Paper 12: Fossil Fuels

More than 85 percent of the world's energy still comes from fossil fuels. Despite centuries of growing use, these fuels remain abundant. Powerful economic and political interests are organized around the fossil-energy system, as are complex social arrangements.

Small Earth models provide a means to investigate the global distribution and association of shale oil/gas, coal, petroleum, and natural gas across adjoining continents at various times throughout Earth history. Recognition of their inter-relationships and distributions over time provides an important means for furthering international and regional search, as well as understanding genetic associations beyond their known occurrences. Data used in this study are based on a number of published global maps. It is acknowledged that information on the location and global distribution of these natural resources may be incomplete or overly simplistic.

Fossil fuels include shale oil and shale gas, coal, petroleum, and natural gas. Studies of the organic content of sedimentary rocks were shown by North in 1990 to be at a maxima during the Cambrian-Ordovician, Carboniferous, Jurassic and Cenozoic times, and at a minima in Silurian-Devonian and Permian-Triassic rocks containing concentrations of evaporite deposits. Hydrocarbon occurrences were considered to correlate with source sediment maxima, with Tiratsoo (1984) showing that the worldwide percentage-by-weight distribution of crude oil and natural gas is greatest in Mesozoic reservoir rocks, followed by the Cenozoic and Palaeozoic.

A major Phanerozoic marine transgression was noted by Hallam *et al.* in 1983 and Exxon (Figure 1) to have occurred during the Cambrian. This occurred before marine life was sufficiently abundant or diversified to provide rich accumulations of organic matter. This transgressive sea-level was followed by a fluctuating period of marine sea-level regression throughout the remaining Palaeozoic, culminating in breakup of Pangaea during the late-Permian.

An extensive marine transgressive period again occurred during the mid-Jurassic and continued with minor setbacks until near the end-Cretaceous. This transgression formed the principle source sediments for fossil fuels in the Middle East, western Siberia, North Sea and Central America and Peru. North also records smaller transgressions during the Oligocene and Miocene which formed source sediments in the Californian, Caucasian, Carpathian and Indonesian provinces.

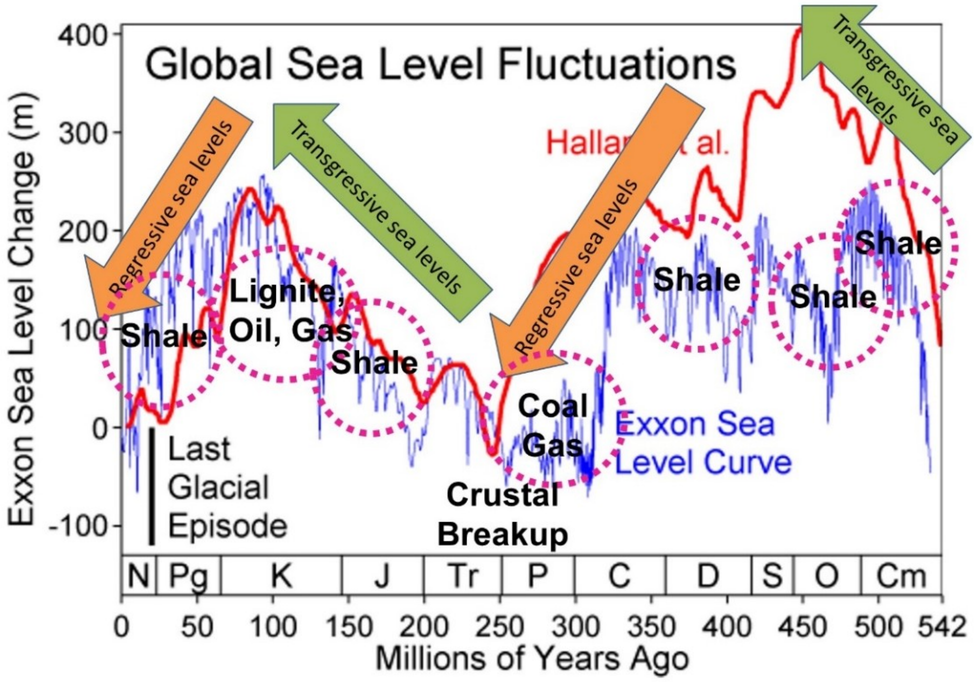

Figure 1 Major peaks in fossil fuel occurrences in relation to sea-level changes during the past 542 million years (sea level curves after Hallam *et al.*, and Exxon).

Shale Oil-Gas

Oil and gas shales are fine-grained sedimentary rocks containing significant amounts of kerogen and belong to the group of sapropel fuels. Most oil and gas shale formation took place during the mid-Cambrian, early- and mid-Ordovician, late-Devonian, late-Jurassic and Paleogene periods (Figure 1). These were formed by the deposition of organic matter in a variety of depositional environments including freshwater to highly saline lakes, epicontinental marine basins and subtidal shelves and were often restricted to estuarine areas such as oxbow lakes, peat bogs, limnic and coastal swamps, and peatlands. Continuous burial and further heating and pressure often resulted in the formation of petroleum and natural gas from the shale source rock.

The global distributions of assessed and non-assessed oil and gas shales are plotted on the Permian small Earth model (Figure 2). Data were sourced from the 2013 U.S. EIA report "Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries outside the United States".

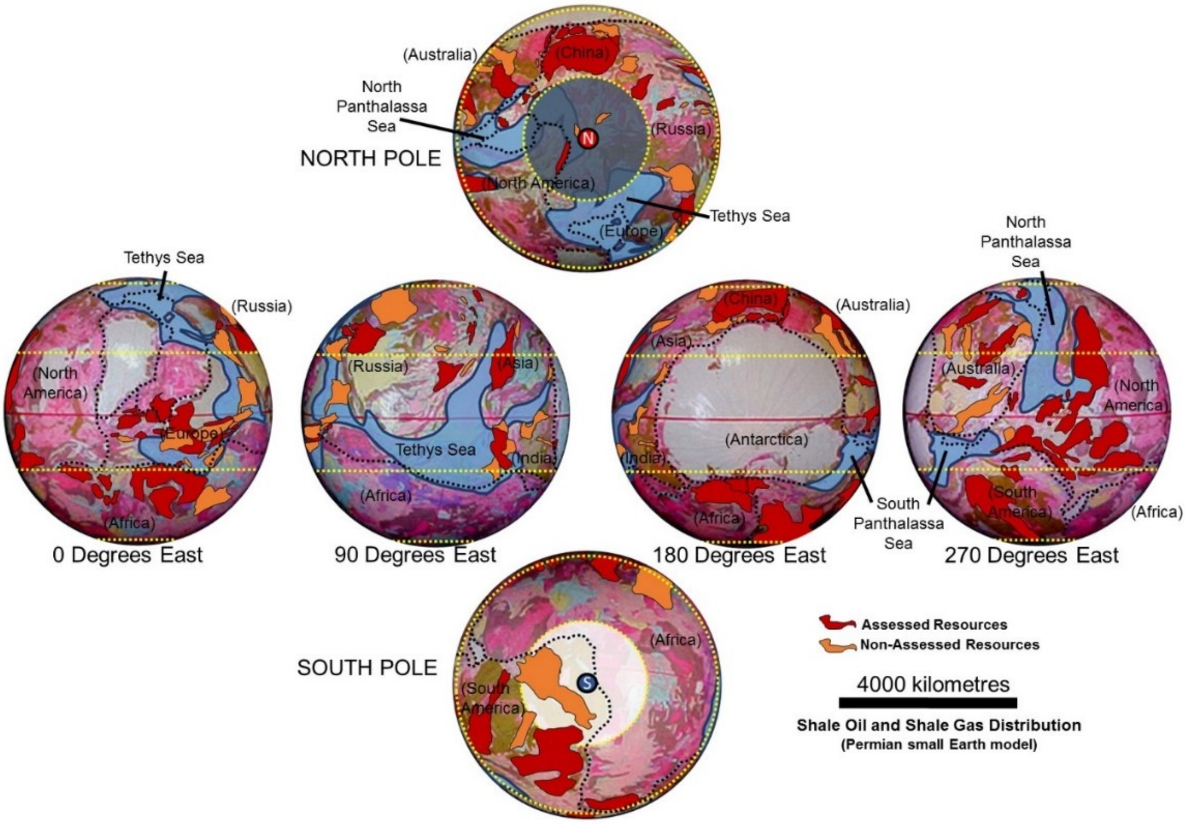

Figure 2 Permo-Carboniferous shale oil and shale gas distributions plotted on a Permian small Earth model in relation to climate zones, the late-Palaeozoic south polar ice-sheet, shaded white, and the distribution of ancient continental seas.

The distributions of oil and gas shales on the Permian small Earth model represent distributions covering the entire Palaeozoic Era. The plotted data show a global distribution extending from high northern to high southern latitudes. While a preference for terrestrial locations is evident in this figure, the changing configuration of continental seas during the earlier Palaeozoic times suggests that the majority of resources in Figure 2 may have been shallow marine with lesser terrestrial environments.

Permo-Carboniferous Coal

The late-Palaeozoic coal age of Calder & Gibling 1994 followed the evolution of vascular plants during the late-Silurian. The distribution of late-Palaeozoic to Triassic anthracite and bituminous coal is plotted on the Permian small Earth model in Figure 3 shown in relation to important coal swamp flora. The distribution of coal data is from the "Major Coal Deposits of the World" map (2010), and fossil data are from the PaleoBioDB, (2015). The coals, highlighted in yellow, are predominantly located within the northern temperate zone, but also extend from high northern to mid-southern latitudes.

The distribution of Permian and Carboniferous lepidodendron as well as glossopteris plant species in Figure 3 highlight the concentration of Permian lepidodendron within Laurasia—now China (orange dots), and Carboniferous lepidodendron within Laurentia—now North America (green dots), and a broad distribution of glossopteris species within both north and south Gondwana (red dots). Very little integration of these species is shown in this figure, possibly representing the presence of physical or environmental barriers such as climate, ancient seas, or topography. In all cases the distributions of these plant species are now constrained to known coal deposits within the northern and southern hemispheres.

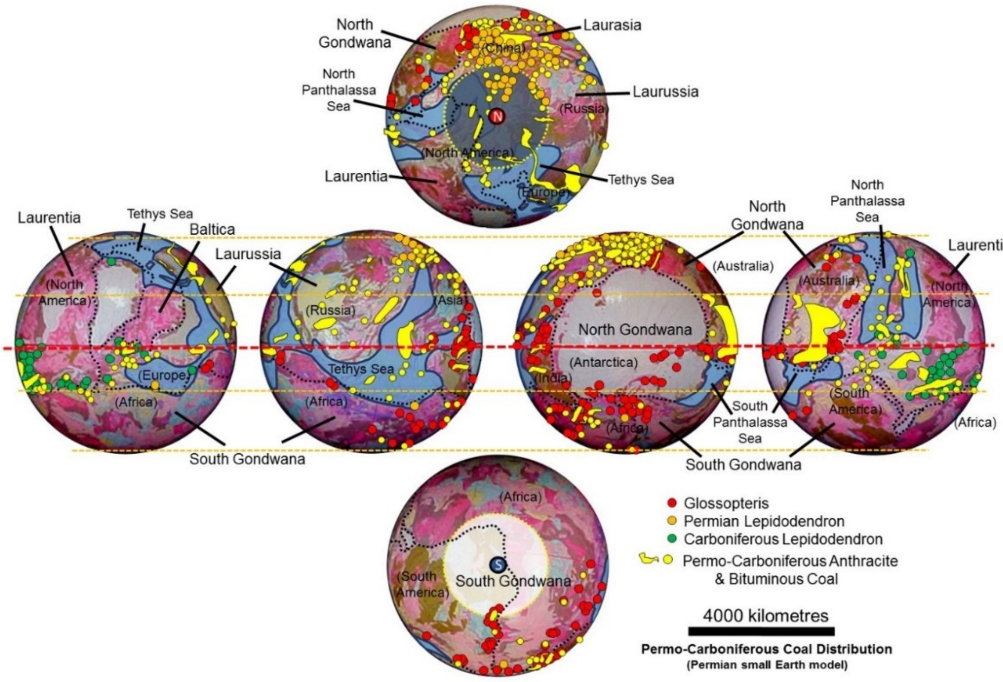

Figure 3 Permo-Carboniferous anthracite and bituminous coal distributions shown as yellow dots and shapes, after "Major Coal Deposits of the World" map (2010), plotted on a Permian small Earth model. The distribution of late-Palaeozoic Glossopteris data are shown as red dots, Permian Lepidodendron data as orange dots, and Carboniferous Lepidodendron data as green dots, after PaleoBioDB, (2015), in relation to climate zones, the late-Palaeozoic south polar ice-sheet, shaded white, and the distribution of ancient continental seas.

Cretaceous Lignite Coal

Cretaceous lignite coals were considered by McCabe and Parrish in 1992 to be distributed in a similar fashion to modern peats. These were further considered to form in mires—wet, soggy, muddy ground—within coastal regions, particularly near the equator where rainfall was presumably higher, or in high mid-latitudes where precipitation may have been relatively high and evaporation low.

Cretaceous lignite coal distribution is plotted on the late-Cretaceous small Earth model in Figure 4. Coal data was plotted after the "Major Coal Deposits of the World" map (2010). The distribution of lignite coal highlights the predominance of deposits located in the northern hemisphere, as noted by McCabe and Parrish, and these can be compared with the distribution of Permo-Carboniferous coals, shown as pale yellow shapes in Figure 4. On an increasing radius Earth, during the late-Cretaceous continental breakup, dispersal, and opening of the modern oceans was well advanced and the spatial configuration of continents was similar to the present-day. During that time sea levels and transgression of continental seas was at its maximum, prior to regression of the seas during the Cenozoic to the present-day configuration and distribution of oceans.

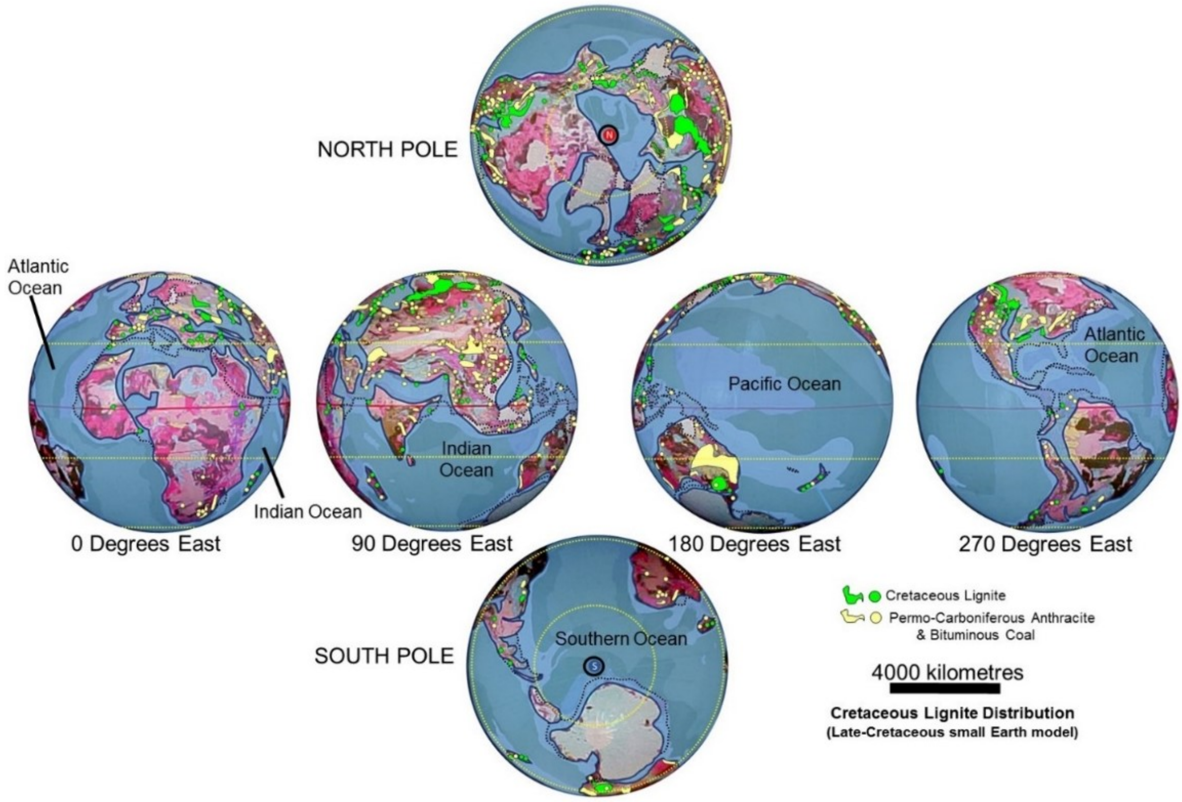

Figure 4 Cretaceous lignite coal distributions, highlighted in green, on a late-Cretaceous small Earth model. Lignite distributions are shown in conjunction with Permo-Carboniferous to Triassic coals, shown as pale yellow. Coal data after "Major Coal Deposits of the World" map (2010).

On small Earth models a latitudinal shift in Phanerozoic coal deposition, as noted by McCabe and Parrish, is a reflection of the rapid opening of each of the modern oceans, along with a northward migration of continents during the Mesozoic and Cenozoic Eras. The predominance of coal deposits in the northern hemisphere is attributed to the greater extent of available landmasses influencing rainfall, as well as the extent of remnant continental basins existing during periods of high sea levels suitable for coal formation in these areas.

Petroleum and Natural Gas

When viewed in context with global and transgressive-regressive sea-level changes (Figure 1) oil and gas development coincides with periods of peak sea-level transgression and maximum areas of continental seas and oceans. These conditions were considered by North to generate the most favoured early basin source sediments, forming at the peak of transgression following a trans-basinal unconformity. The Cretaceous, in particular, coincides with a period of post-late-Palaeozoic glacial melting, rapid opening of modern oceans, generally warm climatic conditions and rapid plant and animal diversification.

The distribution of petroleum and natural gas resources is shown on the Permian small Earth model in Figure 5. Cretaceous oil and gas resources are shown for context only. Petroleum and gas data were sourced from the "World Oil and Gas Map" (4th edition) produced by the Petroleum Economist (2013).

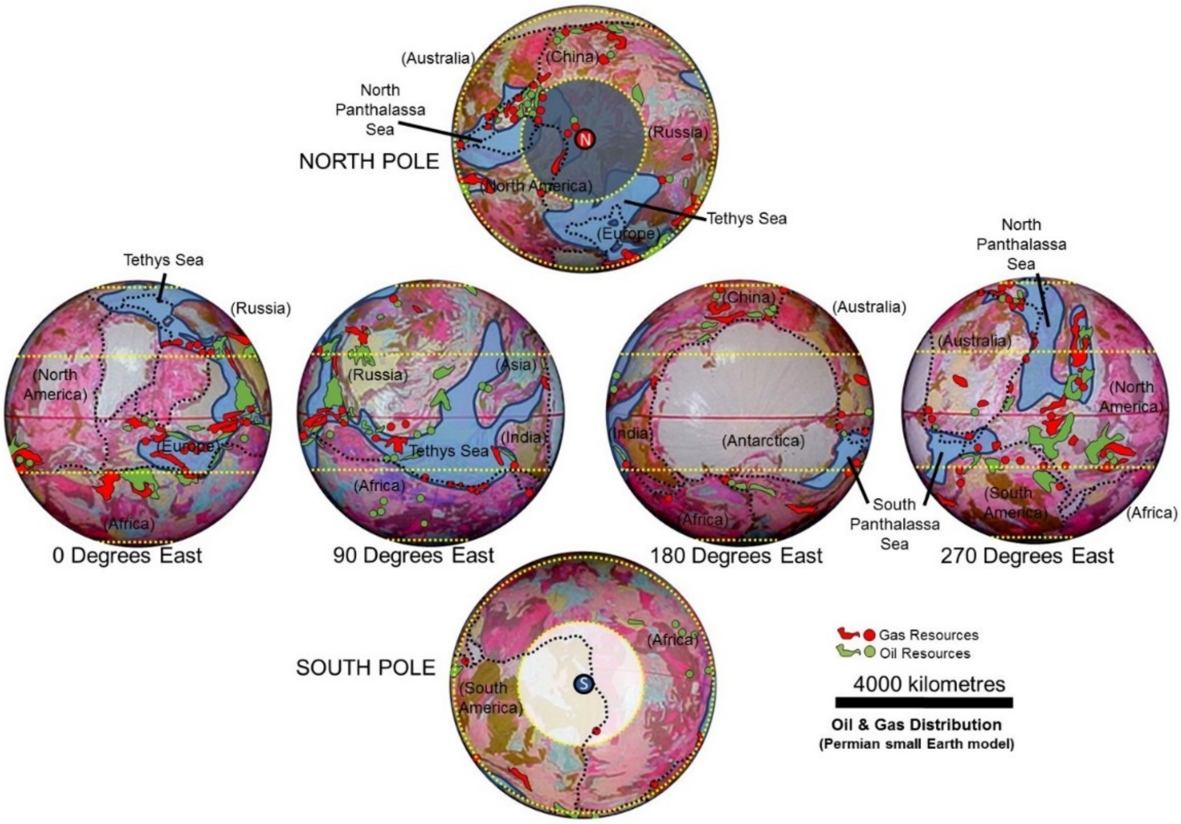

Figure 5 Oil (red shapes) and gas (green shapes) resource distributions shown on a Permian increasing radius small Earth model. Petroleum and gas data are sourced from the "World Oil and Gas Map" (4th edition) produced by the Petroleum Economist (2013).

Figure 5 confirms the distribution of both petroleum and natural gas coinciding with development of major Phanerozoic continental to marginal basin settings, with resources extending from high northern to high southern latitudes. A broad zonation of resources is evident in this figure, straddling the ancient equator and extending from low southern to mid-northern latitudes. This distribution highlights a northward shift in continents, and hence climatic zonation, over time.

Fossil Fuel Global Distributions

Plotting fossil fuel data distributions on small Earth models provides a unique opportunity to display the data holistically in relation to the distribution of ancient continental seas and supercontinental lands. The data for Phanerozoic shale oil and gas, coal, petroleum, and natural gas are summarised from previous Figures 2 to 5 and are layered onto the Permian small Earth model in Figure 6. Oil and gas shale distributions are shown as pink shapes, anthracite and bituminous coal distributions as yellow shapes, and petroleum and natural gas distributions are shown as green shapes. Cretaceous lignite coal distributions are not shown. Petroleum and natural gas distributions include major occurrences from the Cretaceous Period and are shown in Figure 6 for context only.

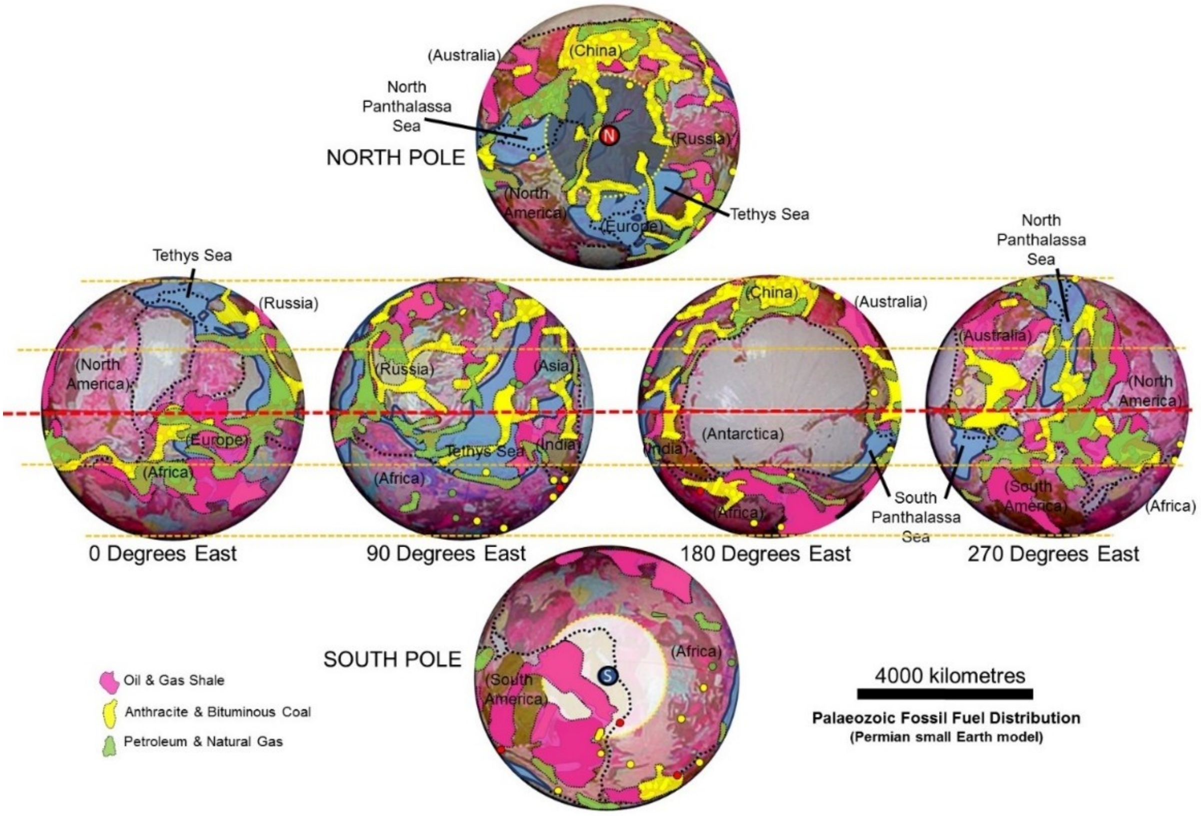

Figure 6 Compilation of oil and gas shale (magenta), coal (yellow), and petroleum and natural gas (green) distributions shown on the Permian increasing radius small Earth model.

The distribution of fossil fuels on the Permian small Earth model (Figure 6) coincides with the documented period of minimum sea levels occurring during the late-Palaeozoic (Figure 1). On an increasing radius Earth the Permian small Earth model represents a time of low sea levels prior to rupture of the Pangaean supercontinent to form the modern continents and opening of the modern oceans. This period was accompanied by regression and draining of continental seas from the supercontinental lands.

Most oil and gas shale deposits had already formed during the mid-Cambrian, early- and mid-Ordovician, and late-Devonian times. The declining sea levels during the Palaeozoic then favoured formation of coal deposits and these are highlighted in Figure 6 by the predominant global distribution of coals during the late-Carboniferous to Permian coal era within equatorial to high northern latitudes. The Permo-Carboniferous coal era terminated during the late-Permian and Triassic Periods during onset of the Pangaean supercontinental breakup and opening of the modern oceans. This event was followed by a rise in sea levels during the Mesozoic and renewed transgression of seas onto the lands.

Cretaceous lignite coal is not shown in Figure 6 but the distribution of lignite coal on the Cretaceous model (Figure 4) highlights the predominance of deposits located in the northern hemisphere. On an increasing radius Earth, during the late-Cretaceous, continental breakup, dispersal, and opening of the modern oceans was well established and the overall continental configuration was similar to the present-day. During that time sea levels and transgression of continental seas was at its maximum, followed by a regression of the seas during the Cenozoic to the present-day configuration of oceans. Similarly, peak petroleum and natural gas development coincides with the Cretaceous period of sea-level transgression and maximum surficial areas of epi-continental seas.

The distribution of all fossil fuels on small Earth models highlights the global interrelationships of resources coinciding with Palaeozoic continental seas and low-lying terrestrial environments. The transition from deposition of oil and gas shale to coal to petroleum and natural gas is consistent with the various periods of maximum and minimum sea level changes occurring during periods of marine transgression and regression.