Chapter – I

Introduction

1.1 The Proterozoic Eon

The Proterozoic Eon (2500-541 Ma) is the longest and one of the most eventful periods in the history of the Earth. Significant biological and geological changes such as the oxygenation of the atmosphere and ocean, evolution of multi-cellular life and assembly and breaking up of supercontinents occurred during this Eon (Fig. 1.1; Young, 2013). The Eon commenced with large scale deposition of Banded Iron Formation (BIF) and the disappearance of mass independent sulfur isotope fractionation in the sedimentary record, the latter being attributed to the oxygenation of the surface ocean (Bekker et al., 2004). This was followed by three major episodes of global glaciations known as the Huronian glaciations (2.29 - 2.25 Ga; Tang and Chen, 2013). The end phase of the glaciations saw the transformation of atmosphere from anoxic to oxic as evidenced by the appearance of red beds. Biological processes thrived following the atmospheric change which was demonstrated by a large scale positive carbon isotope anomaly called Lomagundi-Jatuli Event (LJE) (2.31 - 2.06 Ga) where $\delta^{13}C$, as recorded in contemporary marine carbonates, had reached between +5‰ and +16‰ (Martin et al., 2013). This sequence of events, from the beginning of the oxygenation of hydrosphere to the end of atmospheric oxygenation, is popularly known as the 'Great Oxygenation Event' (GOE; ~2.5 – 2.2 Ga; Bekker and Holland, 2012; Holland, 2002; Tang and Chen, 2013).

These major perturbations in the global climate were followed by the establishment of a steady state in the late Paleoproterozoic which continued throughout the Mesoproterozoic (Bartley and Kah, 2004). The ocean bottoms remained largely anoxic with pockets of euxinia at restricted basin margins and biologically productive regions while the atmospheric oxygen levels have likely remained < 0.01 times of the present atmospheric levels (PAL) (Lyons et al., 2014). This remarkable stability in the climate led to the coining of the term 'the boring billion' (2.0 –

1.0 Ga; Brasier and Lindsay, 1998). Contrary to the stability that the climate had provided, the planet underwent a number of significant tectonic changes during the Mesoproterozoic. The Era witnessed the amalgamation and breaking-up of the supercontinent Columbia following its maximum packing at ~1.45 Ga, and the beginning of amalgamation of the early Neoproterozoic Rodinia (Meert and Santosh, 2017). It also saw major protistan radiation as suggested by the discovery of oldest taxonomically resolved eukaryote, *Bangiomorpha* from the ~1.2 Ga Hunting Formation, Arctic Canada (Butterfield, 2000), and the recent reports of *Rafatazmia and Ramathallus*, from the ~1.6 Ga Vindhyan Supergroup, Central India (Bengtson et al., 2017).

The end of the Proterozoic Eon known as the Neoproterozoic Era (1000-541 Ma) witnessed five major geological events: 1) the emergence of first animal life known as the Ediacaran fauna, its evolution and disappearance (Glaessner, 1959; Narbonne, 2005); 2) two major global glaciations called the Sturtian (~720 Ma) and the Marinoan (~635 Ma), when the entire globe was covered with ice leading to a "snowball Earth" and a less extensive glaciation called the Gaskiers (~580 Ma; Halverson and Shields-Zhou, 2011; Hoffman et al., 1998; Pu et al., 2016); 3) the Shuram anomaly where $\delta^{13}C$ of the marine carbonates dropped to -12‰ globally (Grotzinger et al., 2011; Le Guerroue, 2006); 4) the oxygenation of the deep ocean and the rise of oxygen to the present atmospheric level (Och and Shields-Zhou, 2012; Sahoo et al., 2012); and, 5) the break-up of supercontinent Rodinia and the amalgamation of the Gondwanaland (Meert, 2003). These events have changed the face of our planet forever, and have left indelible chemical signatures in the contemporary sedimentary record. This thesis is an attempt to locate and decipher such chemical signals from the Proterozoic sedimentary record of the Indian shield.

1.2 The Proterozoics of India – The Purana Basins

Sedimentary rocks serve as an archive of the environmental changes and surface processes of the Earth. The chemogenic sediments act as a proxy of the global oceanic conditions while the clastic sediments give insights into the paleogeography and tectonic changes. India has always been part of various Proterozoic supercontinents (Li et al., 2008; Nance et al., 2014; Rogers and Santosh, 2002) and contains sedimentary sequences covering almost the entire Eon (Fig. 1.2). The Proterozoic sedimentary basins of India are largely made up of undeformed and unmetamorphosed marine and fluvial siliciclastics and marine carbonates, and are collectively referred to as the 'Purana basins'. They are traditionally believed to have been deposited during the mid-Paleoproterozoic to terminal Neoproterozoic-early Cambrian time period (Ramakrishnan and Vaidyanadhan, 2010). In spite of the fact that they are likely to yield valuable information about the tectonics and climate of the Proterozoic, only a handful number of geochemical studies exist on these rocks and a great majority of them have been carried out only in the Paleo/Meso Proterozoic basins like Vindhyan, Cuddappah, and Chhattisgarh (Ray et al., 2003; Sarkar et al., 2010) and early Paleoproterozoic metasediment sequences like Aravalli and Sausar Supergroups (Mohanty et al., 2015; Sreenivas et al., 2001). Detailed studies in other basins are lacking.

The extent to which the Neoproterozoic is represented in the rock records of India remains uncertain. Only a few basins are thought to contain rocks of this Era. Paleomagnetic studies aimed at reconstructing the continental configuration shows that India was also at the tropics during this Era like other continents such as Australia, Arabian-Nubian shield, and South China from which overwhelming evidence in support of the Neoproterozoic global glaciations as well as Shuram anomaly have been reported (Davis et al., 2014; Li et al., 2008). Therefore, one expects similar kind of evidence from the Neoproterozoic sedimentary basins of India too. However, no unambiguous evidence supporting these events has yet been reported from the peninsular India. Some earlier studies in the Krol Group of the Lesser Himalaya (e.g., Kaufman et al., 2006) have shown that it had formed later than the glacial events and hence does not possess any chemical evidence of the glaciations, and the Blaini Formation (a tillite/diamictite) underlying the Krol could have formed during the Marinoan glaciation.

1.3 Aim and objectives

In an attempt to decipher the Proterozoic records in India, I had concentrated my efforts on two of the largest Proterozoic basins of India, the Neoproterozoic Marwar and the Mesoproterozoic Chhattisgarh. The Marwar Supergroup of western India offered a unique geologic record, since the deposition of sediments in this basin happened approximately between 750 Ma and 540 Ma (McKenzie et al., 2011; Meert et al., 2013); a time period during which 'snowball Earth' events, Gaskiers glaciation, Shuram anomaly, and the dismantling of Rodinia and the initiation of the amalgamation of Gondwanaland took place. Similarly, the sedimentation in the Chhattisgarh basin got initiated around 1450 Ma (Das et al., 2011) and continued at least up to 1000 Ma (Patranabis-Deb et al., 2007), forming ~2.2 – 2.5 km thick repository of sediments. Being deposited in the 'boring billion' these sediments provided an opportunity to explore this time period to find evidence for the evolution of oceans, continents and life on our planet. In particular, this basin is likely to hold clues to our understanding of the dynamics of Mesoproterozoic Ocean and carbon cycling, as well as the tectonic evolution of the Indian shield subsequent to the break-up of supercontinent Columbia.

My attempts were focussed on answering a range of questions such as whether these sedimentary basins preserved any chemical evidence of global environmental changes, what were the sources of the sediments and their nature and what were the tectonic settings that controlled the evolution of the basins.

The major objectives of my thesis were to:

1. look for chemical and physical evidence for the two Neoproterozoic global glaciations, Gaskiers glaciation and Shuram anomaly in peninsular India,
2. constrain the ages of the carbonates which are likely hosts of above evidence, using Sr isotope stratigraphy and $\delta^{13}C$ isotope stratigraphy,
3. better understand the evolution of the Meso and Neoproterozoic oceans using stable carbon and oxygen isotopes,
4. decipher the regional tectonics that governed the evolution of these basins and the Indian shield in general, during the Neo and Mesoproterozoic Eras, using geochemical provenance analysis of the siliciclastics,

from the sedimentary records of both the Marwar and Chhattisgarh basins.

1.4 Methods and approach

In order to achieve the objectives mentioned above, extensive field studies and geochemical methods were employed. Field works were carried out in and around Jodhpur, Bilara and Nagaur in Rajasthan, and Raipur and Raigarh in Chhattisgarh. Carbonate sampling was done in transects across the basin from limestone quarries whereas siliciclastic samples were collected from various locations within the basins and from the surrounding lithologies. Stable

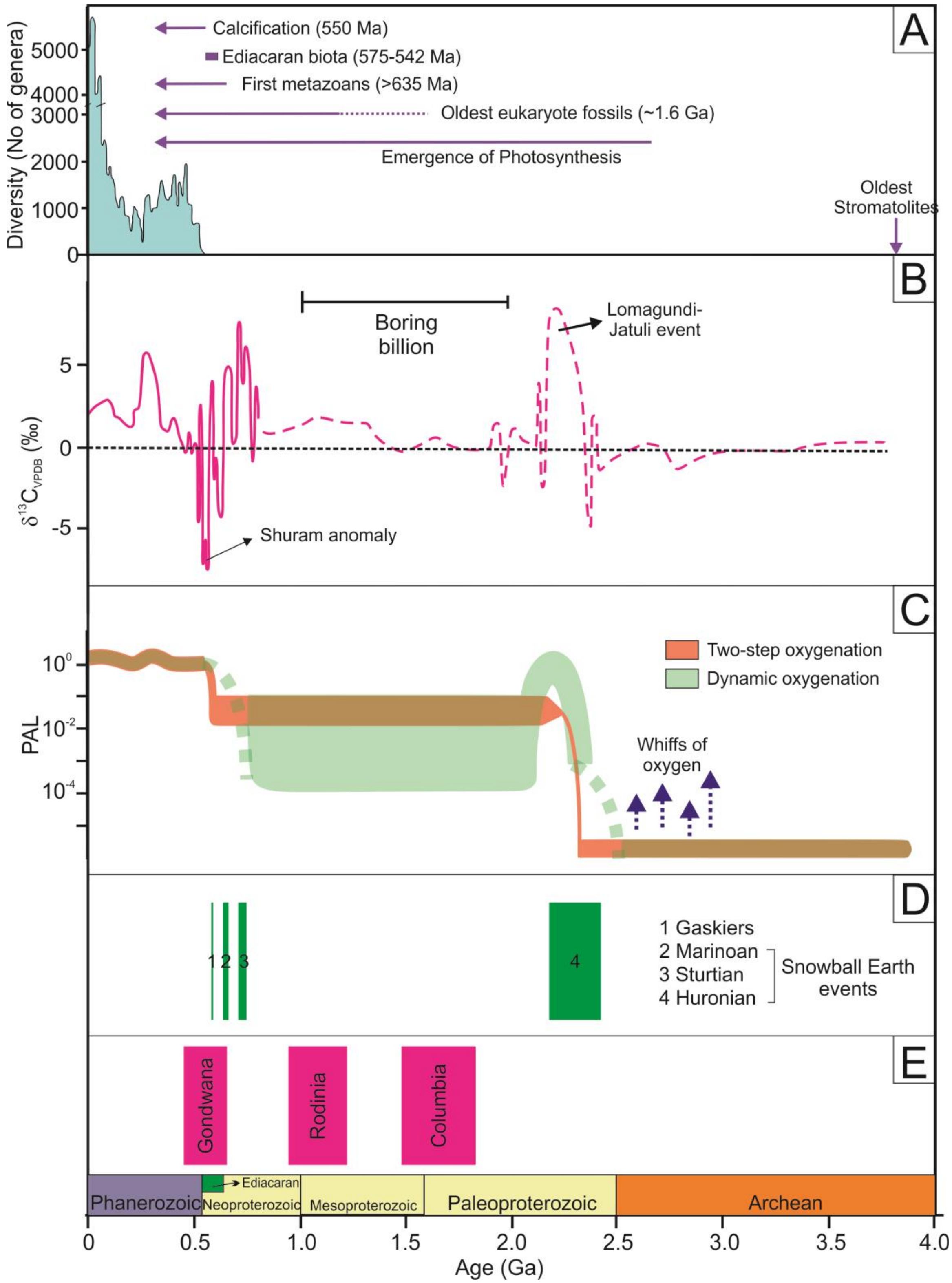

Figure 1.1: Major geo-biological events that happened during the Proterozoic. A) Evolution and diversification of life B) Variation in the $\delta^{13}C$ record of marine carbonates C) Classical and emerging views on the evolution of oxygen D) Major glacial events during Proterozoic, and E) Major supercontinents formed during Proterozoic. Figures compiled from Och and Shields-Zhou, (2012); Lyons et al., (2014)

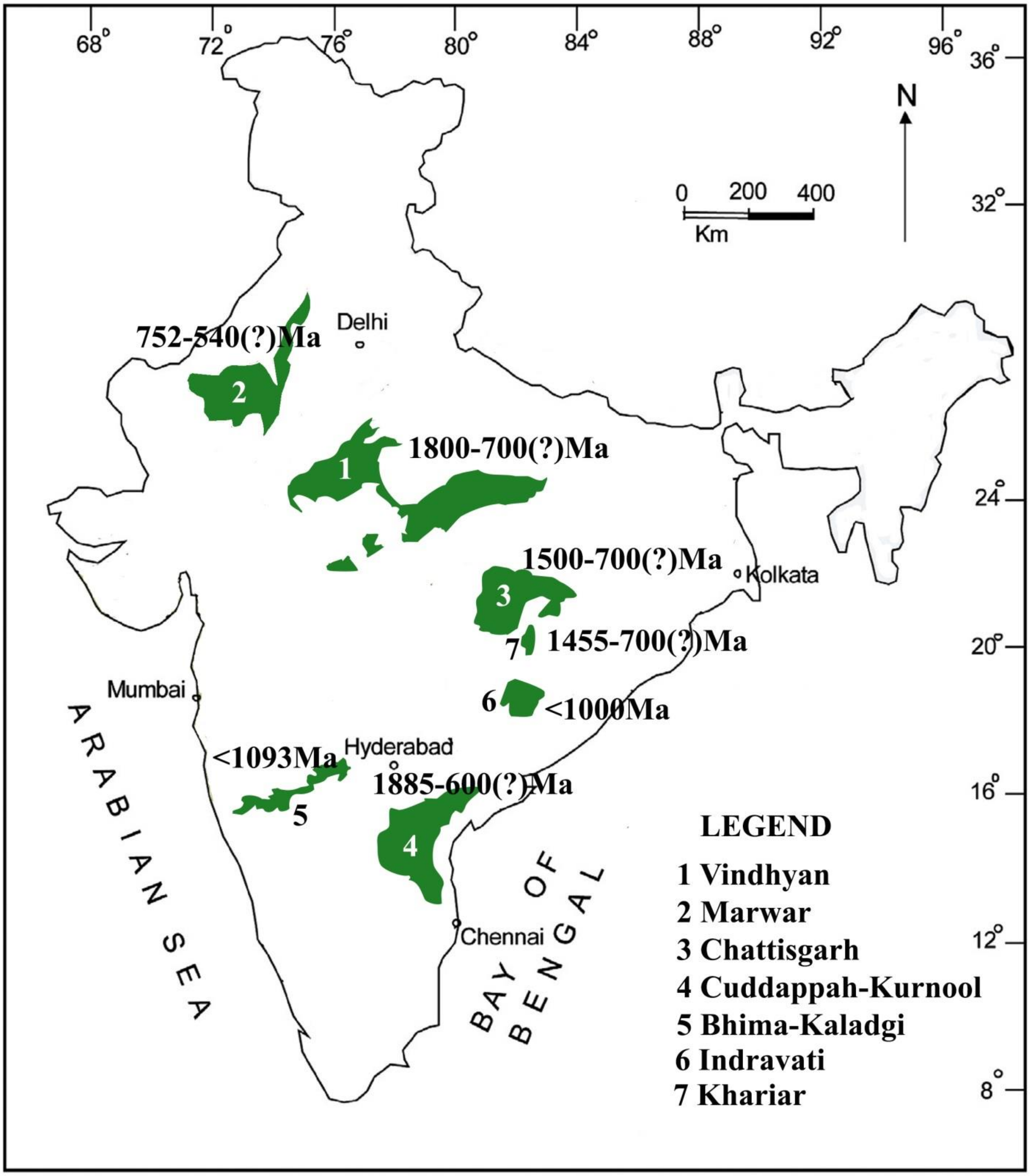

Figure 1.2: Locations of the major Proterozoic sedimentary basins of the peninsular India

carbon and oxygen isotope analysis were carried out to understand the paleo-oceanic conditions and to identify the Neoproterozoic global events. The ages of various formations in the basins were constrained by dating the volcaniclastics using Rb-Sr whole-rock isochron method, and the carbonate sequences using Sr isotope stratigraphy and $\delta^{13}C$ isotope stratigraphy. Provenance of the siliciclastics was identified using trace element analysis and isotope fingerprinting using Nd and Sr isotopic ratios.

1.5 Outline of the thesis

This thesis is organized in five chapters. The first chapter briefly describes the importance of the Proterozoic Eon and the major events that happened during this time period. It also summarizes reports of such events from the Proterozoic sedimentary basins of India. The latter part of the chapter explains the motivation to study the geochemical evolution of the Proterozoic basins and specifies the objectives of the thesis. The final part of the chapter summarizes the methods and approach that has been taken to achieve the specific objectives and the organization of the thesis. The second chapter explains the sampling strategy and details of the various geochemical techniques employed during the course of study. The third and fourth chapters give a detailed account of the major results and discuss their regional and global significance. The third chapter gives sample details and discusses the major results from the Neoproterozoic Marwar basin whereas the fourth chapter describes the major discoveries from the Mesoproterozoic Chhattisgarh basin. The fifth chapter summarizes the major results, their global implications and recommendations for future endeavours.