# PROTEROZOIC HISTORY

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## Contents



## Summary

The transition between the Archean and the Proterozoic around 2500 Ma was characterized by some of the most significant changes in Earth's development. Many small continental blocks characterized the Archean, and in contrast, the Proterozoic plates were larger and more rigid and plate tectonic activity similar to modern analogs was possible. During the same overall transition period, the composition of the upper continental crust changed from tonalitic to granodioritic–granitic, and the atmospheric content of oxygen increased until it approached present day levels at the beginning of the Phanerozoic.

Stromatolites are some of the only known organisms from the Early and Middle Proterozoic. However, as climatic and atmospheric conditions changed towards the end of the Proterozoic, metazoans flourished, and in the early part of the Cambrian (during the so-called "Cambrian explosion"), the first organisms with mineralized hard body parts appeared.

## 1. Overview

The Precambrian Era (4500–544 Ma) spans almost 90% of Earth's history, hence an understanding of the geology and dynamics of this period is crucial for our understanding of Earth's geological development and ultimately, our present physical environment. The Proterozoic Eon represents the younger half of the Precambrian and is defined as the period from the end of the Archean at 2500 Ma to the beginning of the Cambrian Period (ca. 544 ma ago).

The gradual changes occurring in the transition period between the Archean, and the Proterozoic Eras are more drastic and more significant than those at any other point in Earth's history, hence a considerable amount of the text below is dedicated to this boundary.

The beginning of the Proterozoic Period at 2500 Ma represents a rather arbitrary division, however it coincides with a range of significant changes. These include, but are not restricted to, changes in the thickness, extent and tectonics of the oceanic and continental lithosphere, changes in the composition of the continental crust and sediments derived there from, and changes in the composition of the hydrosphere and atmosphere.

Many, small crustal blocks characterized the Archean Earth. During the later part of the Archean Era, these gradually merged and grew to form larger masses. The Early Proterozoic Era is marked by the earliest formation of several large, rigid continents. It is now generally accepted that plate tectonic processes very similar to those observed in the Phanerozoic orogens were active in the Proterozoic Era, hence the modern plate-tectonic paradigm is used as a descriptive framework here. It should be noted, that it is widely believed that some form of plate tectonics, including horizontal tectonics, were also active in the Archean Era, however the extent to which it resembled modern plate tectonic processes is strongly debated.

During the Early and Late Proterozoic Period, widespread orogenic activity along the margins of the continental blocks gave rise to the formation of extensive linear mountain belts during several phases of large-scale tectonism (mainly 2000–1800 Ma, and 1000–900 Ma). Figure 1 shows the distribution of Archean and Proterozoic rocks and the broad extent of Proterozoic orogens.

Figure 1.Schematic illustration of the distribution of Archean, Proterozoic and Phanerozoic rock. The map shows the configuration of continents at Permian time (286-248 Ma). The black areas indicate where Archean rocks make up a significant proportion of the exposed rocks. The gray areas show the extent of Proterozoic cratons and Archean rocks affected by Proterozoic orogenesis, and are surrounded by Phanerozoic cratons (e.g. Alpine-Himalayan belt) in white. Illustration from Windley (1977,) here reproduced with the permission of John Wiley & Sons, New York.

While rocks of Proterozoic age can be found on all continents (see Figure 1,) this section will focus much more on the general dynamic and rock-forming processes. Some field examples will be mentioned in the text, but it is meant to provide well-known occurrences rather than offer an exhaustive catalogue of Proterozoic rocks worldwide. For more information, the reader is urged to consult the literature, including the general reviews given in the reference list that may provide a good starting point.

## 2. Changes from the Archean to the Proterozoic: Plate Tectonics

One of the controlling physical parameters to have varied throughout geological time is heat flow. The heat flow observed at the surface results largely from the decay of radioactive elements in Earth's core, mantle, and crust. It is generally assumed that the heat flow was higher in the early part of Earth's history, and that it has decreased exponentially up through time. At 4500 Ma heat flow was ca. four times greater than present day values, and during the Proterozoic Period it decreased from ca. twice today's value at 2500 Ma to approximately today's value at the beginning of the Phanerozoic Era.

The decreasing heat flow through the Precambrian Period caused the lithosphere to become thicker and more rigid, and by approximately 2500 Ma, the continental lithosphere had obtained a degree of mechanical rigidity comparable to todays. This allowed plate tectonic processes similar to those observed in the Phanerozoic Era to take place, including all the elements of the Wilson cycle (i.e., opening and closure of ocean basins).

The upper continental crust in the Archean and Early Proterozoic Periods was of tonalitic composition. Through continued melting at upper mantle and lower crustal levels and emplacement of magmas at higher crustal levels, the overall composition of the upper continental crust gradually changed from tonalitic towards granodioritic and granitic (*i.e.*, from less siliceous to more siliceous).

The processes which lead to the initiation of subduction in the Early Proterozoic Era are not fully understood at present, however, at some point, the buoyancy contrast between the oceanic lithosphere and the asthenosphere underlying the continental lithosphere was sufficient to allow subduction. Once subducted, the push exerted on the oceanic plate by convective forces in the mantle and by material intruded and extruded at the mid-oceanic ridges provided the driving mechanism along with the pull provided by the negatively buoyant sub ducted slab.

Subduction of oceanic crust under the continental margins causes partial melting during descent. Fluids released from the sub ducted material (basaltic rocks of the oceanic lithosphere and sediments from the ocean floor and from the deep trenches along the continental margin) triggers melting in the upper mantle and the lower crust. These magmas intrude and extrude along the margin of the continents. The composition of rocks in these so-called *magmatic arcs* is controlled by the depth of melting, the thickness of overlying continental crust (i.e. distance from margin,) and the composition of the crust through which the magmas ascends. This compositional relationship is important for unraveling the geometry and development of Proterozoic collision and subduction zones as most evidence for the paleogeometry, and geography has been obliterated.

Subduction zones may develop slightly outboard of the continental margin, in which case the magmatic arcs will be hosted entirely by oceanic crust. These magmatic arcs can be accreted to the continent in several ways. As part of the overall collisional environment, translation along large- scale thrusts can juxtapose the magmatic arcs and the continental crustal block. In other cases, *back-arc basins* have developed between the continent and the magmatic arc, and when these close via subduction and collision, the magmatic arc will be juxtaposed, along with oceanic crustal material from the back-arc basin, with the continent.

The understanding of subduction and all the related processes have come largely from studies of younger, better preserved orogens, but most of the characteristic processes and features, including those mentioned above, can be identified in Proterozoic orogenesis.

Proterozoic orogenesis were for a long time believed to be largely ensialic, meaning that they developed in the internal parts of large crustal blocks, and that no oceans were generated or consumed during orogenesis. More recent data has allowed important modifications to this view, and most Proterozoic orogenic activity is now regarded in terms of the Wilson cycle, involving initial formation and growth of oceanic basins and subsequent ocean closure and collision between continental blocks. Many observations support this view, including: (1) provenance studies of sediments, which indicate that rocks now juxtaposed had distinctly different protoliths (e.g., because they were deposited on opposite sides of a developing ocean basin); and (2) recognition of components of ancient *ophiolites* (remnants of oceanic crust, for example pillow lavas, sheeted dykes, peridotites). The Cape Smith belt in northern Labrador, Eastern Canada, is a good example of an Early Proterozoic collisional orogen with well-preserved remnants of ophiolite.

## 3. Characteristic Lithologies of Proterozoic Age

A number of distinct rock types and -associations formed as a result of processes characterizing the Proterozoic Era, especially those related to the significant tectonic changes that occurred during the Late Archean—Early Proterozoic Eras. In the following, a selection of such rocks and their tectonic setting and compositional characteristics is described.

### 3.1 Basic Intrusive Rocks

After the growth and stabilization of the Late Archean—Early Proterozoic crustal blocks, the continents were subjected to extensional forces, and deep-seated major fault and fracture systems were established. These fractures and zones of weakness acted as conduits for a range of intrusive rocks, including those of basic to ultra basic composition, which are discussed here:

Giant basic dykes, the best known of which is the Great Dyke of Zimbabwe. This dyke is almost 500 km long, *ca.*6 km wide and was emplaced at *ca.*2500 Ma. This extensive body consists of several layered basic-ultra basic complexes, each generated as a result of an individual magma pulse. Compositionally, the layered complexes range from basal seams of chromites ($FeCr_2O_4$) up through a cycle of peridotites, pyroxenites, gabbros, and norites to quartz-gabbros. The overall composition is similar to alkaline olivine basalts.

Basic dyke swarms. The Archean terrains (both granite-greenstone belts and high grade gneiss terrains) and their Early Proterozoic cover rocks were cut by extensive swarms of basic dykes after 2700 Ma. Most of these were emplaced between 2500 Ma and 1500 Ma, but dyke swarms occur throughout the Proterozoic. Emplacement of these swarms is believed to be associated with crustal extension of up to 5% in some regions, to account for the extra space taken up by the dykes. Well known dyke swarms include the Scourie dykes in NW Scotland, Kangâmiut dykes in West and East Greenland, and the Mackenzie swarm in Canada. The latter extends for 3000 km and is up to 500 km wide. Many of the swarms were emplaced largely in intracratonic settings, and thus may reflect the continents' (incipient) attempt to rift.

The intrusion of such large volumes of basic material represents one of the major changes in magmatic and tectonic activity of the Earth during the Late Archean—Early Proterozoic transition. Dykes preferentially follow zones of weakness in the crust, hence their orientation give information about the stress-state of the crust, and therefore the larger scale tectonic configurations at the time of emplacement. Compositionally, the dykes vary from basic to ultra basic, however Fe-rich holistic compositions are most common. The generation of these magmas requires substantial fractionation of the parental magma prior to emplacement. The final magma composition may also be modified by contamination from continental crust host rocks, however, the magnitude and significance of this is a much-debated issue.

Layered complexes. Two large basic layered complexes stand out: The Stillwater complex in Montana is of Late Archean age (ca. 2750 Ma) and is composed of unmetamorphosed basic to ultra basic rocks. The complex was originally emplaced as a broadly horizontal sheet in Archean gneisses and supracrustal metasediments, but was subsequently tilted to its present, steeply dipping position. A maximum stratigraphic (composite) thickness of 6 km is presently preserved. The Bushweld complex in South Africa was emplaced at ca. 2000 Ma and constitutes the largest igneous body on Earth. The complex covers 66 000 $km^2$ and has preserved a vertical stratigraphic thickness of up to 8 km. The central part of the complex is made up largely of (younger) granitic rocks and the two marginal lobes are composed of dunites to norites, anorthosites, and ferrodiorites, including the Pt, Ni-rich unit called the Merensky Reef. In the basal parts of the ultra basic units, there are huge reserves of Pt-group elements, Cu, Ni, Au, and V. The younger granitic rocks are rich in Sn, and F.

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## Biographical Sketch

**Flemming C. Mengel** is a Danish citizen, who received his M. Sc. degree from the University of Aarhus, Denmark in 1982 (on metamorphism and geo chemistry of mafic dykes from SW Greenland). From 1983 to 1987 he was at Memorial University of Newfoundland, Canada, funded by scholarships from the University of Aarhus and from Memorial University of Newfoundland. His Ph. D. thesis was finished in 1987 and was on the structure and metamorphism of the Archean–Proterozoic transition in the Torngat Orogen, Northern Labrador. From 1988 to 1994, Dr. Mengel held post-doctoral positions at Memorial University of Newfoundland, University of Toronto, INRS-Georesources at Centre Geoscientifique du Quebec and Geological Museum, Copenhagen. From 1994 and 1998, Dr. Mengel was a senior researcher at the Danish Lithosphere Center, Copenhagen, and worked on the structural and metamorphic evolution of the Nagssugtoqidian Orogen in West Greenland. In June 1998, Dr. Mengel accepted employment with Conoco Inc., a major integrated oil and gas company. The first assignment was in Midland, Texas, and was a structural evaluation of hydrocarbon plays in the Appalachian Orogen. Presently, Dr. Mengel is an exploration and development geologist in the Lobo Asset Team, and has relocated to Houston, Texas. Dr. Mengel has authored or co-authored 25 papers and 50 abstracts, mainly on structural and metamorphic aspects of pre-Cambrian geology in Labrador and Greenland.