Chapter 1

Introduction

1.1 Introduction

Erosive forces play a dominant role in shaping the surface of the Earth. Active mountainous regions are subject to persistent effects of weathering. Physical and chemical weathering of rocks on continents determines the exogenic cycles of elements and material transfer within and among surficial reservoirs. These erosive processes also play an important role in the biogeochemical cycles of elements by supplying nutrients and solutes to surface reservoirs such as soil, atmosphere, oceans and sediments. Rivers are a major agent of erosion. The signatures of the intensity and nature of weathering and erosion of rocks are contained in the abundance and composition of dissolved and particulate phases of rivers.

The Himalaya is a major geomorphic feature on the surface of the Earth. It stretches over ~2500 km in length, from the Nanga Parbat in the west to Namche Barwa in the east with high rise peaks ranging between 500-8000 m above the mean sea level. It is one of the rapidly eroding landforms contributing ~6-12% of global sediment discharge to the oceans (Milliman and Meade, 1983; Hay, 1998; Galy and France-Lanord, 2001). A number of river systems drain the Himalaya, among them the Ganga-Brahmaputra (G-B) system ranks first among the world rivers in sediment supply to the ocean and fourth in water discharge (Holman, 1968; Milliman and Meade, 1983; Berner and Berner, 1997; Hay, 1998). Together these two rivers discharge ~1×10^{12} m^3 of water annually to the Bay of Bengal (UNESCO 1971; Sarin et al 1989; Krishnaswami and Singh, 2005) containing ~100 million tons of dissolved solids (Sarin et al., 1989; Galy and France-Lanord, 1999; Singh et al., 2005) and ~1000-2300 million tons of particulate matter (Milliman and Meade, 1983; Hay, 1998; Ludwig and Probst, 1998; Galy and France-Lanord, 2001).

There have been a number of studies on the major ion chemistry of the Ganga-Brahmaputra rivers and on their solute and sediment fluxes (Meybeck,1979; Sarin and Krishnaswami, 1984; Sarin et al., 1989; Harris et al., 1998; Galy and France-Lanord, 1999; Islam et al., 1999; Galy and France-Lanord, 2001; Dalai et al., 2002; Bickle et al.,2003; Singh et al., 2005; Hren et al., 2007).

These studies led to better understanding of chemical and physical erosion rates of these basins, various factors influencing them and their impact on CO_2 drawdown from the atmosphere. A major goal of many of these investigations has been to test if young orogenic belts such as the Himalaya are undergoing rapid erosion of silicate rocks resulting in enhanced CO_2 drawdown and thus contributing to global cooling since the Cenozoic (Raymo and Ruddiman, 1992; Ruddiman, 1997; Huh, 2003). Further, these studies also have raised interesting issues pertaining to physical and chemical erosion of these basins, which continue to be topics of research among geochemists. For example, modeling and field based measurements have led to various suggestions on the relative roles of factors controlling erosion in different mountainous regions including the central Himalaya. Intensity and spatial distribution of physical erosion in the G-B drainage have been identified as key factors that determine sediment supply to the Bay of Bengal and play important role in regional tectonics of the Himalaya (Finlayson et al., 2002; Singh, 2006). Some of the important questions regarding physical erosion of the central Himalaya, particularly the Ganga basin, include (i) which are the dominant sources of sediments to the Ganga plains, e.g. Higher Himalaya and Lesser Himalaya, and/or peninsular India (ii) what is the variability in the rate of erosion among its sub basins (e.g. Ghaghra, Gandak, Kosi etc.) and what are its contributing factors? (iii) what is the interplay between physical erosion and regional tectonics?

Erosion rates of different regions of the Himalaya have been determined using various methods. These include thermo-chronology, (Burbank et al., 2003; Molnar 2003; Wobus et al., 2003, Hodges et al., 2004; Thiede et al., 2004) cosmogenic nuclides (Lal et al., 2004; Leland et al., 1998; Vance et al., 2003), mineralogical composition of particulate phases (Galy and France-Lanord, 2001; Garzanti et al., 2004, 2007) sedimentological properties (Sinha and Friend, 1994; Islam et al., 1999) and geochemical and isotopic measurements (Bouquillon et al., 1990; Clift et al., 2002; Singh and France-Lanord, 2002; Campbell et al., 2005; Foster et al., 2007; Singh et al., 2008). A key finding of some of these studies is the high and focused erosion in tectonically active regions, viz the

Western syntaxis, Nangaparbat (Leland et al., 1998) and the Eastern syntaxis, Namche Barwa (Burg et al., 1998; Singh and France-Lanord, 2002; Singh, 2006).

Sr and Nd isotope studies of sediments from the Bay of Bengal (France-Lanord et al., 1993) and the Brahmaputra basin (Singh and France-Lanord, 2002) suggest that sediment budget in these basins is dominated by supply from the Higher Himalaya. Further, some of these studies also brought out large variability in physical erosion among the various sub-basins of the Brahmaputra with maximum in the Eastern Syntaxis (Singh, 2006). Similarly, the limited available results (Galy, 1999; Galy and France-Lanord, 2001) from the Ganga basin in Bangladesh also seem to show the dominance of the Higher Himalayan source in its sediment budget, but the role of various sub-basins in contributing to sediment budget is only poorly understood. A detailed and comprehensive study of the chemical and Sr and Nd isotopic composition of sediments from the Ganga mainstream and its major tributaries has been carried out as a part of this thesis to address some of these issues, particularly to (i) trace the sources of contemporary sediments to the rivers of the Ganga System and the Ganga mainstream in the plain in terms of major geological units in its drainage, (ii) determine the fraction of sediments supplied from various sub-basins to the Ganga in the plain and (iii) estimate physical erosion rate over the western and the central Himalaya to assess their spatial variability, the various factors controlling it and its impact on regional geomorphology.

Physical erosion is considered as one of the drivers of chemical erosion (Bluth and Kump, 1994; Edmond et al., 1995; Louvat and Allegre, 1997; Gaillardet et al., 1997, 1999b; Anderson et al., 2002; Millot et al., 2002). Chemical weathering of silicate rocks exerts significant control on the CO_2 budget of the atmosphere and hence moderates the Earth's climate (Walker at al., 1981, Raymo and Ruddiman, 1992; Edmond and Huh, 1997; France-Lanord and Derry, 1997; Ruddiman, 1997; Berner and Berner, 1997; Krishnaswami et al., 1999). The role of temporal variation in silicate weathering rates as a driver of climate change is a topic of debate among geochemists.

Orogenic uplift of mountains such as the Himalaya results in the development of high relief, steeper slopes and intense precipitation all of which promote enhanced erosion. Such enhanced erosion exposes primary minerals to chemical weathering. In this context, impact of the uplift of the Himalaya in contributing to enhanced silicate weathering and associated CO_2 drawdown has been a subject of investigation during the last couple of decades (Raymo, 1991; Raymo and Ruddiman, 1992; Molnar and England, 1992; Edmond and Huh, 1997; Galy and France-Lanord, 1999; Krishnaswami et al., 1999; Dalai et al., 2002; Jacobson et al., 2002; Huh, 2003; Bickle et al., 2005; Singh et al., 2005; Tipper et al., 2006; Hren et al., 2007). Contemporary silicate weathering rates in the Ganga-Brahmaputra-Indus (G-B-I) basins are higher compared to the global average as derived from major ion composition of river waters. These estimates rely on the knowledge of various end members that include atmospheric deposition, silicate/carbonate/evaporite weathering and groundwater input contributing to major ion abundances in rivers, their composition and the geochemical behaviour of elements in rivers (Krishnaswami et al., 1999). Both forward and inverse models have been used to estimate the silicate derived cations (Negrel et al., 1993; Krishnaswami et al., 1999; Galy and France-Lanord., 1999; Gaillardet et al., 1999b; Millot et al., 2003; Wu et al., 2005; Moon et al., 2007). In these models, particularly in the forward model, Na corrected for chloride is used as a proxy for silicate weathering.

These studies have yielded important data on the contribution of major ions to the Himalayan rivers from various sources and their impact on CO_2 drawdown from the atmosphere. In this context, one of the end members that can contribute Na to rivers is alkaline/saline salts of the Siwaliks, the Ganga plain and peninsular drainage. Reliable estimation of silicate erosion rates (and hence that of CO_2 consumption) in the Ganga basin therefore requires knowledge of the role of these soils in supplying Na to the Ganga. This forms a part of investigation of this thesis on chemical erosion in the Ganga plain and peninsular drainage and its role in contributing to major ion flux transported by the Ganga to the Bay of Bengal. Further, in this study attempt has been made to derive silicate erosion rates in the Ganga basin based on chemistry of both dissolved and particulate phases. This is based on the chemical composition of particulate matter transported by rivers and that of parent rocks (Martin and Meybeck, 1979, McLennan 1997, Stallard 1995; Roy et al., 1999; Canfield, 1997; Das and Krishnaswami, 2007). The advantage of particulate based approach is that it can directly yield silicate erosion rates, unlike that based on dissolved phase data which require apportionment of major ion contribution from silicate to the solute budget and estimate silicate weathering rates. Further, unlike the water data which yields contemporary erosion rates, the sediment data yields erosion rates averaged over the residence time of particles in the basin.

The potential of Sr isotope as a proxy for silicate weathering has prompted a number of studies on Sr isotopes in Himalayan rivers, particularly in the Ganga Brahmaputra system (Krishnaswami et al., 1992; Palmer and Edmond, 1992; Galy et al., 1999; Jacobson et al., 2002; Bickle et al., 2003). These studies have generated large volumes of high quality data which have wide implications on the Sr isotope budget of these rivers, their sources and their role in Sr isotope evolution of the ocean. The results show that G-B waters have moderate Sr concentration with highly radiogenic $^{87}Sr/^{86}Sr$ (Krishnaswami et al., 1992, 1999; Palmer and Edmond, 1992; Galy et al., 1999; Bickle et al., 2003; Dalai et al., 2003; Singh et al., 2006). The sources for radiogenic Sr in these waters are still debated. Chemical weathering of highly radiogenic silicates of the basin (Edmond, 1992; Krishnaswami et. al., 1992; Singh et al., 1998; Bickle et al., 2003), metamorphosed carbonates and vein calcites (Quade et al., 1997, 2003; Blum et al., 1998; Jacobson and Blum, 2000) have been suggested as potential sources. One of the issues pertaining to Sr isotope geochemistry of the Ganga waters is that Sr budget and isotopic composition is difficult to be explained in terms of supply only from silicates and carbonates (Krishnaswami and Singh, 1998; Krishnaswami et al., 1999; Dalai et al., 2003). This has led to propose that there are additional sources for Sr with low $^{87}Sr/^{86}Sr$ to balance its budget and/or that the contribution of Sr from carbonates estimated based on Ca abundance in water can be lower limit due to non-conservative behaviour of dissolved Ca, which results in its precipitation from water as calcite (Jacobson et al., 2002; Dalai et al., 2003). To probe into these issues in some detail and to better constrain Ca and Sr budgets in the Ganga, studies on chemical and Sr isotopic composition of waters, particulates and precipitated carbonates from the Ganga and its tributaries, have been carried out.

Enhanced drawdown of CO_2 due to silicate weathering in active mountains such as the Himalaya has been suggested as a potential cause of global cooling during the Cenozoic (Raymo and Ruddiman, 1992; Ruddiman, 1997). An alternative hypothesis is that of enhanced carbon burial in coastal and shelf sediments (Raymo, 1994; France-Lanord and Derry, 1997, Galy et al., 2007a). Photosynthetic production of organic matter is one of the principal mechanisms of atmospheric CO_2 consumption. A fraction of this organic matter is buried in sedimentary basins and can remain stored for extended periods of time under suitable conditions. This makes the sequestration of atmospheric CO_2 via burial of particulate organic carbon an important sink for atmospheric CO_2. However, the relative roles of carbon burial vs silicate weathering in determining atmospheric CO_2 budget is still a topic of investigation (France-Lanord and Derry, 1997; Galy et al., 2007a). In this study particulate organic carbon flux of the Ganga has been measured to determine its flux to the Bay of Bengal and compare with CO_2 consumption by silicate weathering.

1.2 Objectives of the thesis

1. To trace the sources of sediments to the Ganga basin in the plain and to determine the relative contributions of various sub-basins to the sediment budget based on Sr, Nd isotopes and sediment composition.
2. To determine the spatial variability in physical erosion rates among the sub-basins of the Ganga drainage and its implications to sediment provenance and regional tectonics.

3. To determine contemporary chemical erosion in the Ganga plain and peninsular sub-basins and their role in contributing to major ion budget of the Ganga at its out flow and the overall chemical erosion of the Ganga basin.
4. To determine major element and Sr abundances of bank sediments, their fine fraction and suspended matter from the Ganga river and apply them to derive silicate erosion rates.
5. To determine the abundance of dissolved major elements, Sr and $^{87}Sr/^{86}Sr$ in the Ganga and its tributaries and use these results in conjunction with sediment data to evaluate contemporary chemical and silicate erosion rates and budgets of Ca and Sr in the basin.
6. To determine the fluxes of particulate carbon transported by the Ganga to the Bay of Bengal based on inorganic and organic carbon contents of bed and suspended sediments and to compare it with CO_2 consumption via silicate weathering.

1.3 Structure of thesis

This thesis is divided into six chapters. The content of these six chapters are as follows.

Chapter-1 outlines the thesis topics addressed in this study. This chapter presents the current state of knowledge on these topics through a brief description of earlier studies in the Himalayan river basins, particularly the Ganga.

Chapter-2 describes the sampling details and analytical methods used for the measurements of various parameters. First part of this chapter discusses the general geology and the hydrogeology of the catchment whereas the latter part gives a brief description of sampling of river sediment and water samples and the various analytical methods used for their chemical and isotope analyses.

Chapter-3 is on the determination of physical erosion rates and its spatial distribution in the central Himalaya carried out in this work using Sr and Nd isotopes. The data has been used to derive information on the present day sources of sediments, erosion rates and its variability among the different sub-basins of the Ganga system. The implications of the results to regional tectonics and global riverine sediment budget are also presented.

Chapter-4 presents major ion data in the Ganga river along its entire stretch, and its tributaries and their temporal variations at selected locations. The chapter also presents results of Sr isotopes in water and Ca/Sr studies in seepage, drip and spring waters and in precipitated carbonates. These measurements have been used to determine chemical erosion rates in the Ganga sub basins (the Ganga plain and the peninsular drainage in particular), dissolved Ca and Sr budgets and to understand the factors contributing to temporal variations in major ion chemistry in dissolved phase.

Chapter-5 presents results of chemical composition of particulate phase of the Ganga and their application to learn about silicate erosion and particulate carbon fluxes to the Bay of Bengal and their implications.

Chapter-6 summarises the results of this thesis and briefly outlines future perspectives.