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Research Paper

Proterozoic Environment and Snowball Earth- A Review

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ABSTRACT
The time period between 2500 M.y to 500 M.y is known as Proterozoic era. During this period the earth underwent many environmental changes. These environmental changes were linked to tectonic activity and silicate weathering. The super continental cycle caused opening of Purana basin I, II and III. These geological processes lead to the development of nascent life forms. Due to the low oxygen level and N-stress condition cyanobacterias existed in deep ocean whereas eukaryotic life existed in the marginal marine environment. The oxygen level crossed minimum threshold value at 570 Ma, causing explosion of life. The tectonism, silicate weathering and high obliquity of earth caused at least five intense glaciations during Proterozoic. During glacial periods land masses as well as marginal marine environment were ice free whereas open oceans were covered with ice. The carbon isotope studies indicate that there were holes in the global ocean ice cover. The Neoproterozoic ocean was animated. The BIF reappeared during Neoproterozoic glaciations. It suggests that deep sulphidic ocean was not a wide spread phenomenon. The erosion of mafic Archean crust and intense tectonic activity were *the reason behind the BIF deposition during Proterozoic.*

KEY WORDS: *Neoproterozoic; Purana basin; ocean; weathering; climate; Palaeoenvironment; Snowball earth*

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I. INTRODUCTION

The Proterozoic era was a time period between 2500 M.y to 500 My. In India Proterozoic deposits can be seen in Purana basins I, II and III (e.g., Krishnan 2006). These are Cuddapah, Chhattisgarh Vindhyan, Indravati, Khariar, Prahnita-Godavari, Kaladgi, Bhima, Kunigal, Kurnool and Marwar basins (e.g., Meert and Torsvik 2003; Malone et al 2008; Chakrabory et al 2012).

This era has witnessed many environmental changes (e.g., Meert and Torsvik 2003). The earth got oxygenated during this period (e.g., Zhou and Och 2011). This was time during which life developed in this planet in its simplest forms (e.g., Anbar and Knoll 2002). During Proterozoic era there were at least five intense glaciations (e.g., Sankararn 2003). The BIF appeared, disappeared, reappeared and then disappeared during this period. During this period the anoxic ocean turned oxic even at the deeper level (e.g., Hoffman et al 1998; Anbar and Knoll 2002). This was also a time of formation and breaking up of supercontinents. There is a link between tectonism, oxygenation, changes in Proterozoic ocean chemistry and evolution of life (e.g., Hoffman et al 1998; Anbar and Knoll 2002; Zhou and Och 2011).

The geochemistry of Proterozoic sediments was entirely different from Archean sediments. This is because Archean crust was mainly mafic in nature whereas Proterozoic crust was mainly felsic (e.g., Raza et al 2010). Tectonism mainly controls the chemical composition of sedimentary rocks (e.g., Osae et al 2006). With the help of major, trace and rare earth element analysis it is easy to understand provenance, palaeoweathering , tectonic setting and environment of deposition of sediments (e.g., Mishra and Sen 2012). The objective of this work is to reconstruct Proterozoic environment, to understand Proterozoic biosphere, to study snowball earth hypothesis and to understand environment of deposition of BIF.

II. TECTONISM

Proterozoic was the time of supercontinent cycle (e.g., Anbar and Knoll 2002; Donnadieu et al 2004). At the time of Palaeoproterozic there was a supercontinent called Columbia which parted away and formed Rodinia at the time of Mesoproterozoic. The Rodinia split apart around 800 Ma. After 650 Ma, plate tectonic activity increased and which culminated in the formation of Gondwana supercontinent around 520 Ma (e.g., Meert and Lieberman 2008; Malone et al 2008; Zhou and Och 2011). The intense tectonic activity during Proterozoic era has ultimately lead to oxygenation of earth, global glaciations and evolution of life (e.g., Hoffman et al 1998; Anbar and Knoll 2002; Ray 2006; Zhou and Och 2011).

III. OXYGENATION OF EARTH

There was a Great Oxygenation Event at around 2.4 Ga (GOE) and Neoproterozoic Oxygenation Event (NOE) almost 2 billion years later (e.g., Zhou and Och 2011). When tectonic activity is high there will be increased organic carbon burial and which in turn release oxygen to the atmosphere (e.g., Millis et al 2014). The increase in oxygen level lead to the development of life in its simplest forms. However Neoproterozoic ocean was sulphidic and ferruginous in nature, and life was adapted to this environment (e.g., Anbar and Knoll 2002; Canfield 2008; Zhou and Och 2011). Even during NOE there was wide spread oceanic anoxia. At the time of Rodinia eukaryotic life forms diversified, but during glacial period the diversification ceased and it restarted after glaciations. At 635 Ma metazoans developed. However, the evolutionary link between unicellular to multicelllar life never broken. Evolution of life happened gradually (e.g., Zhou and Och 2011). After Cambrian the life evolved rapidly because the oxygen level crossed minimum threshold value. This minimum threshold value reached around 570 Ma. Eukaryotic life forms required bio essential trace metals such as Fe and Mo for N_2 fixation and NO_3^- assimilation (e.g., Anbar and Knoll 2002). During Mid-Proterozoic Fe, Mo and other bio-essential trace elements were very low in the oceans. Hence there was N stress in the ocean during Mid-Proterozoic. Eukaryotic life forms cannot adjust with N stress environment (e.g., Anbar and Knoll 2002; Donnadieu et al 2004). Hence they were limited to marginal marine environments. The cyanobacterias were able to adjust with N stress condition, so they existed in the deep ocean during Mid-Proterozoic (and even during during Neoproterozic global glaciations). For evolution of life there must have been an ecological cause and a genetic cause. The tectonism and oxygenation were the ecological cause (e.g., Hoffman et al 1998; Anbar and Knoll 2002; Zhou and Och 2011).

IV. GLOBAL GLACIATIONS

Tectonic activity silicate weathering and ice albedo effects were cited as the reasons for Proterozoic global glaciations (e.g., Hoffman et al 1998; Sarin 2001). Increased CO_2 draw down due to increased silicate weathering will ultimately lead to global glaciations. The atmospheric CO_2 reduction will be possible up to a balancing point and beyond which mantle degassing begins as a feed back mechanism (e.g., Sarin 2001; Donnadieu et al 2004).

Among the five glaciations during Proterozoic, the Neoproterozoic glaciation was the most intense one (e.g., Sankararn 2003). Due to continental break-up there were two intense glacial periods i.e. between 716- 670 Ma and 650- 635 Ma, which reached even at low latitudes called Snow Ball Earth hypothesis. During snowball earth, the world ocean was covered with ice and land masses were ice free (e.g., Hoffman et al 1998; Donnadieu et al 2004). The evidences are (1) palaeomagnetism, (2) occurrence of BIF, (3) higher ^{12}C ratio during snowball earth, indicating organisms were rarely present. However Kennedy et al (2001), found high ^{13}C ratio during Neoproterozoic, indicating presence of life. Hence there were holes in the global ocean ice cover during Neoproterozoic. The pre-glacial deposits have high value of $\delta^{13}C$, which became low during glacial periods. After glaciation cap carbonate was deposited, having high $\delta^{13}C$ value. Carbonate deposits in warm alkaline condition, (4) high obliquity (54^0) during Proterozoic (e.g., Williams 1994; Hoffman et al 1998; Sankararn 2003; Donnadieu et al 2004). The snowball earth ended 590 M.y ago and the reason may be the mantle degassing occurred in connection formation of Gondwana supercontinent. The glacial units- Chuos Formation and Ghaub Formation of Namibia have age from 700 to 760 M.y. They were at low latitudes during Neoproterozoic (e.g., Hoffman et al 1998; Anbar and Knoll 2002; Zhou and Och 2011).

During Neoproterozoic India was 30^0 to 15^0 N latitude (e.g., Torsvik et al 2001; Meert and Lieberman 2008). The high CIA values of Neoproterozoic deposits of Bhima basin, India, Buem sandstone, Southeastern Ghana and presence of mega fossils in the Neoproterozoic deposits of Vindhyan basin, India suggest that marginal marine environments were ice free during this time (e.g., Kumar and Srivastava 2003; Osae et al 2006; Nagarajan et al 2007). The depleted oxygen isotope value reported for Neoproterozoic Shahabad Formation, Bhima basin, Karnataka suggests that shallow sea was warmer (e.g., Nagarajan et al 2008; Sreedhar 2010). Since mid Proterozoic, warm humid climate prevailed in the land areas (e.g., Tripathy and Rajamani 2003; Rashid 2005; Mishra and Sen 2012). Hence it is highly probable that there existed water circulation from warm shallow sea to cool open ocean since mid-Proterozoic (e.g., Sreedhar 2010). However Hoffman et al (1998), reported that the world ocean was inanimated during Neoproterozoic snowball earth. By considering supercontinental cycle, high obliquity of earth and less luminous sun, it is highly probable that there were many Snowball earths during Proterozoic. During Neoproterozic, the separated micro continents were clustered around low latitude and which in turn caused increased weathering, CO_2 draw down and glaciation of global extent. If the micro continents are clustered around mid-high latitude the climatic parameters will not be sufficient to create a global glaciation and this was the situation during Gaskiers glaciations of 580 to 565 Ma (e.g., Donnadieu et al 2004).

V. BIF DEOPSITION

Before 1800 M.y oxygen level was low at surface environment and oceans were anoxic. During this time Banded Iron Formation (BIF) was deposited, because of alternate precipitation of Fe^{2+} and silica (e.g., Krishnan 2006; Anbar and Knoll 2002). After 1800 Ma oxygen increased at the surface level and deep ocean became sulphidic in nature. When oxygen level increased, there was more SO_4^{2-} input to the ocean. The SO_4^{2-} reacts with organic C resulting in the formation of H_2S, the cause for the deep sulphidic ocean (e.g., Anbar and Knoll 2002; Kah et al 2004). Increases in the δ^{34} S isotope fractionation, increased pyritisation and high ratio of reactive Fe in pyrite/Total Fe are the evidences for deep sulphidic ocean. During this time Fe^{2+} forms insoluble sulphidic complex, the BIF disappeared (e.g., Krishnan 2006; Anbar and Knoll 2002; Kah et al 2004). During Neoproterozoic, the oceans became anoxic due to ice cover which in turn resulted in the reappearance of BIF (e.g., Anbar and Knoll 2002). Since Fe forms insoluble complex under sulphidic ocean, the reappearance of BIF indicate that only oceans with restricted circulation were sulphidic during Neoproterozoic (e.g., Reinhard et al 2013). There were many Oceanic Anoxic Events (OAE) in the geological history (e.g., Leckie and Bralower 2002; Grocke et al., 2011) but BIF never reappeared after Proterozoic era. The predominantly mafic nature (e.g., Raza et al 2010) of Archaen crust (which became mainly felsic during Proterozoic) and intense tectonic activity might be the reason for the BIF deposition during Proterozoic.

VI. CONCLUSION

There is a connection between tectonic activity, oxygenation of earth and evolution of life. Since mid proterozoic cyanobacterias were thrived in the deep ocean whereas eukaryotic life forms existed in the marginal marine environment.

During Neoproterozic the separated microcontinents were clustered around low latitude and this was the reason behind Neoproterozoic snowball earth. During glacial periods marginal marine environment as well as land masses were ice free. Since mid-Proterozoic there existed water circulation from warm shallow sea to cool open ocean and warm humid climate prevailed in the land areas.

BIF deposition took place before 1800 Ma, during which oceans were anoxic. After 1800 Ma deep oceans became sulphidic and as a result BIF disappeared. Oceans with restricted circulation only had sulphidic bottom waters. Although there were many oceanic anoxic events in the geological history, the BIF never reappeard after Proterozoic. The erosion of mafic Archean crust and intense tectonic activity might be reason behind Proterozoic BIF deposition.

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