ellesmerian that are found there.

Upper Devonian - Early Carboniferous (Frasnian – Famennian - Tournasian) (375 Ma): This is a transition time between general divergence of continental blocks seen in the Early Paleozoic and the collisional events that mark the Late Paleozoic. The first collision has already happened, suturing of Baltica to North America-Greenland ('Laurentia') in the Caledonian Orogeny. This is followed by suturing of Laurentia to Gondwana in the Variscan - Appalachian orogenies. Siberia and Kazakhstan are lining up for their eventual Late Carboniferous-Permian collision and the eastern Asian blocks are lining up for their eventual Permian through Mesozoic assembly. Gondwana is almost entirely in the southern hemisphere.

Late Permian (250 Ma): Orogenic events that culminated in formation of the supercontinent Pangea were completed during the Permian. By the Late Permian, a single land mass connected Siberia through Europe and North America to Gondwana, stretching almost from pole to pole. The Tethys was almost enclosed by Pangea and the still-separated East and Southeast Asia blocks. The Permian was a time of great climate change, from an icehouse with widespread glaciations to widespread greenhouse conditions in the Triassic (Kidder and Worsley, 2004). One of the greatest extinctions occurred close to the Permo-Triassic boundary, perhaps enhanced by end-Permian eruption of the Siberian Traps (Wignall, 2001).

Upper Jurassic - Callovian - Kimmeridgian (154 Ma): This map is also significant for source-rock deposition, this time in the North Atlantic from Norway through the North Sea to Newfoundland. There were several rifting events in the North Atlantic from Permian through to the final ocean-forming event in the Paleocene; the Kimmeridgian was the most economically significant for its source-rock accumulation. North America separated from Gondwana in the Early Jurassic, and the Kimmeridgian was the first time that marine waters penetrated north as far as Norway in a precursor to the future North Atlantic. In Gondwana, the first split occurred between West and East Gondwana in the Early Jurassic. Asia was seeing the end of the Indosinian Orogeny, with final amalgamation of the China blocks and Indochina with Asia. In our interpretation, this final event was a sinistral strike slip event with a large system of strike slip faults running from Tarim to eastern Mongolia, ending in the northeast at the Mongol-Okhostk suture.

Late Cretaceous - Cenomanian - Turonian (89 Ma): The Turonian was significant in the Atlantic for widespread deposition of ORRs that became the sources of several major hydrocarbon accumulations (e.g., offshore Angola, Congo). In the Tethyan realm, it was the time when India separated from Madagascar and began its northward trip that eventually resulted in the Asian collision (see Eocene map). This was also the time when a spreading system developed in the eastern Mediterranean and off northeast Arabia that was later (in the Campanian) obducted onto the Arabian margin. This obducted oceanic spreading system is preserved today in a string of ophiolites from Cyprus through Bayr Bazit, Neyrizh to Oman. There is not yet general agreement as to the precise mechanism of how this 4,000-km long belt of ophiolites was obducted—the disagreements hinge mainly on whether there was a fully developed island arc associated with the obduction.

Eocene (49 Ma): This time was selected as it is close to the commonly accepted time of initiation of the India-Asia collision. As mentioned previously, the amount of deformation of Asia and India was derived by using the position of India relative to Asia as derived from the oceanic data. From this, the intervening space was filled by restoring the northern edge of India (600 kilometers of Himalayan compression) and assigning the rest of the gap to Asian deformation. As can be seen, the amount of deformation implied for Asia is extremely large, and it is questionable whether there really has been such extreme compression of Asia. Replumaz and Tapponnier (2003) have investigated this deformation by back-tracking measured strike slip and palinspastically restoring Asia through time.

They found that it was possible to account for about the past 30 my of India-Asia motion with known strike slip faults, but that earlier retrodeformation was difficult to account for. There is still much to be understood about how India and Asia accommodated almost 50 million years of deformation since collision.

Present Day: A present-day plate map is shown for comparison with the other maps. It shows the main data used to constrain Jurassic to present plate reconstructions, namely oceanic magnetic lineations and fracture zones. It also labels such representative plate tectonic settings as passive margins, continental interiors, and so on.

With the plate-tectonic foundations in place, we now consider how they interact with the processes that control the accumulation of ORRs.

PROXIMATE CONTROLS ON ACCUMULATION OF ORGANIC MATTER

Organic matter content is influenced by four proximate controls: 1) primary production, 2) destruction of organic material, 3) dilution by non-organic material, and 4) accommodation (e.g., Bohacs, 1998).

Primary **production** by photosynthetic organisms generates both organic matter (rich in hydrogen and carbon) and biogenic skeletal material (poor in hydrogen). Production is enhanced where the nutrient supply is large (e.g., upwelling zones or terrigenous runoff). Within the modern ocean, most primary production and organic-carbon rich sediments occur in relatively shallow waters along continental margins. Production in these localities is controlled by nutrient supply to surface waters. These nutrients are mostly recycled from thermocline depths by advection to surface waters through upwelling induced by persistent wind systems. The depth to the thermocline varies considerably— in areas where the thermocline is deeper, nutrient advection and marine phytoplankton production is reduced. The location of thermocline depth and intensity of upwelling are controlled by the circulation of winds and oceans. The global wind system that drives ocean circulation is governed mainly by the temperature difference between pole and equator and rotation of the earth, modified by landmass distribution. Using plate-tectonic reconstructions and applying the rules that govern wind and surface currents one can estimate paleo-production zones in the geologic record. In addition, the paleolatitude distribution of plates influences production through the amount of sunlight exposure and plate history controls continental hypsography that, convolved with eustacy influences the development of areas of productive shallow seas and shelves.

Most organic matter is destroyed near its zone of production (by being consumed or oxidized). **Preservation** of significant amounts of organic matter requires relatively rapid movement to an environment where consumers are excluded and oxidation is inhibited, both typically due to low-oxygen conditions. (Oxygen has been shown to be the primary oxidant in marine settings, e.g., Emerson et al. 1985; Heinrichs and Reeburgh 1987; Alperin et al. 1994). Low oxygen conditions result from high oxygen-consumption rates relative to oxygen-delivery rates. High oxygen consumption arises from elevated rates of primary production. Low oxygen delivery rates are due to restricted circulation, salinity or temperature stratification, burial in the sediment column (where oxidant diffusion rates are low), and sluggish ocean circulation (because of low latitudinal temperature gradients). These processes are significant on broad shelves, epeiric seas, silled basins, and upper slopes where water is shallow, burial rates are relatively rapid, and enhanced production and higher respiration results in a corresponding reduction in oxygen concentration. (Consumers are also excluded by conditions of high salinity, extreme pH, or unstable substrates, cf. Savrda and Bottjer, 1991). Plate tectonics directly influences preservation through paleolatitude distribution and basin bathymetry, and, convolved with atmospheric and oceanic circulation, affects oxygen delivery, salinity, and temperature, and clastic influx. Identifying the potential for enhanced production, restricted circulation, and moderate sediment accumulation rates is the initial step in identifying areas of enhanced preservation.

Non-organic matter influx (mineral matter and biogenic debris) can enhance organic-matter delivery to the bottom, help preserve organic matter by burial, or dilute organic content, depending on its rate relative to primary production. Above a critical threshold rate, **dilution** by mineral or skeletal matter decreases the concentration of organic matter in the sediment. Clastic dilution is at a

relative minimum in settings distal to clastic shorelines or lateral to submarine dispersal systems. A rise in water level moves the shoreline away from the basin center, traps clastics in estuaries, and enhances concentration of organic matter. Biogenic dilution can be important at very high production rates (e.g., Monterey Formation, Isaacs and Rullkotter, 2001; Bohacs et al., 2005). Very slow burial rates can also hamper organic preservation because organic matter remains within the zone of active microbial reworking near the surface too long, exposed to oxidants in pore waters, and prone to erosion and transport (Heinrichs and Reeburgh, 1987; Betts and Holland, 1991; Hartnett et al., 1998; Schieber, 1994, 1998). Thus, an optimal rate of sediment accumulation maximizes preservation of organic carbon during shallow burial (the concept of "burial efficiency"; Heinrichs and Reeburgh, 1987).

Plate-tectonics effects on exposed bedrock and topography, convolved with local climate, are the primary controls on yields of clastic sediments (Figure 2). In shelfal settings, large-scale transgressions are a primary influence on clastic influx, so long-term eustatic transgressions and highstands are generally prospective intervals for accumulation of organic-matter-rich rocks (because such transgressions also enhance primary production and preservation through changes in oceanic circulation and local climate).

The combination of subsidence, compaction, and eustacy provides a**ccommodation** for accumulation of sediment and the spatial distribution of accommodation affects the location and intensity of production, destruction, and dilution. Plate tectonics influences accommodation through the spatial and temporal distribution of subsidence, topographic and bathymetric evolution, sediment supply, and long-term eustacy (Figure 2).

Source Rock Settings

Even within an overall background of favorable conditions for accumulation of organic matter, the properties and distribution of potential source rocks vary systematically at several vertical and lateral scales, from lamina to super sequence, spanning tenths of millimeters to thousands of meters (Bohacs, 1990, 1993, 1998; Schwalbach and Bohacs, 1992; Creaney and Passey, 1993; Bessereau and Guillocheau, 1995). These systematic variations are controlled by depositional environment and stratal stacking. Depositional processes intrinsic to the environment form lithofacies packages and stratal surfaces that are the basic building blocks of the geologic record. Extrinsically controlled accommodation stacks these facies building blocks into a stratal hierarchy. Each major physiographic setting accordingly accumulates characteristic vertical and lateral distributions of lithofacies recorded in their stratal stacking, mineralogy, and organic-matter content. These characteristic lithofacies distributions are recorded in quasi-periodic, parasequence-scale packages that stack systematically to form depositional sequences whose expression varies significantly within the marine depositional realm, and from the paralic and continental realms.

The **marine realm** includes three physiographic settings that accumulate significant organic-matter-rich rocks: **constructional shelf margin**, **platform/ramp**, and **continental slope/basin**. (Table 1 lists representative examples.) Both constructional-shelf-margin and platform/ramp settings occur on continental crust: the shoreline clastic dispersal system directly controls the basinal depositional system in the **constructional-shelf-margin setting**; the resulting parasequences generally decrease in thickness towards the basin (Van Wagoner et al., 1988). In the **platform/ramp setting**, in contrast, the basinal system is decoupled from the shoreline and parasequences are relatively thick in basinward positions and lap on or thin landward. Organic-matter distribution differs significantly between these two settings: the constructional shelf margin shows the "normal" landward increase in terrigenous material, whereas the platform/ramp setting shows little or no organic-facies changes towards the landward limit of fine-grained deposition (Grabowski and Glaser, 1990; Wignall, 1991; Leckie et al., 1990; Tyson, 1995). The **continental slope/basin setting** occurs where distinct and significant relief develops, due in large part to the transition from continental to oceanic crust (Vanney and Stanley, 1983). The position and bathymetry of this setting leads to strong interaction with open-oceanic currents and processes. Clastic dispersal systems are dominated by mass gravity flows and organic deposition by pelagic and hemipelagic sedimentation, although some settings may have significant input of terrigenous organic matter (e.g., Congo Fan, deepwater Mahakam Delta). Relations

among organic parameters and physical processes may differ significantly from those on continental shelves (Bohacs, 1990, 1993; Peters et al., 2000). Bathymetry strongly controls the distribution of fine-grained sediments and their organic-matter content through its effects on oceanic processes and circulation patterns.

The **paralic realm** contains environments that occur around oceanic shorelines where complex interactions of myriad processes tend to form intricate mosaics of facies tracts. Organic matter comprises a mix of *in situ* planktic input with advected marine and terrigenous material. Preservation is mainly controlled by local restrictions of oxidant access and relatively rapid burial by sediment precipitated in the local water column and transported from land and shelf. Dilution can be by siliciclastic or carbonate sediment and is a very strongly controlled by the associated shoreline type: wave, river, or tide dominated. Accumulations may range from thin organic-matter-rich laminae in subtidal carbonate mudstones to thick coal bedsets.

Approximately 20% of current worldwide production of hydrocarbons is associated with organic matter that accumulated in the **continental realm**: mire and lake physiographic settings. **Mires** preserve significant volumes of terrigenous organic-matter-rich rocks (peat) only when and where the overall increase in accommodation approximately equals the accumulation rate of peat (see discussions in Bohacs and Suter, 1997). Primary organic production is a function of local flora and requires nutrient and water supply from groundwater and overland flow: mires thrive in areas of groundwater discharge. Mires with some open water areas may accumulate coals with significant amounts of algae, spores, or pollen. (The amount and hydrocarbon source potential of a coal varies with nutrient supply, climate, local hydrology, and geological age— Cretaceous and Cenozoic coals tend to be more oil prone due to the evolution of land plants with more hydrogen-rich components; e.g., Langenheim, 1990.) Preservation occurs only below the water table because of low rates of oxidant supply and the generation of low pH and antiseptic compounds by decomposition of plant material. Stable river channels and shorelines as well as raised mires minimize dilution, favoring coal accumulation within mid to upper lowstand and lower to mid highstand systems tracts.

Lake strata contain three end-member lacustrine facies associations with significant differences in organic-matter richness, quality, and timing of petroleum generation relative to basin thermal history. The character and distribution of both organically enriched and inorganic facies are strongly influenced by lake-basin hydrology, water chemistry, processes of shoreline regression, and basin fill architecture. These proximate controls are strongly influenced by the ratio of rates of sediment+water supply and potential accommodation over the time span of deposition of depositional sequences to sequence sets (bed to member scale) (Carroll and Bohacs, 1999, 2001; Bohacs et al., 2000) and can be summarized by three stability fields: a large ratio (more sediment+water than potential accommodation) results in a mostly open hydrology lake with fresh waters and a stratal record dominated by progradational stacking of mostly clastic lithologies, and is termed an overfilled lake basin type marked by the fluvial-lacustrine facies association. An intermediate ratio yields an intermittently open hydrology lake whose waters typically fluctuate between alkaline/saline and fresh. Its stratal record is a mixture of progradational and aggradational stacking of both clastic and biogenic/chemical lithologies of the fluctuating profundal facies association and it is termed a balanced-fill lake basin type. A low ratio (more potential accommodation than sediment+water) produces a dominantly closed hydrology lake with saline to hyper-saline waters and a stratal record dominated by aggradational stacking of widely varying mixtures of clastic, biogenic, and chemical rock types with a significant component of evaporative lithologies— the evaporative lake-facies association. This corresponds to the underfilled lake basin type. The facies associations and interpreted lake-basin types can be used to make first-order predictions of hydrocarbon generation type and timing from limited geologic data such as reflection seismic lines, well logs, or core of non-source strata (see discussions in Bohacs et al., 2000; Carroll and Bohacs, 2001; Bohacs et al., 2003).

Models at the scale of physiographic settings provide the bridge between global and local controls on organic matter accumulation, integrating the global and derivative influences on the proximate controls of production, destruction, dilution, and accommodation. The various settings also provide a practical way to recognize key local controls and estimate the distribution and character of organic

matter in a particular area. Hence, one looks at global reconstructions with an eye to areas favorable for the development of each particular physiographic setting (at the regional to basinal scale) and then uses parameters of the physiographic setting model to understand and extrapolate organic-matter-rich rock occurrences and character at the sub-basin to local scale.

APPLICATION OF CONCEPTS TO PREDICTING SOURCE ACCUMULATION

The primary factors, or proximate causes, of production, destruction, dilution, and accommodation are ultimately controlled by the larger scale processes of plate tectonics, atmosphere-ocean circulation, and biological activity (Figure 2). Applying these concepts to paleogeographic maps identifies potential areas of organic-matter-rich rock accumulation and highlights the importance of different mechanisms of organic enrichment and preservation in space and time. Processes that are minor in the modern oceans assume a more significant role in the past, whereas some 'rules' derived from today's ocean are likely to be poor predictors of source rocks in ancient successions. Organic-matter production and preservation, however, vary systematically through time as continental drift reconfigures atmosphere-ocean circulation, climate, and shelf distribution patterns. This implies that global-scale processes can be good predictors of more local-scale organic-matter-rich-rock distribution and properties. Recognizing these processes and convolving them with source depositional models allows for a better assessment of source properties at local scales. The close link between source-rock deposition and continental configuration implies that consideration of continent-scale changes at million-year time scale is appropriate even where local (prospect-scale) information is sought. Table 2 outlines the process for constructing a regional map that can be used to focus on source prediction at a basin or local scale. This approach builds on the classic methodology of Parrish (1982) using insights and advances inspired by her work and that of her colleagues as well as of others. We explicitly expand into paralic and continental realms throughout the Phanerozoic, extend into the detail of physiographic settings, and incorporate the influences of changing flora and fauna character and distribution on paleoclimate and organic matter accumulation.

Utility of Paleocirculation Models for Predicting Source Rock Distribution

Relatively recent time intervals have continental and circulation patterns that differ little from the modern and prediction of organic-matter-rich rocks is relatively straightforward and confident. For example, the Eocene map (Plate 7) shows the most detailed circulation reconstruction, including deep water and monsoonal circulation, that is well documented from paleoceanography and paleoclimatology data.

Predicting areas of source enrichment on an Ordovician map is more challenging, however, because of the radically different configuration of continents and oceans (Plate 2) and the paucity of basin paleoceanographic and paleoclimatic data. Documented locations of organic enrichment in the Ordovician are not predicted well using simple modern-day analogues. Differences in continental configuration are significant enough that atmospheric and oceanographic controls on ORRs result in different source-distribution patterns. For instance, the commonly used rule of thumb that present-day east-facing margins have poor production potential does not account for the common occurrence of ORRs on east-facing margins in the Ordovician (Plate 2). The common occurrence of ORRs at high latitudes in the Ordovician is also not characteristic of modern organic-matter-rich-sediment distribution. These differences make sense when viewed against the restored circulation and shelf positions for the Ordovician. These important differences include:

1. Widely dispersed and low-lying continents in the southern hemisphere and minimal land area in the northern hemisphere.
2. Broad shelves underlie highly productive low-pressure zones at 0° and 60° S.
3. East-west coastlines oriented parallel to trade wind orientation were common (versus the north-south coastlines of the modern and Eocene world).
4. Pole to equator temperature gradient was asymmetric in the northern and southern hemispheres and potentially substantially lower than at present.

5. Land plants had not yet become significant, affecting erosion, runoff, and fluvial style, but reducing the gas-risk associated with terrigenous organic matter.
6. Few planktic producers of skeletal material had evolved, so biogenic dilution was minimal.
7. Estimates of deep-water circulation are very problematic, as there are no constraints on ocean bathymetry and areas of deep-water formation.

The general east-west alignment of many coastlines (i.e. east and west-facing margins) suggest relatively little modification of zonal-wind patterns and associated coastal upwelling. A lower pole-to-equator temperature gradient would result in reduced zonal-wind strength and reduced importance of zonal upwelling relative to the modern ocean. High-latitude shelves, however, provide good potential for preserving organic matter sinking from the productive sub-polar lows. Although the fundamental processes controlling source accumulation do not change between modern and ancient ocean settings, the relative importance of the various processes does change.

The Ordovician example serves to illustrate the utility of paleocirculation-paleogeographic maps for source prediction. Continental position and tectonic settings alter predicted circulation patterns relative to shelf positions: areas of high production and shelf accumulation are different from those of the modern ocean. Processes that are insignificant for ORR accumulation in the modern oceans **are** significant in the Ordovician world, such as potential ORR accumulation on broad, high-latitude shelves situated beneath centers of low-pressure-system upwelling. Recognition of the varying relative importance of these processes can substantially aid the evaluation of the prospectivity of a particular time interval.

This example also highlights the need to apply fundamental concepts to plate-reconstruction maps to construct a global source model rather than use derivative generalizations such as 'east-facing margins have poor potential'. Once generated, the model can be tuned with available paleoenvironmental data and tested against the occurrence of organically enriched strata. Finally, local areas and intervals of good source potential can be investigated further using regional stratigraphic data combined with physiographic setting models (Bohacs, 1998) within the paleoenvironmental context provided by the global ORR model.

Applications of the concepts to the Jurassic and Permian

The Permian and Jurassic maps (Plates 4, 5) illustrate how paleogeographic reconstructions can be used as a basis for predicting the occurrence of ORR. Differences in continental configuration and resultant climate and circulation patterns of the late Paleozoic—Mesozoic supercontinent Pangea favored different interactions of source depositional processes and models than those operating in the modern ocean.

Late Permian— Major factors and processes influencing ORR deposition:
Continental area and monsoonal circulation
- The large contiguous landmass would seem to favor development of ubiquitously strong monsoons. Monsoonal development was, however, probably less widespread, especially in the southern hemisphere, because of the strong albedo effect of the southern ice sheet on continental heating. Warmer sea surface temperatures estimated for the equatorial Tethys Ocean would also reduce the land-sea temperature contrast. This could be significant, for in the Neogene a much more subtle contrast of land and sea temperature controls the strength of the Indian Monsoon (along with the topography of the Himalayas and Tibetan Plateau— Anderson and Prell, 1991; Kutzbach and Guetter, 1986).
- Monsoons likely did, however, drive strong seasonal upwelling over the broad shelves of the western margin of Tethys (North Africa, Arabia, and northwest Australia).
Strong equatorial-pole temperature gradient
- Strong deep-water circulation may have provided cold oxygenated water to the ocean bottom reducing preservation potential in areas open to the Panthalassa Ocean.

- Strong zonal circulation resulted in strengthened coastal upwelling along the broad shelves of the western margins of Pangea. (Widespread deposits of biogenic phosphate in many localities supports interpretations of strong upwelling— Parrish, 1987; Herring, 1995).

Enhanced Preservation in Circulatory Deadends
- Assembly of Pangea resulted in numerous restricted seaways and circulatory dead-ends (western North America, northern Europe, and northern and southern South America).
- Partial restriction of the Tethys ocean by continental fragments enhanced preservational conditions. Isolation from the Panthalassa Ocean reduced access to cold, oxygen rich polar waters. Tethyan deep water was likely to be saline and warm with low oxygen and good preservation potential.

Broad shelfal area
- The broad shelfal area extending along the southern Tethyan margin provided good preservation potential beneath high production zones along the eastern margin of Tethys.

Summary of ORR accumulation in the Late Permian

Significant accumulations of organic-matter-rich rocks also occur in the Permian. More than eight hydrocarbon systems have late Permian sources that generated about 2.6 x 10^{10} BOE (Ulmishek and Klemme, 1990). Most of these source rocks accumulated in platform/ramp or continental slope/basin settings, influenced by enhanced production due to strong circulation and upwelling or by enhanced preservation due to restrictive bathymetry from extensive rifting and eustatic changes.

Late Jurassic— Major factors and processes influencing ORR deposition:
- *Extensive mid-latitude continental areas* in both the northern and southern hemisphere result in summer lows developing on either side of the Tethys ocean during northern summer and southern summer, producing a double monsoon and potentially reversing surface oceanic circulation.
- Low pressure draws winds inland parallel to the western Tethyan margin inducing *seasonal upwelling* along this coastline (Plate 5). Strong upwelling on this east-facing margin would not be inferred from simple zonal circulation patterns.
- *Monsoon influence* on climate belts results in an extensive dry continental region. Dry conditions over the mid-latitudes reduced the production and flux of gas-prone terrestrial organic material to deltaic systems.
- *High latitude low-pressure upwelling:* The broad shelfal area in the arctic region is situated beneath the sub-polar low pressure system, a region of likely high production and good preservation. This may partially explain the good source potential of the Kingak Formation (north Alaska).
- *Weak equatorial-pole temperature gradient:* Sluggish deep-water circulation slows the supply of oxygen to the lower ocean potentially enhancing preservation from an expanded oxygen minimum. Weak zonal circulation implies reduced coastal upwelling along the western margins of continents similar to El Nino conditions in the modern ocean.
- *Initiation of Pangean break-up*: Provides restricted basins in the North Atlantic, Gulf of Mexico, and Proto Indian Ocean with enhanced preservation potential (e.g., Kimmeridge Formation, Smackover Formation).
- *Broad shelfal area:* The broad shelfal area extending under the arctic and southern Tethyan shelves increase the potential areas for source preservation. This is especially true where subbasins within carbonate platforms may have been restricted or stratified, possibly accounting for highly enriched source intervals such as the Hanifa Fm on the Arabian Platform.

Summary of ORR accumulation in the Late Jurassic

These factors resulted in the accumulation of significant volumes of organic-matter-rich rocks. More than 15 hydrocarbon systems have late Jurassic sources, accounting for approximately 25% of discovered hydrocarbons (Ulmishek and Klemme, 1990). Most of these source rocks accumulated in constructional-shelf-margin settings (Plate 5) influenced by enhanced production under seasonal upwelling and by enhanced preservation and

optimized dilution. These conditions arose from restricted circulation in broad shallow seas under high global sea level and warm greenhouse conditions. Local conditions are also important, however, as a single platform/ramp occurrence less than 30 m thick probably generated most of the oil on the Arabian platform (the Hanifa Formation; Cole et al., 1993, 1994). This setting owes its richness to the interaction of beneficent global conditions and a propitious local setting.

Each plate (see enclosures) contains a listing of key factors affecting ORR accumulation, ranging from plate tectonics and orogenies, through continental distribution and paleogeography, sea level trends, seaways and landscape development, climate mode, oceanography, and biological evolution, to critical combinations of factors.

CONCLUSIONS

1. Global paleogeographic reconstructions are useful for predicting the occurrence of ORR because of close linkages among continental configuration, ocean and atmosphere circulation patterns, and regions of marine organic-matter production and preservation with development of local physiographic settings.
2. Processes that control ORR deposition arise at global scales and impact basin and local-scale areas through their influence on the production, destruction, and dilution of organic matter and on accommodation.
3. Although a wide range of ORR accumulation processes operates in the modern ocean, changing continental configuration through earth history resulted in some ORR depositional processes assuming a greater importance in the geologic past. Including these ORR depositional mechanisms expands potential areas for source accumulation.
4. ORR accumulation is a complex function of many interacting processes. Successful prediction requires an integrated approach with appropriate expertise on fundamental processes and experience with contingent combinations in the geological record.

References:

Alperin, M.J., Albert, D.B., and Marens, C.S., 1994, Seasonal variations in production and consumption rates of dissolved organic carbon in a n organic-rich coastal sediment: Geochemica et Cosmochemica Acta, v. 58, p. 4909-4930.

Anderson, D.M., and Prell, W.L., 1991, Coastal upwelling gradient during the Late Pleistocene. Proceedings of the Ocean Drilling Program, Scientific Results Leg 117. Ocean DrillingProgram, College Station, TX.

Bessereau, G., and Guillocheau, F., 1995, Stratgraphie sequentielle et distribution de la matiere organique dans le Lias du bassin de Paris: Comptes Rendu de l'Académie des Sciences, v. 316, p. 1271-1278.

Betts, J.N., and Holland, H.D., 1991, The oxygen content of ocean bottom waters, the burial efficiency of organic carbon, and the regulation of atmospheric oxygen: Global and Planetary Change, v. 5, p. 5-18.

Bohacs, K.M., 1990, Sequence stratigraphy of the Monterey Formation, Santa Barbara County: Integration of physical, chemical, and biofacies data from outcrop and subsurface: SEPM (Society For Sedimentary Geology) Core Workshop No. 14, San Francisco, California.

Bohacs, K.M., 1993, Source quality variations tied to sequence development in the Monterey and associated formations, southwestern California *in* Katz, B.J., Pratt, L.M., eds., Petroleum source rocks in a sequence-stratigraphic framework: AAPG Studies in Geology, v. 7, p. 177-204.

Bohacs, K.M., 1998, Contrasting expressions of depositional sequences in mudrocks from marine to non marine environs, *in* J. Schieber, W. Zimmerle, and P. Sethi, editors, Mudstones and Shales, vol. 1, Characteristics at the basin scale: Stuttgart, Schweizerbart'sche Verlagsbuchhandlung, p. 32-77

Bohacs, K.M. and Suter, J.R., 1997, Sequence Stratigraphic Distribution of Coaly Rocks: Fundamental Controls and Paralic Examples. AAPG Bulletin, v. 81, p. 1612–1639.

Bohacs, K.M., A.R. Carroll, J.E. Neal, P.J. Mankiewicz, 2000, Lake-basin type, source potential, and hydrocarbon character: an integrated sequence-stratigraphic— geochemical framework. *in*: E.H Gierlowski-Kordesch, and K.R. Kelts, eds., Lake basins through space and time: AAPG Studies in Geology 46, p. 3-34.

Bohacs, K.M., Carroll, A.R., and Neal, J.E., 2003, Lessons from large lake systems—Thresholds, nonlinearity, and strange attractors, *in* Chan, M.A., and Archer, A.W., eds., Extreme depositional environments: Mega end members in geologic time: Boulder, Colorado, Geological Society of America Special Paper 370, p. 75–90.

Bohacs, K.M., G.J. Grabowski, Jr, A.R.Carroll, P.J. Mankiewicz, K.J. Miskell-Gerhardt, J.R. Schwalbach, M.B. Wegner, J.A. Simo, 2005, Production, Destruction, Dilution, and Accommodation— the many paths to source-rock development. in Harris, N. (editor) The deposition of organic carbon-rich sediments: Mechanisms, Models and Consequences, SEPM Special Publication 82, p. 61-102.

Bramwell, M. (editor), 1977, Atlas of the oceans. Mitchell Beazley Ltd., London.

Bunge, H.-P., and Grand, S.P., 2000, Mesozoic plate-motion history below the northeast Pacific Ocean from seismic images of the subducted Farallon slab: Nature, v. 405, p. 337–340.

Carroll, A. R., and K. M. Bohacs, 1999, Stratigraphic classification of ancient lakes: Balancing tectonic and climatic controls: Geology 27(2), p. 99-102.

Carroll, A. R., and K. M. Bohacs, 2001, Lake type controls on hydrocarbon source rock potential in nonmarine basins, AAPG Bulletin v. 85, p. 1033-1053.

Cocks, L.R.M. and T.H. Torsvik, 2002, Earth geography from 500 to 400 million years ago; a faunal and palaeomagnetic review. ournal of the Geological Society of London. 159, p 631-644.

Cole, G.A., Carrigan, W.J., Colling, E.L., Halpern, H.I., Al Khadhrawi, M.R., Jones, P.J., 1993, Jurassic source rocks and their associated oil distribution in the Eastern Province of Saudi Arabia *in* Glass, D. (editor), Carboniferous to Jurassic Pangea, First international symposium; program and abstracts. p 58.

Cole, G.A., Carrigan, W.J., Colling, E.L., Halpern, H.I., Al Khadhrawi, M.R., Jones, P.J., 1994, The organic geochemistry of the Jurassic petroleum system in eastern Saudi Arabia *in* Embry, A.F., Beauchamp, B., Glass, D.J. (editors), Pangea; global environments and resources. Canadian Society of Petroleum Geologists Memoir 17, p. 413-438.

Creaney, S., and Passey, Q.R., 1993, Recurring patterns of total organic carbon and source rock quality within a sequence stratigraphic framework: AAPG Bulletin, v. 77, p. 386-401.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Current plate motions, Geophys. J. Int., 101, 425-478, 1990.

Didenko, A. and D. Pechersky, 1993, Revised Paleozoic apparent polar wander paths for E. Europe, Siberia, N. China and Tarim plates, L.P. Zonenshain Conference, extended abstracts.

Emerson, S., Fischer, K, Reimers, C., and Heggie, D., 1985, Organic carbon dynamics and preservation in deep-sea sediments: Deep-Sea Research, v. 32, 1-21.

Grabowski, G.J., Jr, and Glaser, K.S., 1990, Depositional model for transgressive marine organic-rich rocks forming in platformal settings: Middle Callovian and Lower Toarcian examples from onshore England. Thirteenth International Sedimentological Congress, Nottingham, UK, Abstracts Volume: p. 196.

Gyllenhaal, E.D., Engberts, C. J., Markwick, P.J., Smith, L.H., Patzkowsky, M.E., 1991, The Fujita-Ziegler model; a new semi-quantitative technique for estimating paleoclimate from paleogeographic maps *in* Ziegler, A.M., (editor) Fossils, models and climate, Palaeogeography, Palaeoclimatology, Palaeoecology v. 86, p. 41-66.

Hafkenscheid, E., Subduction of the Thetys Oceans reconstructed from plate kinematics and mantle tomography, Ph.D. Thesis, Geologica Ultraiectina, 241, 200 pp., 2004.

Hartnett, H.E., Keil, R.G., Hedges, J.I., 1998, Influence of oxygen exposure time on organic carbon preservation in continental margin sediments: Nature, v. 391, p. 572-574.

Hellinger, S. J. (1981). The uncertainties of finite rotations in plate tectonics. J. Geophy. Res. 86B 9312-9318.

Heinrichs, S.M., and Reeburgh, W.S., 1987, Anaerobic mineralization of marine sediment organic matter: rates and the role of anaerobic processes in the oceanic carbon economy: Geomicrobiology Journal, v. 5, p. 191-238.

Herring , J.R., 1995, Permian phosphorites; a paradox of phosphogenesis *in* Scholle, P.A., Peryt, T.M., Ulmer Scholle, D.S. (editors) The Permian of northern Pangea; Volume 2, Sedimentary basins and economic resources, p. 292-312.

Isaacs, C.M. and Rullkötter, J., editors, The Monterey Formation: From Rocks to Molecules: Columbia University Press, New York, 234 pp.

Isaacs, C.M., 2001, Depositional framework of the Monterey Formation, California, *in* Isaacs, C.M. and Rullkötter, J., editors, The Monterey Formation: From Rocks to Molecules: Columbia University Press, New York, p. 1-30.

Katz, B.J., 1990, Controls on distribution of lacustrine source rocks through time and space *in* Katz B.J. (editor) Lacustrine basin exploration; case studies and modern analogs. American Association of Petroleum Geologists Memoir 50, p. 61-76.

Kearey, P. and F.J. Vine (1990) Global Tectonics, Blackwell, pp. 302.

Kidder, D.L. and T.R. Worsley, 2004, Causes and consequences of extreme Permo-Triassic warming to globally equable climate and relation to the Permo-Triassic extinction and recovery, Palaeogeography, Palaeoclimatology, Palaeoecology, 203, 207-237

Kirkwood, B. H., Royer, J.-Y., Chang, T. and Gordon, R. (1999). Statistical tools for estimating and combining finite rotations and their uncertainties. Geophys. J. Int. 137 408-428

Kutzbach, J.E., and Guetter, P.J., 1986, The influence of changing orbital parameters and surface boundary conditions on climate simulations for the past 18,000 years. Journal of Atmospheric Science, V. 43, p. 1726-1759.

Langenheim, J.H., 1990, Plant resins. American Scientist v. 78, p. 16-24.

Leckie, D.A., Singh, C., Goodarzi, F. and Wall, J.H., 1990, Organic-rich, radioactive marine shale: a case study of a shallow-water condensed section, Cretaceous Shaftesbury Formation, Alberta, Canada. Journal of Sedimentary Petrology 60, 101-117.

Leith, H., 1964, Versuch einer kartographischen Darstellung der Produktivitat der Pflanzendecker auf der Erde. Geographisches Taschenbuch, 1964/1965, Weisbaden, Max Steiner Verlag, p. 72-80.

Lisitzin, A. P., 1972, Sedimentation in the world ocean. Society of Economic Paleontoligsts and Mineralogists Special Publication 17, pp. 218.

Matte, P. 1986, Tectonics and plate tectonics model for the Variscan Belt of Europe, Tectobophys., 126, 329-374.

Neruchev, S.G., 1995, Neftematerinskiye porody; raspredeleniye, usloviya, prichiny i periodichnost' formirovaniya. Translated Title: Source rocks; distribution, conditions, reasons and period of formation. Anonymous In: Pervaya mezhdunarodnaya konferentsiya; geokhimicheskoye modelirovaniye i materinskiye porody neftegazonosnykh basseynov; tezisy dokladov Translated Title: First international symposium on Geochemical modeling and source rocks of petroleum-bearing areas; abstracts, p. 36-37.

Parrish J.T., 1982, Upwelling and petroleum source beds, with reference to Paleozoic. American Association of Petroleum Geologists Bulletin v. 66, p. 750-774.

Parrish J.T., 1987, Palaeo-upwelling and the distribution of organic-rich rocks *in* Brooks, J. and Fleet, A., editors, Marine petroleum source rocks: Geological Society of London Special Publication 26, p. 199-205.

Peters, K.E., Snedden, J.W., Sulaeman, A., Sarg, J.F., Enrico, R.J., 2000, A new geochemical-sequence stratigraphic model for the Mahakam Delta and Makassar slope, Kalimantan, Indonesia. American Association of Petroleum Geologists Bulletin v. 84, p. 12-44.

Replumaz, A. and P. Tapponnier, Reconstruction of the deformed collision zone Between India and Asia by backward motion of lithospheric blocks, J. Geophys. Res., 108, 2285, doi:10.1029/2001JB000661.

Savrda, C.E., and Bottjer, D.J., 1991, Oxygen-related biofacies in marine strata; an overview and update, *in* Tyson, R.V. and Pearson, T.H., editors, Modern and ancient continental shelf anoxia: Geological Society Special Publications, v. 58, p. 201-219.

Schieber, J., 1994, Evidence for high-energy events and shallow-water deposition in the Chattanooga Shale, Devonian, central Tennessee, U.S.A., Sedimentary Geology, v. 93, p. 192-208.

Schieber, J., 1998, Sedimentary features indicating erosion, condensation, and hiatuses in the Chattanooga Shale of central Tennessee; relevance for sedimentary and stratigraphic evolution. *in* J. Schieber, W. Zimmerle, and P. Sethi, eds.., Mudstones and Shales, vol. 1, Characteristics at the Basin Scale: Stuttgart, Schweizerbart'sche Verlagsbuchhandlung, p. 187-215.

Schwalbach, J.R. and Bohacs, K.M., 1992, Sequence stratigraphy in fine-grained rocks: examples from the Monterey Formation: Pacific section, SEPM Guidebook, v. 70, 80 p.

Steiner, M.B., 2003, A cratonic Middle Jurassic paleopole: Callovian-Oxfordian stillstand (J-2 cusp), rotation of the Colorado Plateau, and Jurassic North American apparent polar wander, Tectonics Vol. 22, No. 3

Tyson, R.V., 1995, Sedimentary Organic Matter: Organic Facies and Palynofacies: Chapman and Hall, London, 615 p.

Ulmishek, G.F. and Klemme, H.D., 1990, Depositional controls, distribution, and effectiveness of world's petroleum source rocks. USGS Bulletin 1931, 59pp.

Van der Voo, R., 1993, Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans, Cambridge Univ. Press, pp 411.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Jr, Vail, P.R., Sarg, J.F., Loutit, T.S., and Hardenbol, J., 1988, An overview of the fundamentals of sequence stratigraphy and key definitions. *in* C.K. Wilgus et al., eds., Sea-level changes: an integrated approach. SEPM Special Publication 42: 39-46.

Vanney, J.R., and Stanley, D.J., 1983, Shelfbreak physiography: an overview. in Stanley, D.J., Moore, G.T., eds., The Shelfbreak: critical interface on continental margins. SEPM Special Publication 33: 1-24.

White, L.D., Garrison, R.E., Barron, J.A., 1992, Miocene intensification of upwelling along the California margin as recorded in siliceous facies of the Monterey Formation and offshore

DSDP sites *in* Summerhayes, C.P., Prell, W.L., Emeis, K.C. (editors), Upwelling systems; evolution since the early Miocene. Geological Society Special Publications v. 64, p.429-442.

Wignall, P.B., 1991, Model for transgressive black shales? Geology 19: 167-170.

Wignall, P.B., 2001, Large igneous provinces and mass extinctions, Earth-Science Rev., 53, 1–33.

Figure Captions

Figure 1a: Modern oceanic production based on estimates of chlorophyll concentrations from satellite data (after Leith, 1964; Bramwell, 1977). Figure 1b: Total organic carbon (TOC) distribution in sea-floor sediments (after Lisitzin, 1972; Broeker, 1974) These maps indicate that organic matter accumulation on the ocean floor varies as a function of primary production and sea-floor preservation. Continental configuration and marine depositional profile relative to global wind and ocean circulation patterns and local input of clastic sediments are important controls on ultimate accumulation. The systematics of the distribution of organic-matter-rich sediments in the modern ocean provides a basis for prediction of analogous strata in the past, but one must exercise caution and clearly differentiate essential processes that function throughout geological history from accidental combinations in modern environments.

Figure 2: Schematic diagram of orders of controls on earth systems and their relation to accumulation of organic-matter-rich rocks. At the global scale, the three ultimate controls are plate tectonics, solar input, and biological activity. These controls interact at the scale of derivative intermediate controls, such as climate distribution, circulation of atmosphere and oceans, accommodation change, global sea level, and evolution of landscapes and bathymetry. These derivative controls combine at local scales to influence directly the proximate controls of production, destruction, and dilution on significant accumulation of ORRs.

Plates:
1. Cambrian
2. Ordovician
3. Late Devonian
4. Late Permian
5. Late Jurassic
6. Late Cretaceous
7. Eocene
8. Modern

Tables:

1 lists representative examples of source rock settings
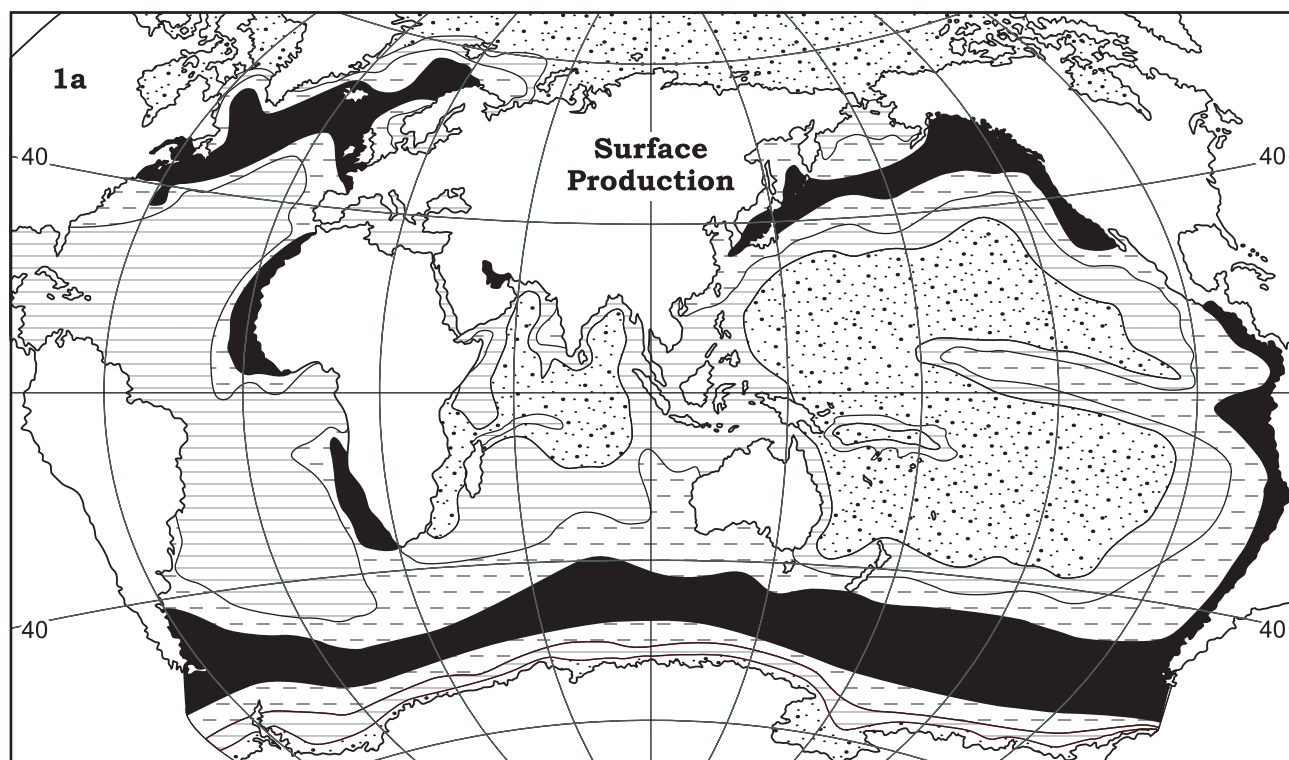2 outlines the process of mapping

Table 1: Representative Examples of Source Rock Physiographic Settings

Unit	Area	Age	Lithology	TOC	OMT
Constructional Shelf Margin:					
Pabdeh Fm	Persian Gulf	Eocene	Marl/Shale	2-4%	II-III
Mowry Shale	western USA	Late Cretaceous	Silic. Shale	1-7%	II, III
Shilaif Fm	Arabian Platform	Early Cretaceous	Shaly Chalk	2-10%	II
Khazdumi Fm	Persian Gulf	Early Cretaceous	Micritic Marl	2-10%	II
Torok Fm	North Alaska	Early Cretaceous	Shale, Ms	1-7%	II, III
Kingak Fm	North Alaska	Jurassic	Shale, Ms	1-7%	II, III
Streppenosa Fm	Italy, Sicily	Late Triassic	Clayey Micrite	1-10%	II
Chattanooga-Ohio Shale	Appalachian Basin	Late Devonian	Shale	2-10%	II-III
Aquinet Ouernine Fm	North Africa	Early Silurian	Black Shale	1-8%	II-III
Platform/Ramp:					
Brown Limestone	Gulf of Suez	Turonian	Micrite	2-8%	I-II
Toolebuc Fm	Eromanga basin	Albian	Chalk	10-25%	I-II
Shilaif Fm	Arabian Platform	Jurassic	Chalk	2-12%	I/II
Schistes Carton	Paris basin	Toarcian	Clay Shale (calc)	2-15%	I/II
Whitby Mudstone	Cleveland basin, U.K.	Toarcian	Clay Shale	2-20%	I/II
Posidonia Shale	Northwest Europe	Toarcian	Lime Ms	2-18%	II
Lower Oxford Clay	Weald/Channel basin	Callovian	Skel. Clayst.	2-12%	I/II
Excello Shale	Central USA	Pennsylvanian	Black Shale	2-25%	II-III
Continental-Slope/Basin:					
Monterey Fm	southern California	Miocene	Phosphatic diatomite	2-27%	II(S)
Ghareb Fm	Levant Coast	Maastrichtian	Phosphatic chalk	10-20%	I-II
Tarfaya Oil Shales	Morocco	Late Cretaceous	Phosphatic chalk	2-20%	I-II
Paralic setting— delta plain, lagoon, estuary:					
Evaporite Group	Gulf of Suez	Miocene	Shale in Evaporites	1-8%	II-III
Oligocene Shales	Sumatra	Oligocene	Carbonaceous Shales	1-10%	II-III
Kapuni/Pakawau Fms	Taranaki Basin	Eocene-Paleocene	Carb. Shale, Coal	1-60%	II-III
Blackhawk Fm.	Uinta Basin, Utah	Campanian	Coal, Carb. Sh.	1-75%	III, II
Safer Fm	Yemen	Jurassic	Shale in Evaporite	2-33%	I-II
Mulussa Fm	Syria	Triassic	Sh. in Evap. & Dol.	1-7%	I-III
Vryheid Fm (Karoo Grp)	South Africa	Permo-Carboniferous	Coal	40-80%	III, III-II
Swan Hills Fm	Alberta Basin	Devonian	Micrite	1.5%	II
Mire:					
Cattamarra Coal Measures	North Perth Basin	Early Jurassic	Coal, Carb. Shale	1-60%	III, III/II
Walloon Coal Measures	Surat Basin	Middle Jurassic	Coal, Carb. Shale	53-75%	II/III
Birkhead Fm	Eromanga Basin	E.-M. Jurassic	Carb. Shale, Coal	1-68%	I-II, II-III
Patchawarra Fm	Cooper Basin	E. Pernian	Carb. Shale, Coal	1-68%	III
Toolachee Fm	Cooper Basin	Permian	Carb. Shale, Coal	0.5-64%	III
Lacustrine:					
Luman Tongue, GRF*	(OF) Wyoming, USA	Eocene	Skeletal Claystone	0-20%	I/II-III
Kissenda Sh	(OF) Gabon	Cretaceous	Calc. Claystone, Ms	0.6–2.2%	III/II, II
Hongyanchi Fm	(OF) Junggar basin, China	Permian	Calc. Claystone, Ms	0.5-7%	II, III
Mae Sot Fm	(BF) NW Thailand	Eocene-Pliocene	Calc., Zeolitic Shale	1.3-17.2%	I-I/II
Laney Mbr, GRF*	(BF) Wyoming, USA	Eocene	Lime Ms, Kerogenite	0-27%	I/II
Lockatong Fm, lower mbr	(BF) Newark Basin, USA	Triassic	Calc. Ms, Kerogenous Sh	2.5-8%	I, I/II
Qianjiang Fm	(UF) Jianghan basin, China	L.Eoc.-E.Oligocene	Dol. Ms, Shale	0.5-6.6%	II, III, I
Wilkins Peak Mbr, GRF*	(UF) Wyoming, USA	Eocene	Dol. Ms, Kerogenite	0-27%	I/II
Jingjingzigou Fm	(UF) Junggar basin	Permian	Dol. Ms, Claystone	0.8–2%	III/II, II

GRF = Green River Fm   OF = Overfilled, BF = Balanced Fill, UF = Underfilled

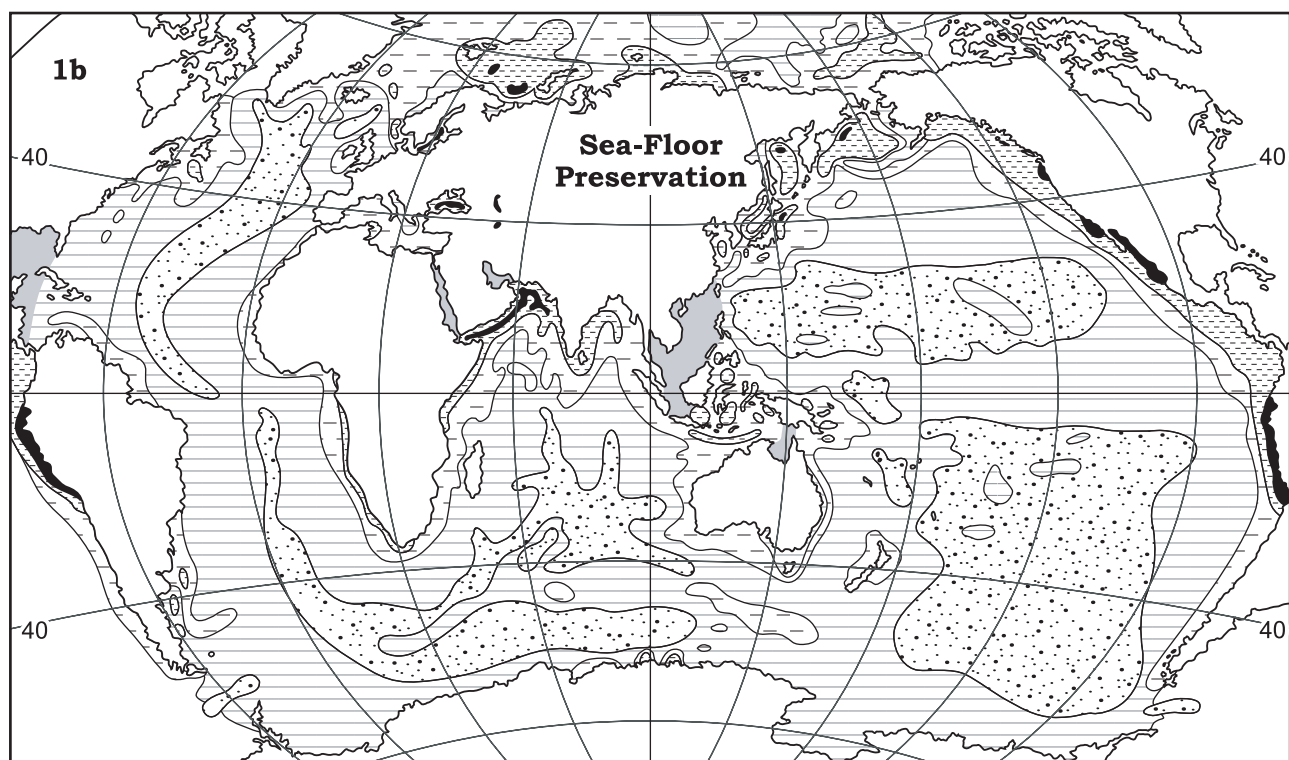**Table 2: Reconstruction of paleoenvironments for addressing source accumulation**

Step	Action
1	**Assemble Materials for the interval of interest:** • Plate reconstruction (highlighting convergent, divergent, and transform margins). • Paleoenvironmental and paleoclimatic data (including bathymetry, topography, uplift, temperature, precipitation, evaporation, salinity, and circulation patterns). • Occurrence of known ORRs and their character (at least to physiographic setting).
2	**Construct a paleogeographic map on the plate tectonic reconstruction base:** • Use paleoenvironmental and paleoclimatic data from interval of interest as well as older and younger intervals (to account for landscape evolution) • Reconstruct areas of deep ocean, shelf, lowlands, and highlands along with orogenic belts and rifts. • Highlight areas prone to developing physiographic settings conducive to accumulating ORRs. • Plot known ORR and climate-sensitive deposits (coals, evaporites, phosphorites, etc.)

3	**Interpret Atmospheric-Oceanic Circulation & Climate:**
	 • Plot atmospheric and oceanic circulation patterns using:
	 » Output of numerical models
	      OR
	 » First principles:
	   - Zonal circulation modified by landmass distribution, Climate mode (ice/hot house)
	   - Potential monsoons based on distribution of land and ocean
	 • Infer likely strength of zonal circulation cells based on global climate models and latitudinal thermal gradient data (e.g., floral and faunal distribution, stable isotopes)
	 • Estimate distribution of oceanic upwelling, precipitation, evaporation potential, and temperature using model output or first principles (see Parrish, 1982, 1987; Gyllenhaal et al, 1991)
	 • Compare atmospheric and oceanic circulation patterns and inferred climates with known climate-sensitive deposits – do they match? If so, proceed to Step 4, otherwise explore possible alternatives such as orographic effects (rain shadows, etc.) or monsoonal circulation

4	**Compare predictions with data on organic-matter-rich-rock distribution:** • Are known ORR in the time slice attributable to recognized processes that enhance organic matter production, preservation, and concentration? If yes, proceed to Step 5. • If no, what are possible local extenuating circumstances that allow ORR deposition? – Could conditions for enrichment extend beyond the known area of ORRs? (e.g., minor mechanisms that produce local upwelling)

5	**Extend & Extrapolate ORR areas:**
	 • By recognizing the processes that control ORR deposition and its physiographic setting, can the distribution of known sources be extended geographically or stratigraphically?
	 • Identify areas where processes that lead to known ORRs are inferred but have not produced ORRs recognized in your data:
	   – Is the database out of date?
	   – Has the area been explored and ORR are known to NOT occur? Why were ORR not present? Does the map (showing favorable conditions) require editing or has exploration missed the best potential (e.g. is the interpretation based on samples or models)?
	   – Is there potential for unrecognized ORR where favorable processes are identified?

6	**Follow up leads and update database:** • Research identified opportunities to better understand their potential • Document changes within your database

1a

Surface Production

Ocean Surface Productivity

⚬ < 25   ▤ 25 to 50   ▬ 50 to 100   ■ > 100 gC/m²/yr
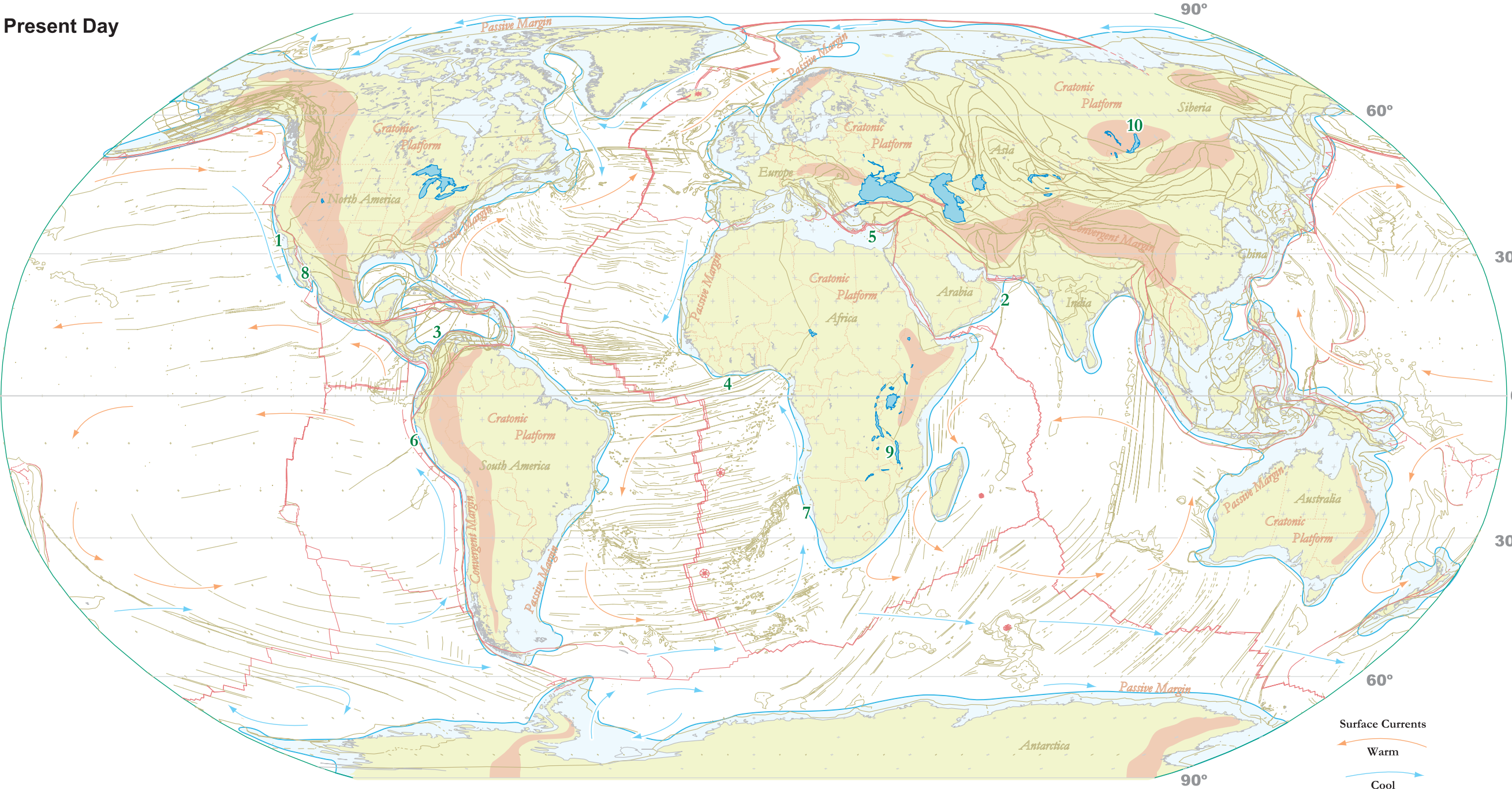
140   60   0   60   180   100   60

1b

Sea-Floor Preservation

Organic Carbon Content (weight %)

⚬ < 0.25%   ▢ 0.25 to 0.5%   ▬ 0.5 to 1%   ▦ 1 to 2%   ■ > 2%

Figure 2

Present Day

90°
60°
30°
0°
30°
60°
90°

Passive Margin
Passive Margin
Cratonic Platform
North America
Cratonic Platform
Europe
Asia
Cratonic Platform
Siberia
China
Arabia
India
Cratonic Platform
Africa
Cratonic Platform
South America
Convergent Margin
Passive Margin
Passive Margin
Convergent Margin
Passive Margin
Australia
Cratonic Platform
Antarctica

Surface Currents
Warm
Cool
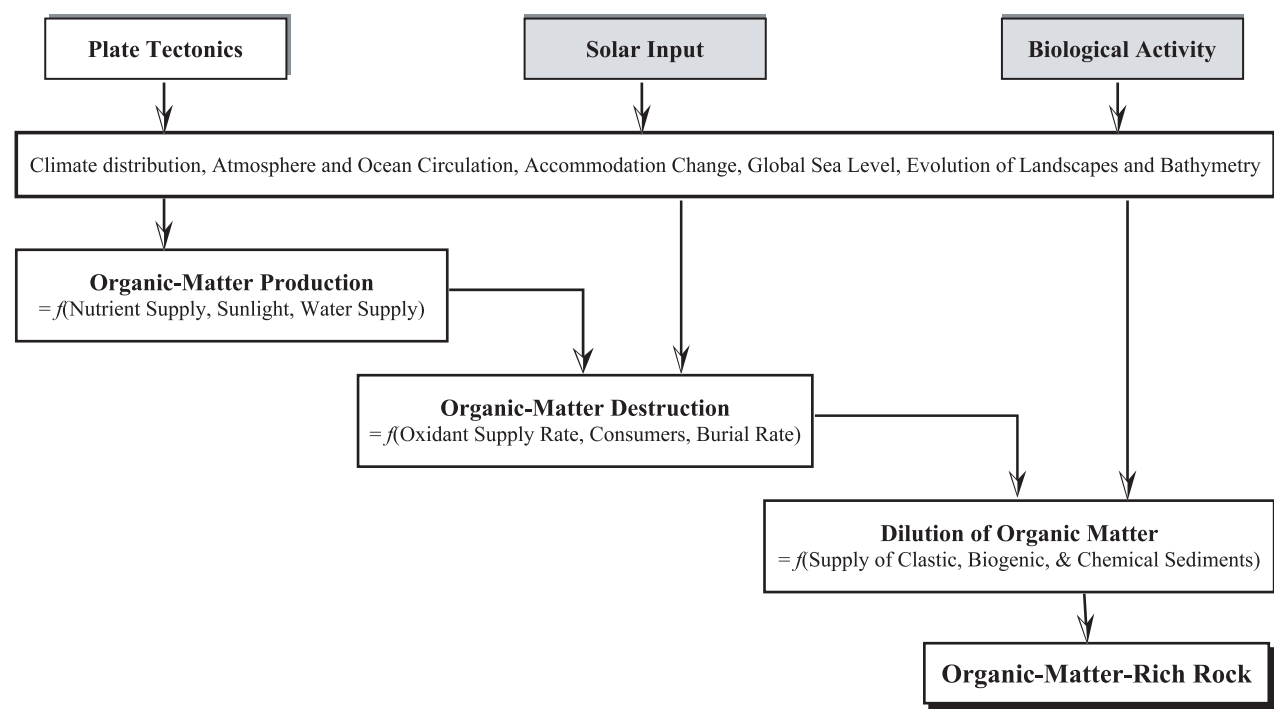
Key Factors
- Continents widely distributed, dominantly north-south orientation
- Continuing Alpine-Himalayan orogeny, Isthmus of Panama closed
- Major sea level rises and falls on an overall rising sea level
- Relative narrow shelves, small area of epicontinental seas, broad high plateaus & mountain belts: Tibet, Colorado, Altiplano
- Continued global climatic cooling, long-term icehouse climate
- Strong latitudinal temperature gradient enhances zonal atmospheric and surface-ocean circulation
- Enhanced thermohaline deepwater circulation, oxygenation of deep water
- Widespread, abundant, waxy oil-prone angiosperm land plants

Representative organic-matter-rich sediments:

Basin	Area	ORR Setting	Reference
1. Santa Barbara basin	California	Slope/Basin (clastic)	Mueller & Suess, 1979
2. Oman margin	Oman	Slope/Basin	Mueller & Suess, 1979
3. Cariaco Basin	Venezuela	Slope/Basin (clastic)	Lyons & Formolo, 2001
4. Guinea Basin	Africa	Slope/Basin (clastic)	Morris, 1987
5. Eastern Mediterranean		Slope/Basin (clastic)	Morris, 1987
6. Offshore Peru	Peru	Constructional shelf margin	Pelet, 1987
7. Offshore Namibia	Namibia	Constructional shelf margin	Mueller & Suess, 1979
8. Gulf of California	Mexico	Constructional shelf margin	Calvert, 1987
9. Lake Baikal	East Siberia	Lacustrine, Overfilled	Flower et al., 1995
10. Lake Malawi	East Africa	Lacustrine, Balanced-fill	Scholz et al., 1990

Map Legend

Highlands
Lakes
Land
Shelf, Carbonate
Shelf, Undifferentiated
Ocean Basin
Hot Spot

Evaporites
Phosphorites
Coal
Subduction Zone
Spreading Ridge
Plate Boundary

Eocene
(48 - 40Ma)
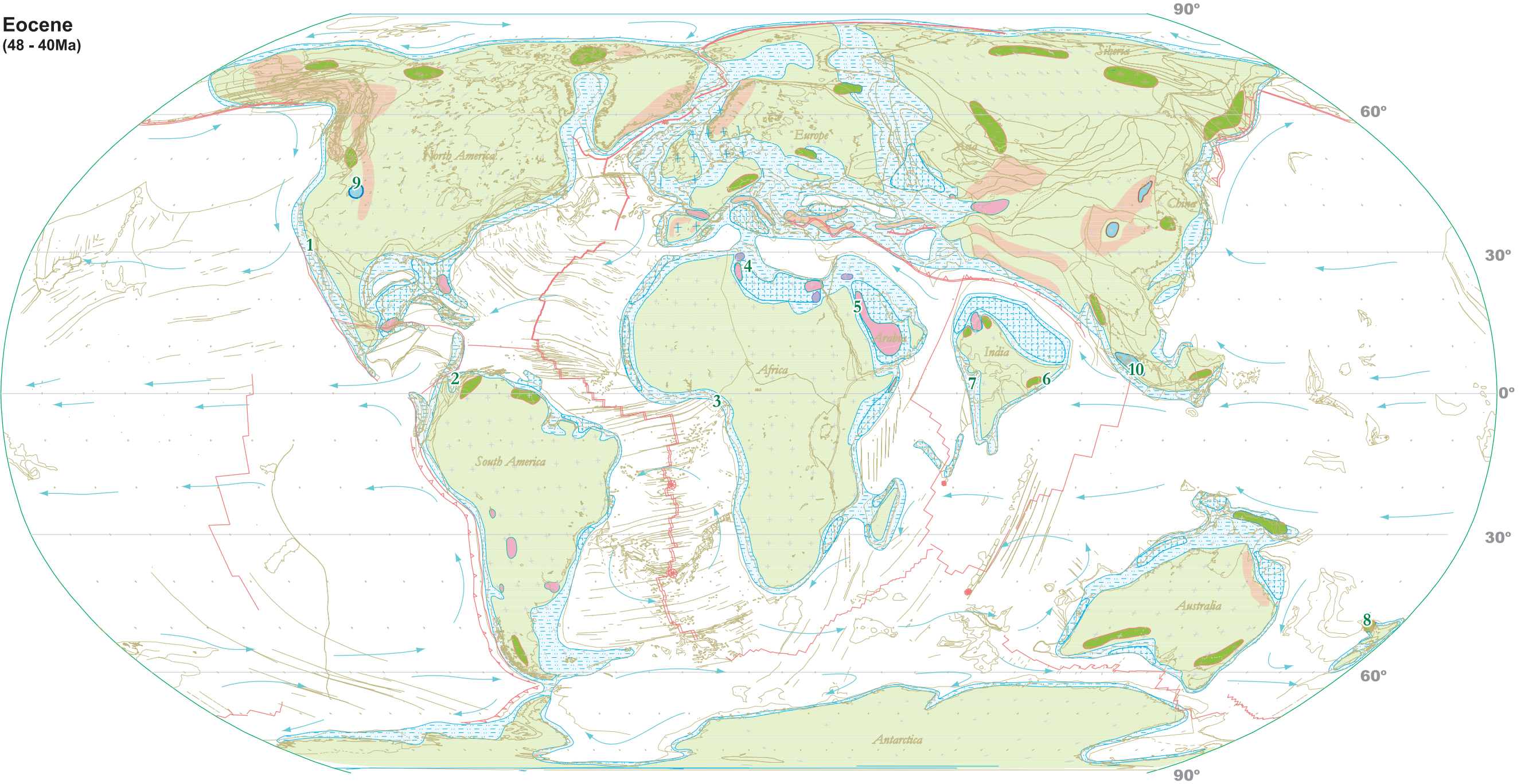
Key Factors

- Continents widely distributed, continued convergence of Africa and Europe, N. & S. America
- India began collision with Asia
- Overall highstand with major lowstands of sea level
- Tethys Ocean became restricted or closed along length
- Deepwater connection between Arctic and Atlantic oceans
- Relatively shallow continental shelves
- Dominantly zonal climate
- Climate reached maximum warmth in early Eocene
- Latitudinal circulation dominated over circum-polar, effective global redistribution of heat
- Warm-water fauna found to almost 80° latitude
- Widespread waxy oil-prone angiosperm land plants

Representative organic-matter-rich rocks:

#	Formation	Basin/Area	ORR Setting
1.	Kreyenhagen Fm	San Joaquin, U.S.A.	Slope/Basin (biogenic to clastic)
2.	Truillo/Miosa Fm	Maracaibo, Venezuela	Constructional Shelf Margin
3.	Akata-Agbata Fms	Niger Delta	Constructional Shelf Margin
4.	Bou Dabbous Sh	s. Pelagian, N. Africa	Platform/Ramp
5.	Thebes Fm	Gulf of Suez	Platform/Ramp
6.	Sylhet Fm	Assam, India	Platform/Ramp to Paralic
7.	Cambay Fm	Cambay, India	Paralic to Constructional Shelf Margin
8.	Kapuni Group	Taranaki basin, N.Z.	Paralic
9.	Green River Fm	Wyoming, U.S.A.	Lacustrine, Balanced-fill, Underfilled
10.	Kelara Limestone	Salayar, Indonesia	Lacustrine, Balanced-fill to Overfilled

Map Legend

- Highlands
- Lakes
- Land
- Shelf, Carbonate
- Shelf, Undifferentiated
- Ocean Basin
- Hot Spot
- Evaporites
- Phosphorites
- Coal
- Subduction Zone
- Spreading Ridge
- Plate Boundary

Late Cretaceous
(Cenomanian-Turonian)
(99 - 89Ma)

Map labels: North America, Siberia, Asia, Europe, China, Okhotsk, Arabia, Africa, South America, India, Kerguelen, Australia, Antarctica
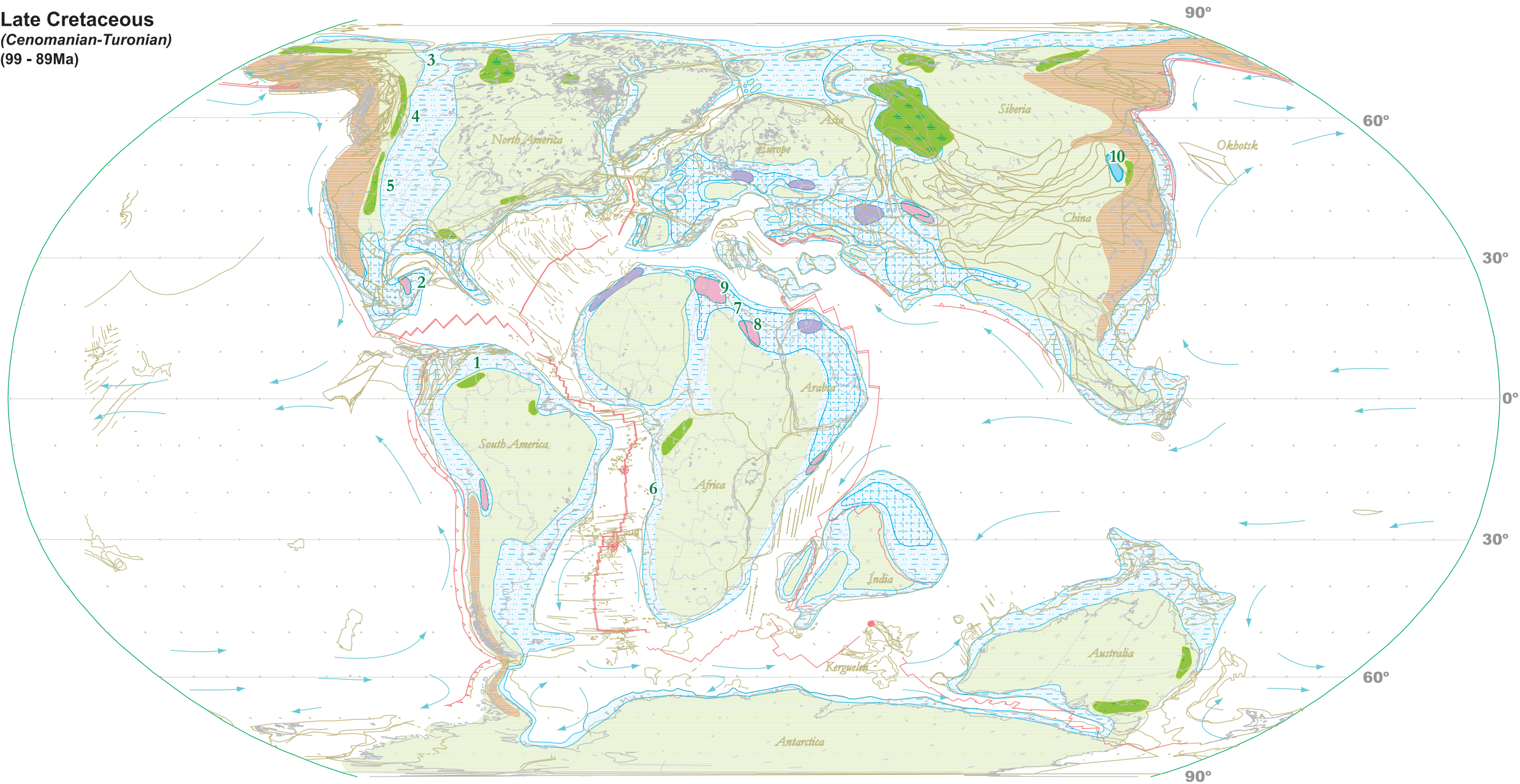
Key Factors
- Gondwana completely disassembled, widely distributed continents.
- Continued break-up of Laurasia
- Subduction-related orogenies in western North America, China, South America
- Highest global sea level in this period, widespread epeiric seas
- Tethyan marine connection across Africa shallow and tortuous, moderated climate in Northern Hemisphere
- Broad equatorial climate band
- Warmest global temperature of the Cretaceous
- Oceanic anoxic event provides good background preservation conditions
- Very sluggish deep oceanic circulation
- Warm saline deep water production in Tethys, proto-Atlantic and Pacific oceans
- Appearance of oil-prone angiosperms
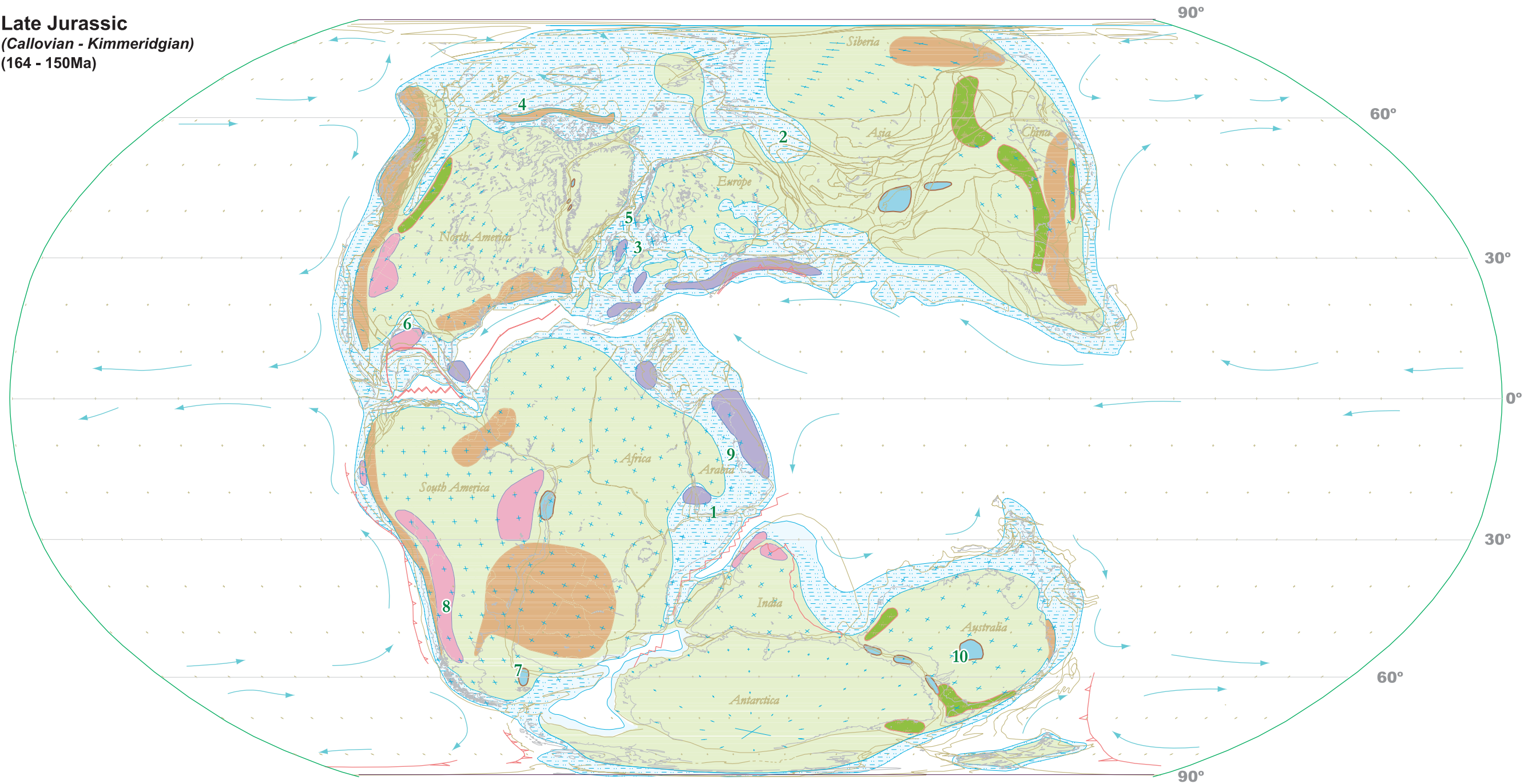
Representative organic-matter-rich rocks:

Formation	Basin/Area	ORR Setting
1. La Luna Shale	Nothern South America	Constructional shelf margin
2. Eagle Ford Shale	Gulf of Mexico, U.S.A.	Constructional shelf margin
3. Boundary Creek Shale	Beaufort, Canada	Constructional shelf margin
4. Second White Specks Sh.	Western Canada Basin	Constructional shelf margin
5. Greenhorn Formation	Denver, U.S.A.	Constructional shelf margin
6. Iabe Formation	Congo, S. Atlantic	Constructional shelf margin
7. Socna Shale	Sirte, Libya	Platform/ramp
8. Abu Roash Fm	Western Desert, Egypt	Platform/ramp
9. Balhoul Fm	S. Pelagian, N. Africa	Platform/ramp
10. Qingshankou-1	Songliao, China	Lacustrine, Balanced - Fill

Map Legend

- Highlands
- Lakes
- Land
- Shelf, Carbonate
- Shelf, Undifferentiated
- Ocean Basin
- Hot Spot
- Evaporites
- Phosphorites
- Coal
- Subduction Zone
- Spreading Ridge
- Plate Boundary

90° 60° 30° 0° 30° 60° 90°

Late Jurassic
(Callovian - Kimmeridgian)
(164 - 150Ma)

Siberia

Asia

China

Europe

North America

Africa

Arabia

South America

India

Australia

Antarctica

90°

60°

30°

0°

30°

60°

90°

Key Factors

- Pangea, broadly distributed about equator, began to breakup
- Numerous rift basins: Atlantic-Tethys, Indian-Africa, Australia-Antarctica
- Sea level rises to Jurassic high in Kimmeridgian, flooding of broad epeiric seas in Eurasia
- Broad shelves line the Tethys ocean and eastern Pangea
- Western Tethys opens circum-equatorial seaway
- Relatively warm global climate, minor high latitude ice formation only in the late-middle Jurassic
- Northern hemisphere climate belts dominated by zonal conditions, intermittent monsoon conditions possible, depending on expanse of epeiric seas. Southern hemisphere climate belts likely to be influenced by monsoon.
- Tethyan ocean provides potential source of warm, low oxygen deep-water.

Representative organic-matter-rich rocks:

Formation	*Basin/Area*	*ORR Setting*
1. Lam Fm	Marib Graben, Yemen	Slope/Basin (clastic)
2. Bazhenov Shale	West Siberia	Constructional shelf margin
3. Kimmeridge Fm	North Sea	Constructional shelf margin
4. Kingak Shale	Colville, Alaska, U.S.A.	Constructional shelf margin
5. Nesna Fm	North Sea	Constructional shelf margin
6. Smackover Fm	Gulf of Mexico, U.S.A.	Constructional shelf margin
7. Spring Hill Fm	Malvinas, Argentina	Constructional shelf margin
8. Vaca Muerte Fm	Nequen, Argentina	Constructional shelf margin
9. Hanifa Fm	Arabian Platform	Platform/ramp
10. Birkhead Fm	Eromanga, Australia	Lacustrine, overfilled to Mire

Map Legend

- Highlands
- Lakes
- Land
- Shelf, Carbonate
- Shelf, Undifferentiated
- Ocean Basin
- Hot Spot
- Evaporites
- Phosphorites
- Coal
- Subduction Zone
- Spreading Ridge
- Plate Boundary

Late Permian
(Guadalupan - Lopingian)
(266 - 254Ma)

Siberia

Asia

NE China

China

N. China

S. China

Indochina

Europe

North America

Wrangelia

Iran

Africa

Arabia

N. Tibet

South America

India

Australia

Antarctica

90°

60°

30°

0°

30°

60°

90°
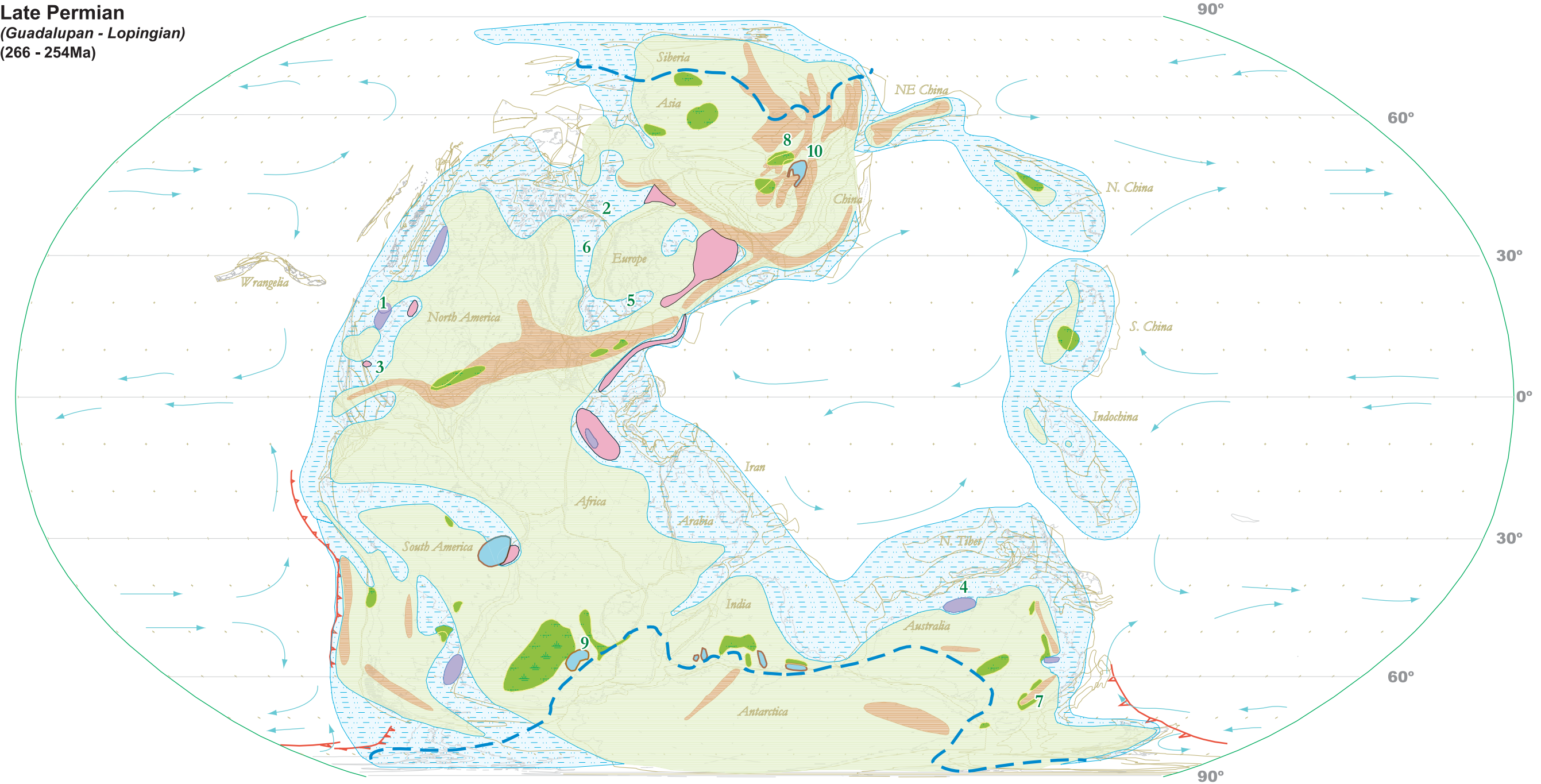
Key Factors
- Pangea fully assembled with most contiguous continental areas south of the equator.
- Major fold belts include the Hercynian, Urals, Karoo, Proto -Tienshian
- Major rifts include Southern Tethys, North Australia Rifts, Arabian Margin, Karoo
- Southern Hemisphere ice sheet reached maximum extent from Westphalian to Artinskian.
- Sea level falling to long-term low at Permo - Triassic boundary
- Paleo Tethys Ocean isolated; Topography significant and seaways restricted
- Strong atmospheric and oceanic circulation
- Zonal circulation in Panthalassa Ocean; Warm Tethys ocean even at 50° latitude
- Monsoonal climates important:
    - Seasonal rainfall more widespread; Extreme climates in interior of southern Pangea
- Cold, dry climate in southern S. Hemisphere, Wet, temperate climate in N. Hemisphere
- Wide variety of source environments governed by local conditions (lakes, coals to basin slope)
- High carbon preservation based on carbon isotope curve

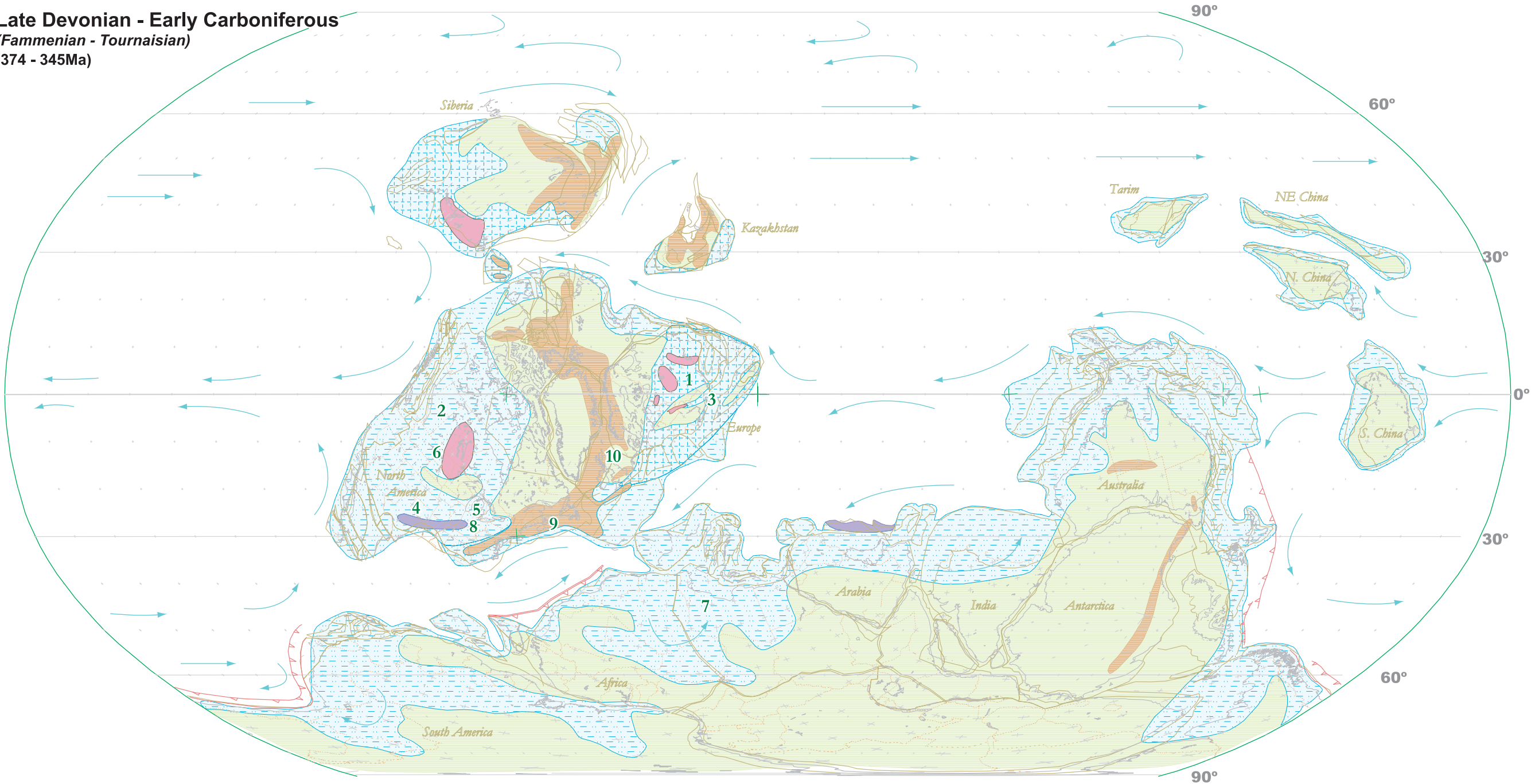**Representative organic-matter-rich rocks:**

	Formation	Basin/Area	ORR Setting
1.	Phosphoria Fm	Western U.S.A.	Slope/Basin (biogenic)
2.	Kazanian-Tatarian	Loppa High	Slope/Basin (clastic)
3.	Cherry & Bell Canyon Fms	Permian, U.S.A.	Slope/Basin (clastic)
4.	Hyland Bay Fm	Bonaparte, Australia	Constructional Shelf Margin
5.	Kupferschiefer/Marl Slate	N. Europe/North Sea	Platform/ramp
6.	Ravnefjeld Fm	East Greenland	Platform/ramp
7.	Illawarra Coal Measures	Sydney, Australia	Paralic to Fluvial
8.	Ulam Gom Fm	NW Mongolia	Mire to Lacustrine, overfilled
9.	Ruhuhu Fm	Karoo, Tanzania	Lacustrine, balanced fill
10.	Lucagou Fm	Tarim, China	Lacustrine, balanced fill

Map Legend

- Highlands
- Lakes
- Land
- Shelf, Carbonate
- Shelf, Undifferentiated
- Ocean Basin
- Hot Spot
- Evaporites
- Phosphorites
- Coal
- Subduction Zone
- Limit of Glaciation
- Plate Boundary

Late Devonian - Early Carboniferous
(Fammenian - Tournaisian)
(374 - 345Ma)

90°
60°
30°
0°
30°
60°
90°

Siberia

Kazakhstan

Tarim

NE China

N. China

Europe

North America

Australia

S. China

Arabia

India

Antarctica

Africa

South America

1
2
3
4
5
6
7
8
9
10

Key Factors
- Much of Gondwana in equatorial or high southern latitudes, distant from fold and thrust belts:
- Active tectonic interval: Development of Appalachian Foredeep
  - Acadian, Antler, Innuitian, Lomonosov, Taberraberan, Famatina, and Borchgrewingk orogenies
  - Rifting in Dniepr - Donets and Pripyat basins, Khatanga, Vilyuy, Amazon
- High eustatic sea level, at culmination of long-term rise (since early Devonian)
- Strong influence on topography on precipitation/evaporation in Laurussia
- Well-developed reef complexes; Widespread epeiric seas
- Generally warm period, carbonates, and evaporites expanded through the Devonian
- Moderate zonal circulation; Limited perennial snow cover at South Pole because of aridity
- Frasnian oceanic oxygen minimum
- Development of vascular land plants and forests
- Widespread occurrence of restricted conditions promotes anoxia

Representative organic-matter-rich rocks:

Formation	Basin/Area	ORR Setting
1. Domanik Fm	Russian Platform	Constructional shelf margin
2. Duvernay Shale	Western Canada	Constructional shelf margin
3. Marine Shale	Pripyat, Russia	Constructional shelf margin
4. Woodford Shale	Anadarko, U.S.A.	Constructional shelf margin
5. Antrim Shale	Michigan, U.S.A.	Platform/ramp
6. Bakken Shale	Williston Basin	Platform ramp
7. Illizi Shale	N.Africa	Platform/ramp
8. New Albany Shale	Illinois, U.S.A.	Platform/ramp
9. Albert Fm	Fundy, U.S.A.	Lacustrine, balanced-fill
10. Mid Old Red Sandstone	Orcadian, U.K.	Lacustrine, underfilled

Map Legend

Highlands
Lakes
Land
Shelf, Carbonate
Shelf, Undifferentiated
Ocean Basin
Hot Spot

Evaporites
Phosphorites
Coal
Subduction Zone
Spreading Ridge
Plate Boundary

Ordovician
(460 - 443Ma)

Siberia

Tarim

Kz

Kazakhstan

N. China

North America

3

2

9

4 8

6 5

S. China

Baltica

Avalon

1

10

Europe

Australia

Antarctica

India

7

South America

Arabia

Africa

90°
60°
30°
0°
30°
60°
90°
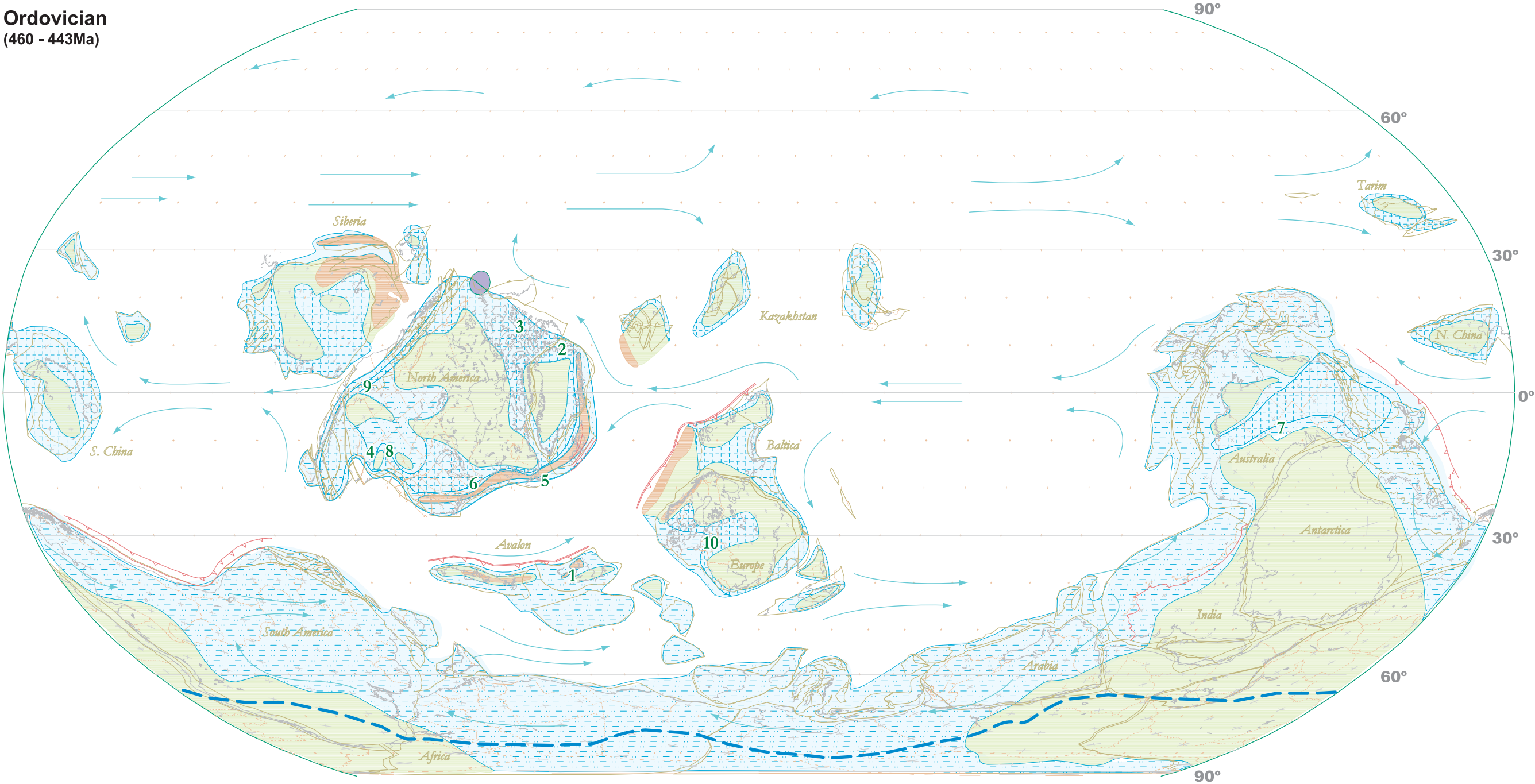
Key Factors
- Most continents at very high southern latitudes
- Taconic, Grampian, Ardennian and Ocloycic orogenies
- Long term sea level fall with significant short-term rise
- Extensive development of epicontinental carbonate sediments
- Extensive epeiric seas, minor exposed land areas
- Late Ordovician glaciation (short duration); "Icehouse" climate
- Dominantly zonal circulation
- Low atmospheric oxygen conditions favor development of dysoxic conditions
- Low relief, limited terrigenous runoff
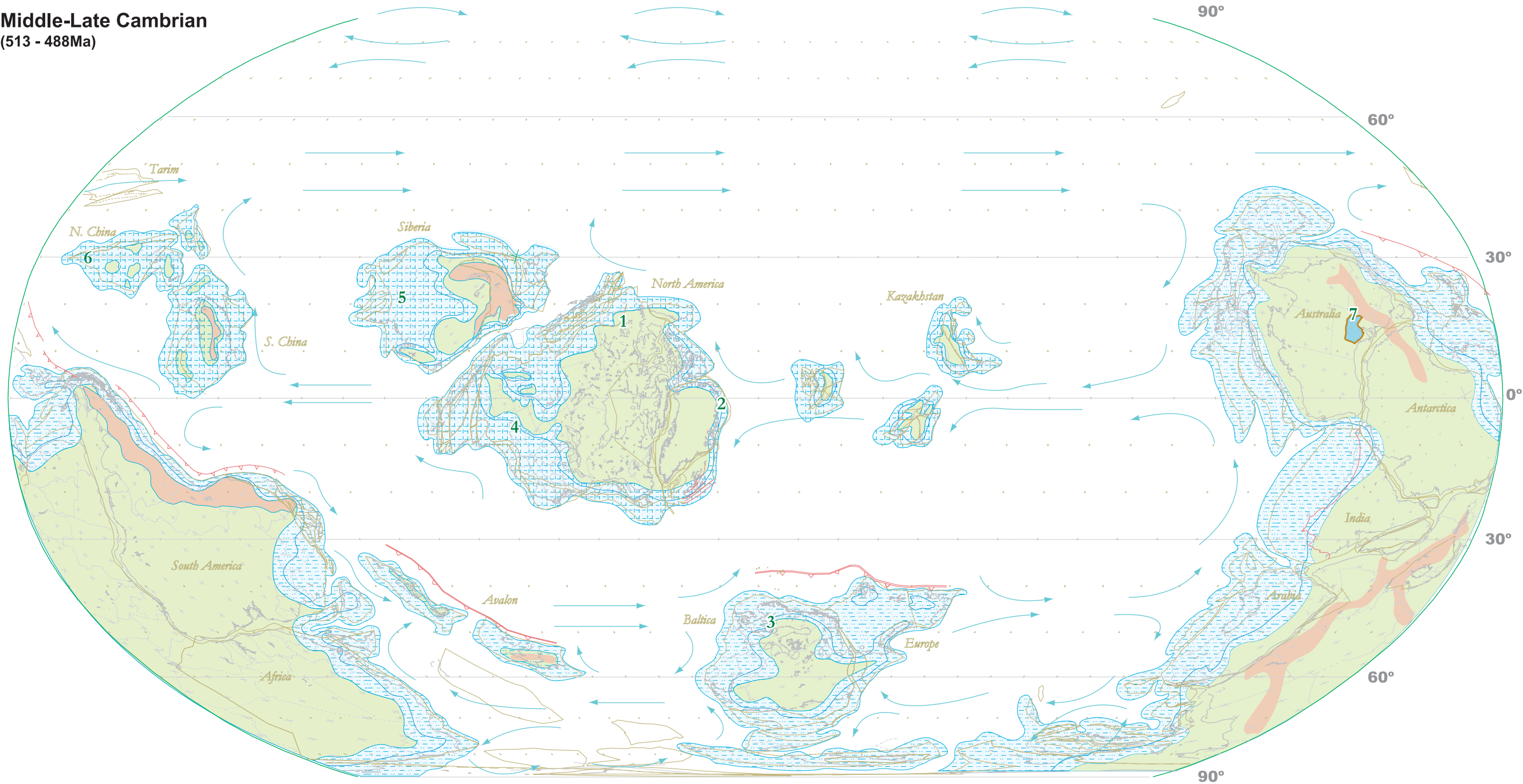- No vascular land plants

Representative organic-matter-rich rocks:

Formation	Basin/Area	ORR Setting
1. Black shales	United Kingdom	Slope/basin
2. Graptolitic shales	North Greenland	Slope/basin
3. Ibbet Bay Fm	Sverdrup, Canada	Slope/basin
4. Ellenburger Fm	Delaware, U.S.A	Construction shelf margin
5. Green Point Fm	Newfoundland	Constructional shelf margin
6. Utica Shale	Appalachian Basin, U.S.A.	Constructional shelf margin
7. Horn Valley	Amadeus, Australia	Platform/ramp
8. Sylvan Shale	Arbuckle, U.S.A.	Platform/ramp
9. Vinini Fm	Nevada, U.S.A.	Platform/ramp
10. Viivikona Fm	Baltic, Estonia	Platform/ramp (kukersite)

Map Legend

- Highlands
- Lakes
- Land
- Shelf, Carbonate
- Shelf, Undifferentiated
- Ocean Basin
- Evaporites
- Phosphorites
- Subduction Zone
- Limit of Glaciation
- Plate Boundary

Middle-Late Cambrian
(513 - 488Ma)

90°
60°
30°
0°
30°
60°
90°

Tarim
N. China
Siberia
North America
Kazakhstan
Australia
S. China
Antarctica
India
South America
Avalon
Baltica
Europe
Arabia
Africa

1
2
3
4
5
6
7

Key Factors
- Three main continents: Baltica, Laurentia, Siberia mostly in far southern hemisphere
- Passive margins widespread following breakup of Rodinia in Late Proterozoic.
- Sea level rising to first-order highstand at end of Cambrian
- Extensive epeiric seas, minor exposed land areas
- Low relief, limited terrigenous runoff
- Waning icehouse in Early Cambrian to Middle-Late Cambrian greenhouse climate
- Dominantly zonal circulation
- Archaeocyathids disappear by Middle Cambrian, result in shift from reefs to platforms with stromatolites and oolites.
- No vascular land plants
- Low atmospheric oxygen conditions enhance development of dysoxic conditions

Representative organic-matter-rich rocks:

	Formation	Basin/Area	ORR Setting
1.	Mt Cap Fm	Great Bear, Canada	Constructional Shelf Margin
2.	Henson Gletscher Fm	Franklin, Greenland	Constructional Shelf Margin
3.	Alum Shale	Kattegat, Sweden	Platform/Ramp
4.	Reagan Fm	Oklahoma	Platform/Ramp
5.	Ulsol'ye suite	Lena-Tunguska, Russia	Platform/Ramp
6.	Qiulitage Fm	Tarim, China	Platform/Ramp to Lagoon
7.	Observatory Hill Fm	Officer, Australia	Balanced-fill Lake

Map Legend

- Highlands
- Lakes
- Land
- Shelf, Carbonate
- Shelf, Undifferentiated
- Ocean Basin
- Evaporites
- Phosphorites
- Subduction Zone
- Plate Boundary
- Surface Current