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Snowball Earth: A Critical Review on Neoproterozoic Glaciation

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Abstract : The Snowball Earth envisaged multiple globally synchronous glaciations persisted for millions of years during Neoproterozoic era leading to a frozen earth. Geological and palaeomagnetic evidences advocate ice sheets may have reached even the tropic caused by 'runaway ice-albedo feedback' due to an unusual prevalence of land masses in the middle and low latitudes. Association of glacial successions with warm lithologies is suggestive of a rapid transition between icehouse and greenhouse. Snowball Earth holds its appeal providing credible explanations for many enigmatic features of Neoproterozoic world. However, critical examination of sedimentological evidences, stratigraphic data and climatic simulation suggest that despite the severity of glaciations some oceans perhaps essentially remained ice-free which were effective for the survival and evolution of early life and continuation of the global carbon cycle as well as hydrologic cycle.

Keywords: Neoproterozoic, Glaciations, Snowball Earth, Slushball Earth

Prologue

The idea of a frozen earth, "complete global glaciation", is not new but always fascinating. Swiss natural scientist Louis Agassiz in 1837 used the term "die Eiszeit" for a great ice age that covered the Earth and killed all life, after which species were regenerated. The roots of the Snowball Earth hypothesis surfaced from the idea of a global glaciations anticipated by Harland, (1964). The term "Snowball Earth" was first coined by Kirschvink, (1992), and the hypothesis was formulated by Hoffman et al., (1998) and Hoffman and Schrag, (2002). Since its inception, many facets of this enigmatic hypothesis have been scrutinized and numerous articles were published in different high impact scientific journals (ca. Hyde et al., 2000; Schrag et al., 2002; Higgins and Schrag, 2003; Pierrehumbert, 2005; Corsetti et al., 2006; Hoffman and Li, 2009; Herwartz et al., 2015; Keller et al., 2018 and references therein). There has been much arguments on the global character of Neoproterozoic ice ages regarding the number of glaciations, their time and durations, latitudinal position, the impact of the possible clustering of continental masses in relatively low latitudes; the sedimentary characteristics, structures ; and isotopic geochemistry of the unusual carbonate rocks immediately associated with the glacial sediments, the climate modeling of the initial glaciations and final escape from a global frozen condition, the modelingof the global carbon cycle; and the oceanic iron deposition (ex. Evans et al., 2000; Etienne et al., 2006; Fairchild and Kennedy, 2007). Snowball earth hypothesis itself has been repeatedly questioned for its scientific validity and limitations (Hyde et al., 2000; Runnegar, 2000; Etienne et al., 2006; Allen and Etienne, 2008; Moczydłowska, 2008). Global distribution of the Neoproterozoic glaciations (preferably at low- to mid- latitudes) and deposits of their aftermath is well demonstrated from almost every continent (Evans, 2000; Hoffman and Schrag, 2002; Hoffman and Li 2009; Evans and Raub, 2011 and references therein). Despite continuing debate, this hypothesis remains an attractive model for evaluating the interesting geological record of Neoproterozoic Earth. However, the survival issue of early life at that time and their evolution in such an environmental stress is critical to answer, for which the model of 'hard' Snowball Earth had been gradually ruled out and an alternative Slush ball (or 'soft' Snowball) Earth model was proposed simultaneously and globally accepted. The current paper presents a brief review on the enigmatic Snowball Earth hypothesis by critically examining the substantial articles published, so far, related to this topic.

Snowball Earth hypothesis

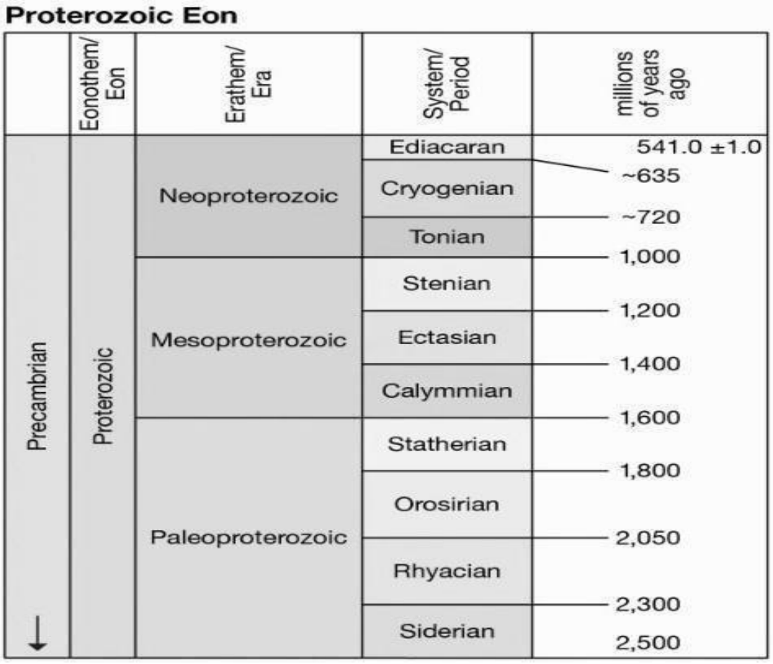
The snowball Earth hypothesis predicts that the entire Earth was covered with ice several times during the Precambrian. The essence of this concept, as postulated by Joe Kirschvink, is an unusual prevalence of land masses in the middle and low latitudes, by raising the planetary albedo with a 6% lower solar constant compared with today leading to a globally frozen Earth (Allen and Etienne, 2008). Kirschvink, (1992) analyzed the palaeomagnetic and sedimentological evidence suggesting that equatorial glaciers descended to sea level and led to ocean anoxia and deposition of iron-oxide formations. He highlighted three implications of his hypothesis which were later tested by Hoffman and Schrag, (2002): a) "glacial units should be more or less synchronous Harland, (1964)"; b) rocks from different continents that preserve a record of rapid climatic fluctuations (glacial units commonly associated by carbonate rocks, a warm water deposit, implying interchange of ice house and greenhouse states) might bear an overall similarity in lithologic character and this would be a result of the global scale of the climatic fluctuations; c) the presence of floating pack ice should minimize evaporation, disconnect oceanic currents from wind patterns and weaken ocean water circulation resulting in ocean anoxia. These would encourage gradual build up of banded iron formation in upwelling areas (generated at the mid-oceanic ridges or leached ferrous iron from the sediments later oxidized during the end of glaciation). The hypothesis is incapable to state directly how the glaciations may be initiated. However, combination of lower solar luminosity (Crowley and Baum, 1993), substantially higher albedo in the tropic to subtropic latitude due to accumulating landmass (Kirschvink, 1992), supercontinental rift-related chemical drawdown of atmospheric CO_2 as a result of high silicate weathering rate (Worsley and Kidder, 1991) and weakening of meridional heat transport by the Hadley cells (Hoffman and Schrag, 2002) may had input to the refrigeration process lead to the growth of large ice caps, nucleated on islands or continents bordering the polar seas.

Neoproterozoic glacial records and Indian context

Neoproterozoic (1000-541Ma), the youngest Precambrian era, is one of the most significant episodes of geological time scale in terms of tectonics, climate and life on earth. It is known for several crucial geological events: a) formation of Rodinia, its breakup and reassembly into a different configuration; b) extensive global glaciations and c) first appearance of ideal metazoans (multi celled animals) bridging the biological transition of pre-Ediacaran to the Phanerozoic counterparts (Seilacher etal., 1998; Hyde et al., 2000; Smith, 2015). The Neoproterozoic era is divided into three periods, Tonian (oldest, 1000-850Ma), Cryogenian (middle, 850-635Ma) and Ediacaran (youngest, 630-541 Ma) (Fig. 1). The name of Cryogenian is derived from cryos (ice) and genesis (birth), as it reportedly includes at least two major glaciations, the younger known as the 'Marinoan' (660-635 Ma), and the older as the 'Sturtian' (ca. 717-660 Ma) besides the controversial Kaigas glaciations (ca. 740) or short spelled middle Ediacaran Gaskiers glaciation (Li et al., 2013; Rooney et al., 2015; Smith, 2015 and references therein).

Neoproterozoic glaciogenic sequences are globally reported from the sedimentary successions in all seven of the present continents (Fig. 2) (Evans, 2000; Hoffman and Schrag, 2002; Hoffman and Li, 2009; Evans and Raub, 2011 and references therein). Diamictites and ice-rafted dropstones within Elatina Formation of South Australia, Striated pavement and Smalfjord diamictite of north Norway, Jbe´ liat diamictite of Mauritaunia, Rapitan diamictite and dropstones at Stone Knife River, Mackenzie Mountains, northwest Canada, Ice-rafted dropstone and Ghaub diamictite of north-west Namibia, Tambien Group tillite in N. Ethiopia, and Atud conglomerate dropstones from Egypt are some well known example of Neoproterozoic glaciations on the Earth (Hoffman and Schrag, 2002 and references therein; Stern et al., 2006). It is interesting and critical to note that, within the Neoproterozoic sedimentary sequences the common association of glaciogenic rocks with apparently low-latitude warm lithological indicators like carbonate rocks and even evaporites (Williams, 1975; Kirschvink, 1992; Evans, 2000 and references therein). Many of these glacial units are reportedly preceded as well as succeeded by thick carbonate sequences.

Among the Indian Proterozoic Basins (Fig. 3) in Peninsular India, some do not fit geochronologically and the rest comprise, as reported so far, the Neoproterozoic sediments devoid of any convincing field evidence of glacial activity; except one controversial report from Marwar Basin in western Rajasthan. Age of Vindhyan Basin had been assigned to Meso-Neoproterozoic (Bose et al., 2001). However, detrital zircon analysis of the Upper Bhander Sandstone, the top most unit of Vindhyan Basin, identifies a youngest age population at ~1020 Ma (Malone et al., 2008); thereby suggesting Vindhyan sedimentation perhaps ceased almost at the Meso-Neoproterozoic boundary. Patranabis-Deb et al., (2007) published a similar age of the Chattisgarh Basin on the basis of zircon U–Pb direct dates (990, 1015, and 1020 Ma) on tuff layers near the top of that basin. Data for Bhima and Kaladgi-Badami basinsare either unavailable or inadequate for chronostratigraphic correlation. These basins have been considered as "possible Neoproterozoics". Kurnool Group of rocks, comprising conglomerate associated with limestone topped by calcareous shale, within the Cuddapah Basin are not older than 1090 Ma and may even be younger than 870 Ma (Crawford and Compston, 1973; Nagaraja Rao et al., 1987).However, a shallow to deep-water carbonate platform (Patranabis-Deb et al., 2012) so far has no record of glaciogenic deposit within this structurally deformed basin. Within the Pranhita- Godavari Basin, the Sullavai Group of rocks represents the Neoproterozoics (K-Ar date: 871±14Ma; Choudhury et al., 1999); though thorough field study (Chakraborty et al., 2010; Choudhury et al., 2012) does not satisfy the claim of Evans, (2000) (see Fig. 1, location no. 38 & Table 2) for "demonstrable glacial influence" within this basin (Evans and Raub, 2011). Within the Indravati Basin the Jagdalpur Formation, reported with a carbonate shelf paleogeography, represents the Neoproterozoic age (Ramakrishnan, 1987). No glacial feature has been recorded so far within this basin too. From the Jodhpur Group of Neoproterozoic Marwar Supergroup in western Rajasthan, Chauhan et al., (2001) reported Pokaran boulder bed comprising massive conglomerate, boulder spread and stratified conglomerate. They interpreted that the boulder spread is glaciogenic, whereas the stratified conglomerate is a product of glacio-fluvial action. However, there have been many arguments regarding the sedimentological inferences drawn by the authors. Perhaps the single globally acclaimed and established record of Neoproterozoic glaciation from India is the Blaini boulder bed near Solan (Himachal Pradesh) in Lesser Himalayan (Fig. 3). The diamictites and capping pink limestone of Blaini Formation, Baliana Group in extra peninsular India managed space in the global map of Marinoan glacial deposits and have been certified to the Neoproterozoic Snowball Earth event and its aftermath, respectively (Oldham, 1887; Holland, 1908; Auden, 1934, p.374; Evans et al., 2000, see Fig.1, location no. 37 & Table 1; Jiang et al., 2003; Kaufman et al., 2006; Hoffman and Li, 2009, see Fig. 1 & Table 1; Etienne et al., 2011; Hoffman, 2011; Tewari, 2012; Hoffman et al., 2017). However, Dey et al., (2020) critically reviewed the existing literatures and inferred based on their field observations that Blaini diamictite and the associated sediments possibly characterize "the prologue of Proterozoic Snowball Earth and not its aftermath".



Proterozoic Eon

	Eonothem/ Eon	Erathem/ Era	System/ Period	millions of years ago
Precambrian	Proterozoic	Neoproterozoic	Ediacaran	541.0 ±1.0
			Cryogenian	~635
			Tonian	~720
		Mesoproterozoic	Stenian	1,000
			Ectasian	1,200
			Calymmian	1,400
		Paleoproterozoic	Statherian	1,600
			Orosirian	1,800
			Rhyacian	2,050
↓			Siderian	2,300
				2,500

Fig.1. Geological timescale for Proterozoic Eon; modified after 2016International Chronostratigraphic Chartproduced by the International Commission of Stratigraphy (ICS).

Snowball Earth vs. Slushball Earth

The Snowball Earth concept, foretells extreme glaciation leading to an entirely frozen Earth for millions of years, caused by runaway ice-albedo feedback. It explains, as Hoffman and Schrag, (2002) summarized, some mysterious phenomenon of Neoproterozoic Earth: (1) the widespread distribution of Neoproterozoic glacial deposits in almost every continent; (2) the palaeomagnetic evidence that glaciation extended close to the equator for long periods; (3) the stratigraphic evidence that glacial events began and ended abruptly; (4) the world-wide occurrence of cap carbonates (commonly indicative of warm water) sharply overlying and sometime underlying also the glacial units and thereby suggesting rapid climatic warming following an ice age; (5) the reappearance of iron formations, exclusively within glacial units, after an absence of 1.2 billion years, thought to reflect ocean anoxia during a long period of ice cover; (6) the existence of very large positive and negative δ13C anomalies, before and after each glacial event, respectively.

Hypothetical variations of Snowball Earth model could range from extensively severe, with the entire ocean frozen over ~10My, "hard" snowball Earth (Hoffman et al., 1998; Evans, 2000) to relatively mild, whereby the latitudinal range of continental ice sheets simply advanced from the polar regions to the equatorial belt, without substantial equatorial sea ice ("soft" snowball Earth). Low-latitude glaciation is the cornerstone of the Snowball Earth hypothesis (Kirschvink, 1992; Hoffman et al., 1998). Another key element of the Snowball hypothesis is that the glaciations should have been long-lived (up to tens of millions of years) in order to atmospheric CO_2 concentrations attaining the levels required to overcome the high-albedo effect of low-latitudes glaciation and trigger melting (Caldeira and Kasting, 1992; Hoffman et al., 1998; Pierrehumbert, 2004). The ocean's thermal inertia resists the ice advance initially (Poulsen et al., 2001), but the ocean is a finite heat reservoir and cooling over thousands of years would leave it powerless to resist the ice encroachment. It is also uncertain if the tropical ocean would ever become entirely ice covered (Hyde et al., 2000; Runnegar, 2000; Baum and Crowley, 2001; Warren et al., 2002; Lewis et al., 2007; Micheels and Montenary, 2008). Kirschvink, (1992) speculated that areas of open water (polynyas) would remain, tracking the zone of highest solar incidence back and forth across the equator and imparting a strongly seasonal climate even at low latitude. Evidence for thick accumulations of glacial sediments and at least transiently open water conditions (McMechan, 2000; Leather et al., 2002), have led some authors to support a less severe climatic scenario-Slushball Earth hypothesis, a counter-premise to the hard Snowball Earth concept. The "slushball" or "soft Snowball" hypothesis was developed by American geologist Richard Cowen and later postulated as a 'loophole' model by Hyde et al., (2000) arguing that Earth was not completely frozen over during periods of extreme glaciation in Precambrian time. Rather some seaways remained open near the palaeo equator. Under this scenario, photosynthetic organisms in low-ice or ice-free regions could continue to capture sunlight and survive long periods of extreme cold. Schrag and Hoffman, (2001) found this alternative 'loophole' model less attractive as it compromises many of the valid explanations given by Snowball Earth model. They, accompanied by other hard Snowball scientists remarked that the Slushball state requires more extensive modeling. They also claimed that as the observations have no parallel in the Phanerozoic, it should not be surprising that the events responsible for them have no Phanerozoic counterparts (Evans, 2000; Hoffman and Scharg, 2002). However, the radical version of the Snowball Earth Hypothesis is hard to accept. An Earth System model with open marine water, ice-free shelf (atleast seasonally) and access to the sea floor is obligatory for the Cryogenian in order to satisfy the living requirements of the biota that survived the period and for the evolution of multicellular organisms (Hyde et al., 2000; Moczydłowska, 2008). The palaeobiological findings are consistent with sedimentological findings that require open marine water and well- functioning hydrologic cycle (Etienne et al., 2006; Allen and Etienne, 2008). The mild version of Snowball Earth (i.e. the soft snowball) or the Slushball Earth model accommodates more adequately these requirements.

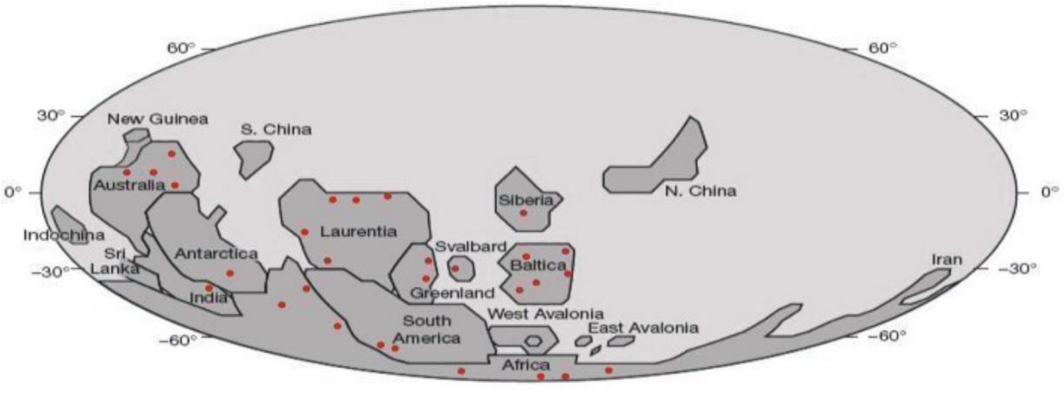


Fig. 2. Neoproterozoic palaeogeography. Circles (red) indicate the locations of Neoproterozoic glacial deposits; modified after Hyde et al., (2000).

Epilogue

- Neoproterozoic era is widely considered to witness a number of severe climatic perturbations recorded in Earth history, with extensive glaciations referred to as 'Snowball Earth' events.
- The Snowball Earth concept grabs attention of global readers as it provides plausible explanations for any interesting features of Neoproterozoic.
- Geological and palaeomagnetic studies indicate ice sheets reached the Equator in the late Proterozoic era (600±800 Myr ago).
- Deposits related to Neoproterozoic glaciations have been well demonstrated from almost every continent around the globe.
- However, alternative models claims despite the severity of glaciations, some oceans must have remained ice-free for the survival as well as diversification of life and functioning of hydrological cycle.

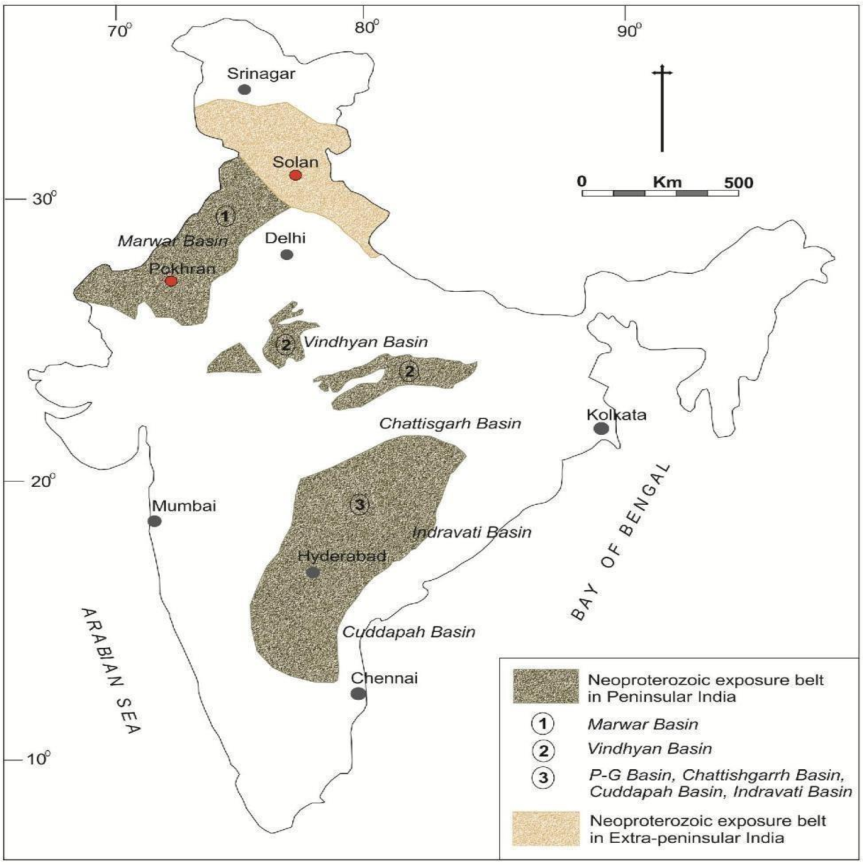


Fig.3. Distribution of Neoproterozoic rocks in Peninsular and Extra-peninsular India; modified after Jiang et al., (2003) and Chaudhuri et al., (2012).

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