CHAPTER 1

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1.1 INTRODUCTION

The atmosphere of Earth is a gaseous envelope which protects life by absorbing ultraviolet solar radiation and warming the surface through heat retention under greenhouse conditions. The rise in atmospheric CO\textsubscript{2} and its linkage with global climate change have provided a mechanism to understand the processes controlling the carbon cycle. Over geological time scales, Earth’s degassing has been reported to have a significant impact on atmospheric CO\textsubscript{2} concentrations (Kerrick & Caldeira, 1998; Evans et al., 2008). In the Himalayan region, geological conditions and associated geothermal systems have led to release of CO\textsubscript{2} during upward movement of geothermal fluid and volatiles. Therefore, these springs can be used as an object to infer about the release of heat inside the Earth.

The natural carbon cycle includes the conversion and migration of lithospheric, atmospheric, hydrospheric and biospheric carbon, primarily in the form of carbon dioxide (CO\textsubscript{2}), carbonate (CO\textsubscript{3}\textsuperscript{2-}), bicarbonate (HCO\textsubscript{3}\textsuperscript{-}), methane (CH\textsubscript{4}), and (CH\textsubscript{2}O). CO\textsubscript{2} being an important atmospheric greenhouse trace gas has been shown to be sourced from the deep crust (Becker et al., 2008) which emanates to the surface as volatiles and dissolved components. The geothermal systems play a key role in mediating the crustal CO\textsubscript{2}
degassing to the atmosphere. Modern researches are directed towards regional and global-scale CO₂ degassing from the deep crust (Kerrick & Caldeira, 1998; Evans et al., 2008). Over the time, a number of studies have shown that CO₂ release from both volcanic eruptions and non-eruptive systems affect the global atmospheric composition (Chaidoni et al., 2004; Sano & Marty, 1995). The non-eruptive systems are generally associated with geomagnetic anomaly zones, shallow earthquake zones, gravity anomalies and high heat flow zones (Rawat, 2012) which could be the potential source of volatiles to the atmosphere.

The Himalayan orogeny, produced by the continent-continent collision, is an ongoing tectonic process across the broad region of south Asia since the last 50 million years. It has resulted from the process of under thrusting of the Indian crust beneath southern Tibet (Hochstein & Regenauer, 1998). During this process, a part of the Indian crust was scraped off which underwent crustal thickening by tectonic imbrications (Molnar et al., 1987; Bilham et al., 1997) with metamorphic reactions and crustal melting (Searle et al., 1997; Henry et al., 1997). The India-Asia collision has induced major topographic and drainage evolutions which in turn have modified the dynamics of the processes affecting the carbon cycle. The rise of the Himalaya has contributed to erosion fluxes through silicate weathering and organic carbon burial as major atmospheric sinks for CO₂. However, certain processes operating within the Himalaya tend to release CO₂ to the atmosphere. These include CO₂ degassing due to metamorphism of deeply subducted carbonate rocks and the oxidation of fossil organic carbon exposed to the surface during fluvial
erosion. The degassing of metamorphic CO₂ from the active orogeny has been suggested as the process in Earth’s carbon cycle having noteworthy controls on the global climate (Kerrick & Caldeira, 1998). Such degassing processes are manifested as geothermal springs continuously emanating volatiles and are noticed mainly along the major structural discontinuity planes in the Himalaya. Thus the Himalaya provides a natural laboratory to study the various aspects of collisional orogeny (Newell et al., 2008) and their consequences in Earth system. The long-term budget of CO₂ in the ocean-atmosphere system is controlled by inputs from different sources including volcanism, metamorphic de-volatilization and the oxidation of sedimentary organic carbon (Molnar & England, 1990; Evans et al., 2008). Therefore this dynamic balance is maintained by outputs to the sedimentary reservoir, through the processes of chemical weathering of silicate minerals, their subsequent precipitation in form of carbonates and the burial of organic matter in flood plains and coastal seas.

In the Himalayan orogeny, the geothermal springs occur in the deeply incised valleys along the Main Central Thrust (MCT) and Indus Tsangpo Suture Zone (ITSZ) which cause significant release of metamorphic CO₂ (Evans, 2002, 2004, 2008; Becker et al., 2008) to the atmosphere. Earlier studies in the Himalayan region (Gyanprakash & Raina, 1975; Tong & Zhang, 1981) have documented ~600 geothermal springs occurring along its ~3000 km long belt, stretching from Pamir to the Yunnan through Tibet. These geothermal systems have been studied for geochemical features and magnitude of heat transfer properties (Hochstein & Yang, 1995). Though the distribution of geothermal
springs is not over all symmetric with respect to the axial part of the Himalaya, several of these, especially those with surface temperatures $T_s > 90^\circ$C in the northwest Himalaya, fall along the major thrust zones. This shows that these are structurally controlled (Hochstein & Regenauer, 1998; Newell et al., 2008). However their genesis is yet to be understood fully in terms of meteoric vs. deep sources etc.

In the year 1991, Geological survey of India (GSI) has documented about 340 geothermal springs and identified more than 300 sites as plausible utilization sites for geothermal energy. Most of these geothermal spring are located in the northwestern Himalayan region and are characterised by high thermal gradient (>100 $^\circ$C/km) and heat flow (>468 mW/m$^2$). The present thesis attempts: (1) to understand plausible mechanisms for the origin of geothermal waters in terms of meteoric vs. deep sources; 2) to address the issue of degassing of metamorphic CO$_2$ in the Himalayan orogenic belt; and 3) to estimate the reservoir temperature of geothermal reservoirs giving rise to thermal springs of the northwestern Himalaya. This study is expected to throw light on the degassing of metamorphic CO$_2$ from Himalaya and its contribution in the global carbon cycle, and to estimate the reservoir temperature for evaluating their potential for the geothermal energy source.

1.2 GEOTHERMAL SPRING

A type of spring having water above the local mean air temperature is termed as geothermal springs (Bates & Jackson, 1987). Generally a geothermal system can be found in regions with slightly above normal geothermal
gradient. Such regions could be around plate margins where, in general, the geothermal gradients are higher than the average value.

Geothermal spring can be understood as the manifestation of convecting water in the upper crust within a confined space where it transfers heat from a source to sink, usually the free surface (Hochstein, 1990). It mainly consists of three major components: a heat source, a reservoir and a carrier fluid that transfers the heat to the surface. The heat source could be either a very high temperature (>600°C) magmatic intrusion that has reached relatively shallow depths (2 to 5 km; Harinarayana et al., 2006) or as a low-temperature systems, which increases with depth. The reservoir could be a volume of hot permeable rocks from which the circulating fluids extract heat. The reservoir is usually overlain by a cover of impermeable rocks and it is connected to a surface recharge area where the meteoric water can partly replace the fluids escaping from the reservoir. The geothermal fluid is water, in the majority of cases meteoric water, which exists in form of liquid or vapour phase depending on its temperature and pressure. This water often carries the chemical constituents and gases such as CO₂, H₂S, SO₂, He, CH₄ etc.

These springs discharge heated groundwater and steam continuously from deep seated faults that describe tectonic boundaries between the Himalaya and Asia (ITSZ) between the Higher and Lesser Himalaya (MCT) and between the Lesser Himalaya and Himalayan Foreland domain (MBT). Based on their heat characteristics, these geothermal springs may have the potential to be exploited for future source of energy. Earlier reports show that India has the potential of an estimated geothermal power of ~10,600 MW (Ravishankar,
1988) which is yet to be developed to generate power. The striking feature of
geothermal energy lies with the fact that it is clean, renewable and does not produce hazardous emissions (Smith, 2007; Younger & Gluyas, 2012). Further, generating energy from geothermal system is three folds economical than the hydroelectric power and therefore it is worth exploring the possibilities of developing geothermal systems as objects of energy for future.

1.3 PREVIOUS WORK

Atmospheric abundance of CO₂ is a crucial component that influences the heat budget and the climate on various time scales. It is regulated by the processes like photosynthesis, chemical weathering of silicate rocks, oxidative weathering of organic matter, burial of organic carbon (in flood plains, and oceanic basins) and metamorphic degassing along the orogenic belts on geological time scales (Gaillardet et al., 1997; France Lanord & Derry, 1997; Krishnaswami et al., 1999; Dalai et al., 2002; Galy et al., 2007, 2008; Evans et al., 2002, 2004, 2008). Therefore the magnitude and rate of degassing of metamorphic CO₂ along the major Himalayan tectonic zones is important to understand the global carbon cycle.

Though these processes have been studied intensively, their relative roles in regulating the atmospheric CO₂ budget are needed to be quantified. Earlier studies (Bickle, 1996; Evans et al., 2002, 2004, & 2008) are based on the geochemical analyses of fluids and volatiles emanating from the natural geothermal springs along the Main Central Thrust (MCT) zone of the Nepal Himalaya. They have indicated that these zones could be the plausible source of CO₂ to the atmosphere with a flux comparable to that by CO₂ consumption
via chemical weathering of silicate rocks. Therefore it is important to study these fluxes in a quantitative fashion. The mechanism for this CO₂ flux is suggested to be induced by metamorphic reactions (decarbonation and decarboxylation) occurring in the subducted Lesser Himalayan sediments beneath the Himalayan front. Further, this process may also have implications on the carbonate-silicate weathering cycle in the Himalaya which is against the paradigm that suggests Himalaya as an important CO₂ sink. However such finding are based on the limited data sets representing only a ~150 km long section of the Nepal Himalaya and southern Tibet against its total stretch of ~3000 km and their generalization for whole of the Himalayan region remains unclear. Therefore it is important to address the degassing of metamorphic CO₂ in the Indian Himalaya for a better and representative estimate of the process. Such an estimate may be useful in quantifying the extent of CO₂ emanating though the northwestern Himalayan region. Further, the origin of these springs has also been contested in terms of meteoric vs. deep sourced volatiles and hence it needs to be tested in Himalayan set up. This work uses the geochemistry and stable isotopic study of the geothermal springs from the northwest Himalaya (India) to address these issues under certain assumptions as follows:

(1) Extrapolation from a measurement of the short-term flux to the geological long-term flux for the whole mountain ranges (Evans et al., 2008). Due to changes occurring over of the thermal history, an orogenic belt could well be a source or a sink of CO₂.
(2) The organic sub-cycle of carbon in the Himalaya does not differ from the whole organic sub-cycle of carbon and is not a major flux of CO₂ consumption. This has recently been challenged by the workers (Galy et al., 2007), who have shown that the Himalaya scavenges a factor of 10 more CO₂ by organic burial than by chemical weathering.

(3) Questions about the time scale at which a mountain range becomes carbon neutral. This means that the CO₂ degassed by the Himalaya eventually reacts with silicate minerals and leads to the formation of carbonate in ocean followed by their heating and degassing to complete the carbon cycle. On the time scale of this geological loop (typically 20 to 50 million years; Gaillardet & Galy, 2008) the net effect of metamorphic CO₂ on the global carbon cycle, at steady state, is null. However, if steady state is not achieved and a fraction of sedimentary carbon is re-injected into the mantle and subsequently degassed at mid-oceanic ridge or hot spots, mountain ranges only become carbon neutral on time scales of billions of years (Gaillardet & Galy, 2008).

(4) Therefore, in light of above, mountain ranges appear to have several impacts on the global carbon cycle and hence global climate. Whether they are net sources or sinks of atmospheric CO₂, it can only be assesses by considering the importance of different processes at their relevant time scales: the consumption of CO₂ by rock weathering (silicate and carbonate), the balance between organic matter burial and oxidation of sedimentary organic matter, and the fluxes of CO₂.
degassing. Further, reconstructing the evolution of atmospheric CO\textsubscript{2} over geological time would depend on how these mechanisms and their respective time scales interact among them.

1.4 OBJECTIVES OF THE THESIS

The present study is attentive on the geochemical (including isotopic) characteristics of geothermal springs in the northwest Himalaya through the following main objectives:

1. To study the isotopic and geochemical characteristics of the geothermal springs in the northwest Himalaya to get insights into their source of origin and degassing of metamorphic CO\textsubscript{2}.

2. To study the altitude effect on stable isotopes of oxygen (\textdelta^{18}O) if these geothermal springs having meteoric affinity.

3. To estimate the reservoir temperature of these springs.

1.5 CONTRIBUTION OF RESEARCH

This work attempts to address some important issues pertaining to the origin of geothermal springs in the northwest Himalaya and their contribution in CO\textsubscript{2} budget to the atmosphere. In addition, majority of the springs, taken up in this study have been demonstrated to be sourced from meteoric waters. These results have facilitated the use of isotopic data to trace the altitude effect of stable isotopes in the Himalayan region. The importance of estimating altitude
effect in this study lies with the fact that it represents an average precipitation (integrated over the residence time of waters in these springs) which could be a better estimate than those based on a single rain sample.

This work focuses on Indian Himalaya to estimate the metamorphic CO₂ flux and the nature of geothermal fluids in terms of their origin. These issues have significant bearing on the on going research whether Himalaya serves as sink or source of CO₂ in global model of climate change. Results obtained in this work may be used for the understanding of the geothermal reservoirs to provide inputs to further energy exploration attempts from the Himalayan region.

1.6 OUTLINE OF THESIS CHAPTERS

This thesis is divided into the eight chapters covering major aspects of northwest Himalayan springs which are briefed as follows.

Chapter 1 Presents the current state of the knowledge of these topics through a brief description of introduction, motivation, and previous studies of the geothermal springs in the Himalayan region.

Chapter 2 Describes the regional geological setup of the Himalaya and geological setup of geothermal springs of the northwest Himalaya. First part of the chapter provides a brief account of the overall geologic and tectonic setup of the Himalaya whereas the second outlines the details of geological and structural attributes of the geothermal springs with discussion on the major tectonic boundaries of the northwest Himalaya.
Chapter 3 Outlines about the sampling details and different analytical techniques adopted for the measurements of various parameters of geothermal springs. It contains information on the isotopic and geochemical analysis. In addition, it describes the field work and sampling strategies of geothermal springs. All the analytical techniques used for their physical, chemical and stable isotopic parameters are presented in a flow diagram, given in the chapter.

Chapter 4 Presents the data on major ions, trace elements, and physical parameters (pH, EC, Temperature, and TDS) in geothermal springs and river waters from the study area. These measurements have been utilized to determine the distribution of major and trace elements and their sources in geothermal waters. These data have also been used to infer about the nature of fluids presents in these springs and to estimate the metamorphic CO$_2$ flux of the degassing process.

Chapter 5 Presents and discusses the data on stable isotopes of ($\delta^{18}$O, $\delta$D) composition of the geothermal springs. These results have been used to discuss the $\delta^{18}$O and $\delta$D relationship and to infer on their altitude effect. It also describes the origin of geothermal waters in terms of meteoric vs. magmatic or deep sources.

Chapter 6 Presents the data on $\delta^{13}$C$_{DIC}$ of geothermal springs which dwells upon the origin of geothermal springs and degassing process of metamorphic CO$_2$ using as an independent proxy. In this chapter, schematic diagrams are also presented to explain the
enrichment process in $\delta^{13}$C composition of thermal springs and their possible link to magmatic or deeply sourced fluids.

Chapter 7  Presents the data on dissolved silica in the water samples from the study area. First part of this chapter discusses about the geochemical thermometry and dissolved silica thermometry using abundance of dissolved silica to estimate the reservoir temperature of individual springs. In the second part, estimates of the reservoir temperature for the individual geothermal springs have been given which may be used to utilization towards geothermal energy.

Chapter 8  Contains the syntheses of the results from this study and major conclusions drawn from them. At the end, with the scopes of future work, it addresses some of the issue that has been borne out of this study. In addition, limitation of this work has also been presented in this chapter.