

PATTERN OF TEMPERATURE STRUCTURES IN HIMALAYAN SUBDUCTION ZONE: A REVIEW

Ismail Hossain* and Md. Rezaul Islam

Department of Geology and Mining, University of Rajshahi, Rajshahi 6205, Bangladesh

*Corresponding author: Ismail Hossain

E-mail address: ismail_gm@ru.ac.bd (I. Hossain)

Abstract: The present study deals with the temperature structures (e.g., mantle wedge and slab) in Himalayan subduction zone. The estimated maximum temperature in the mantle wedge, T_r is 1420°C , whereas temperature at the top of the slab, T_s ranges from $1081.3\text{--}1119.5^{\circ}\text{C}$. The average value of the temperature and standard deviation at the top of the slab is $1103\pm 10.7^{\circ}\text{C}$. The study shows that the temperature of the mantle wedge is more or less stable and the slab temperature of the entire Himalayan belt is slightly varied. The mantle wedge temperature of the Himalayan subduction zone is correlated with Kamchatka subduction zone (1450°C) and Tohoku subduction zone (1400°C) in Northeast Japan. From overall observation, the Himalayan subduction zone is characterized with high compression and high seismic activity of the entire tectonic boundary along both the eastern and western sections. In these contexts, there might have a great possibility for large earthquakes to creep up in this region. The results of the research may contribute to explain geometry, rheology, heat transport and petrological processes of Himalayan subduction zone. Generally a temperature dependent process in the mantle wedge is responsible for the focusing of volcanic activity at the sharp fronts to the arcs.

Key words: Temperature structures, Himalayan subduction zone, volcanic activity, mantle wedge and slab, Himalaya-Tibetan orogen.

সারংশ: বর্তমান গবেষণায় হিমালয়ান সাবডাকশন জোনের তাপমাত্রা-বিন্যাস সম্পর্কে আলোকপাত করা হয়েছে। এতে পরিমাপকৃত ম্যান্টল ওয়েজের (T_r) সর্বোচ্চ তাপমাত্রা নিরূপণ করা হয়েছে 1420°C সে., যেখানে স্লাবের উপরিভাগের তাপমাত্রার (T_s) বিস্তৃতি $1081.3\text{--}1119.5^{\circ}\text{C}$ থেকে $1103\pm 10.7^{\circ}\text{C}$ সে. এবং গড় তাপমাত্রা $1103\pm 10.7^{\circ}\text{C}$ সে.। ম্যান্টল ওয়েজের তাপমাত্রা মোটামুটি স্থির হলেও স্লাবের উপরিভাগের তাপমাত্রা হিমালয়ের বিভিন্ন স্থানে কিছুটা ভিন্নতা দেখা যায়। এ ম্যান্টল ওয়েজের তাপমাত্রার সাথে কামচাট্কা সাবডাকশন জোন (1450°C সে.) এবং উত্তর-পূর্ব জাপানের তোহোকো সাবডাকশন জোনের (1400°C সে.) কিছুটা মিল পরিলক্ষিত হয়। হিমালয়ান সাবডাকশন জোনের পূর্ব ও পশ্চিমের সামগ্রিক বিশ্লেষণে দেখা যায় এর উচ্চ চাপ (compression) এবং উচ্চ সিজমিক (seismic) ক্রিয়াশীলতা টেকটোনিক রেখা বরাবর প্রযুক্ত রয়েছে। এসব লক্ষণ থেকে ধারণা করা যায় এ অঞ্চলে যে কোন সময়ে বড় ধরনের ভূমিকম্প হওয়ার আশঙ্কা রয়েছে। হিমালয়ান সাবডাকশন জোনের উপর প্রভাবিত গবেষণার ফলাফল জ্যামিতিক বিশ্লেষণ, এর গতিশীলতার বৈশিষ্ট্য, তাপমাত্রা স্থানান্তর এবং শিলাতাত্ত্বিক প্রক্রিয়ার বিশ্লেষণে ভূমিকা রাখতে পারে। এছাড়া ম্যান্টল ওয়েজের তাপমাত্রা-বিন্যাস পরবর্তীতে হিমালয় পর্বত শ্রেণীতে আগ্নেয়গিরির জ্বালান গঠন প্রক্রিয়ায় ভূমিকা পালন করতে পারে।

Introduction

The Himalayan subduction zone is where Indian plate dives under Eurasian plate and the collision causes earthquakes along it and melts the rocks (Fig. 1). Several major earthquakes have occurred at the plate interiors and boundaries in the Indian subcontinent during the last three decades (Sridevi 2004). The molten rock may also have enough pressure to break the surface to form magma chambers or volcanoes. Recently England et al. (2004) observed that the depth of the top of the intermediate depth seismicity beneath arc volcanoes (lying close to the top of the slab) varies systematically with the speed of descent of the slab has motivated them to seek the scaling relations for temperature structure in subduction zone in order to develop understanding of this systematic variation, and to provide a simple framework in which to investigate its implication for the process of melting and melt transport in subduction zone. So, how much temperature of the top of slab and the mantle wedge along the Himalayan range are varied with convergence rates, depth to the mantle wedge and the top of the slab, and the angle of the subducting slab, and associated

plate deformation? This general inquiry is the leading motivator to instigate the study. As one of the largest mountain belts, the modern Himalaya-Tibetan orogen is a natural laboratory for investigating the distribution of melt in an active orogen and for studying the melt products during its growth (Jamieson et al. 2011).

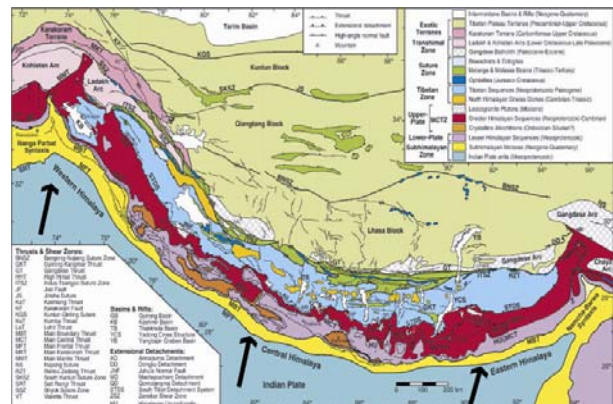


Figure1 Location of the entire area of the Himalayan subduction zone with simplified geology of the Himalayan Orogen, showing main tectonostratigraphic rock units and major structures (slightly modified from Goscombe et al. 2006).

Similar observation from other active mountain belts has been accomplished at different subduction zones in the world like the Aleutian-Alaska subduction zone (Abers et al. 2005), Costa Rica–Nicaragua subduction zone (Peacock et al. 2004), Kamchatka subduction zone (Portnyagin and Manea 2008), Cocos plate under the Caribbean plate at the Nicoya Peninsula, Costa Rica (Harris and Wang 2002), Central Andean subduction zone (Springer and Föster 1998) but in our study area this type of approximation is not available, except some of related studies (e.g., Bollinger et al. 2004; Bilham et al. 1997a; Bilham 2008; Sridevi 2004; Catherine 2004). So, these observations facilitate to provide sufficient interest to review the temperature structures in Himalayan subduction zone.

Methods

There are various data set based on the variable convergence rates in place to place in the Himalayan subduction zone, and those data were collected from various published sources (Sridevi 2004; Bilham et al. 1997a; Bilham et al. 1997b; Bilham et al. 2001; Bollinger et al. 2006; Paul et al. 2001; Parkash et al. 2011; Johnson 2001; Peltzer and Saucier 1996; Wesnovsky et al. 1999; Molnar 1987) for reviewing in detail temperature structures of the Himalayan subduction zone. To evaluate the temperature structures along the Himalayan subduction zone, it is necessary to resolve the maximum temperature in the mantle wedge, T_r and the temperature at the top of the slab, T_s . The estimation of these two parameters (T_r and T_s) is done using a simple mathematical model from England and Katz (2010). Although calculations of the full temperature field in subduction zones require numerical models, their results can be encapsulated in simple scaling relations that show that temperatures within the mantle wedge and at the top of the slab depend upon a single parameter, $Vr\delta^2/k$ (Fig. 2a, 2b). The maximum temperature in the mantle wedge, T_r is given by-

$T_r = T_o \exp(-B (Vr\delta^2/k)^B)$ (1) and the temperature at the top of the slab, T_s is-

$$T_s = T_r/1+C (Vr\delta^2/k)^\gamma$$
..... (2)

The required dimensionless parameter, $v r \delta^2 / k$ for evaluating the maximum temperature in the mantle wedge can be written as-

$$Vr\delta^2/k = VR_D\delta^2/k = V\delta^2 (D-Z_w)/k \sin(\delta)$$

Then, the radial distance from the wedge corner-
 $r = R_D = D-Z_w / \sin(\delta)$ (3)

Table 1 Notation with expressions for, or values of, parameters.

Symbol	Definition	Notation/value
k	Thermal diffusivity	$8 \times 10^{-7} \text{ m}^2/\text{s}$ (England and Katz 2010)
V	Convergence rate	Variable
r	Radial distance from wedge corner	?
δ	Dip of the slab	14–19° and 20° (Kaneko et al. 2003; Jamieson et al. 2011).
T_o	A scale temperature	1420 °C (England and Katz 2010)
B, C	Constants	3.3, 1.4 (England and Katz 2010)
β, γ	Constants	-0.8, -0.06 (England and Katz 2010)
T_r	Maximum temperature in the mantle wedge	?
T_s	Temperature at the top of the slab	?

Using the parameters mentioned in Table 1, we estimated the maximum temperature in the mantle wedge, T_r and the temperature at the top of the slab, T_s with the help of the equations 1 and 2, and a program have been prepared using MATLAB (Version, 7.8.0.347, R2009a) to calculate the maximum mantle wedge temperature T_r and the slab temperature at the top of the slab, T_s , and the results are shown in Table 2 and Table 3.

Regional Tectonics

The Indian craton was once part of the supercontinent of Pangea. At that time, it was attached to Madagascar and Southern Africa on the south west coast, and Australia along the east coast 160 Ma (ICS 2004) during the Jurassic period, rifting caused Pangea to break apart into supercontinents namely, Gondwana (to the south) and Laurasia (to the north). The Indian craton remained attached to Gondwana, until the supercontinent began to break apart in the Early Cretaceous, about 125 Ma (ICS 2004). The Indian plate then drifted northward toward the Eurasian plate, at a place that is the fastest movement of any known plate. It is generally believed that the Indian plate separated from Madagascar about 90 Ma; however some biogeographical and geological evidences suggest that the connection between Madagascar and Africa was retained at the time when the Indian plate collided with the Eurasian plate about 50 Ma (ICS 2004). General consensus that the crustal thickening driven by collision between India and Asia began 50–55 Ma ago. The Indian plate and its leading edge now lies under the

Tibetan plateau, about 300 km north of the Indus-Tsangpo suture zone that marks the surface expression of the collision boundary (Nábělek et al. 2009). Plate reconstructions show that the convergence velocity between Indian subcontinent and Eurasia changed dramatically 50–35 Ma (Copley et al. 2010). The rate of convergence started decreasing at about the time of the initial contact of the Indian and Asian continental margins and the cessation of marine sedimentation in the western Himalayas (Guillot et al. 2003). The relative velocity continued to decrease as the Himalayan orogen developed and the Tibetan Plateau was uplifted. Rowley and Currie (2006) suggest the Tibetan Plateau had attained close to its current elevation at 35 Ma, after which the Indian plate motion stabilized. This orogeny, which is continuing today, is related to closure of the Tethys Ocean. The closure of this ocean which created the Alps in Europe, and the Caucasus range in western Asia, created Himalaya Mountains and the Tibetan Plateau in South Asia.

In the Early Tertiary, the first phase of the Himalayan Orogeny, the Karakoran phase occurred, the Himalayan orogeny is continuing to the present day (ICS 2004). The current orogenic event is causing of the Asian to deform westward and eastward on either side of the orogeny. The present day crustal thickness beneath the Himalaya exceeds 80 km, and inferred temperatures in the middle to lower crust are well above 700°C (Nelson et al. 1996; Klemperer 2006). Geological and geophysical evidences indicate that melting began at about 30 Ma and continues till this day (Jamieson et al. 2011).

Results

Analyses have been carried out considering the convergence rates, depth to the mantle wedge and the top of the slab, and the angle of the subducting slab along the Himalayan subduction zone for getting temperature structures (Table 2 and Table 3).

Table 2 Estimated maximum temperature in the mantle wedge and the temperatures at the top of the slab depending on the maximum and minimum value of $D \approx 80\text{-}160$ km, $Z_w \approx 40\text{-}80$ km, and $\delta \approx 14\text{-}19^\circ$.

Convergence rate (V) mm/yr	Region	Source	Max. temperature in the mantle wedge, T_r °C	Max. temperature at the top of the slab, T_s °C	Min. temperature at the top of the slab, T_s °C
10-20	Kashmir to Arunachal	Sridevi, 2004	1420	1116.32	1086.74
10-12	Sikkim	„	1420	1108.94	1086.74
10-18	Garhwal	„	1420	1114.81	1086.74
10-18	Kumaun	„	1420	1114.81	1086.74
14-20	Ladakh	„	1420	1116.32	1091.86
20±5	Lhasa	„	1420	1119.51	1092.91
20±3	Tibet	Bilham et al. 1997a	1420	1118.32	1094.79
18.5±2		Bilham et al. 1997b	1420	1116.47	1094.07
16-20		Bilham et al. 2001	1420	1116.32	1093.88
21±1.5	Along MFT	Bollinger et al. 2006	1420	1118.01	1096.85
18±7		Paul et al. 2001	1420	1118.76	1088.19
21.5±1.5	Hardwar	Parkash et al. 2011	1420	1118.32	1097.23
15-20		Johnson 2001	1420	1116.32	1092.9
13	Pakistan	Johnson 2001	1420	1110.11	1090.73
9-14	Central Plateau, Pakistan	„	1420	1111.19	1085.13
7	Eastern Plateau, Pakistan	„	1420	1101.02	1081.25
18	Nepal, Assam	Peltzer and Saucier 1996	1420	1114.81	1095.65
10	Jammu	„	1420	1106.28	1086.74
17.2	Nepal	Bilham et al. 1997b	1420	1114.16	1094.97
13.8±3.6	Central India	Wesnovsky et al. 1999	1420	1114.33	1087.04
18±7	Central India	Molnar 1987	1420	1119.51	1088.2

Table 3. Estimated maximum temperature in the mantle wedge and the average temperature at the top of the slab depending on the average value of $D \approx 120$ km, $Z_w \approx 60$ km, $\delta \approx 16.5^\circ$.

Convergence rate, V mm/yr (Average)	Region	Maximum temperature in the mantle wedge, T_r °C	Average temperature at the top of the slab, T_s °C
15	Kashmir to Arunachal	1420	1103.86
11	Sikkim	1420	1099.27
14	Garhwal	1420	1102.84
14	Kumaun	1420	1102.84
17	Ladakh	1420	1105.71
20	Lhasa	1420	1108.08
20	Tibet	1420	1108.08
18.5		1420	1106.94
18		1420	1106.54
21	Along MFT	1420	1108.80
18		1420	1106.54
21.5	Hardwar	1420	1109.14
17.5		1420	1106.13
13	Pakistan	1420	1101.75
11.5	Central Plateau, Pakistan	1420	1099.93
7	Eastern Plateau, Pakistan	1420	1092.48
18	Nepal, Assam	1420	1106.54
10	Jammu	1420	1097.84
17.2	Nepal	1420	1105.88
13.8	Central India	1420	1102.63
18	Central India	1420	1106.54

The convergence rate in Ladakh ranges from 14–20 mm/yr and the T_s ranges from 1092–1116°C whereas in Lhasa it is 20±3 mm/yr and the T_s value range from 1093–1120°C (Sridevi 2004). The rate of slip of India beneath Tibet is found within the range of 20.5±2 mm/yr and the related T_s value ranges from 1095–1118°C (Bilham et al. 1997b). Similarly the convergence rate in Sikkim is 10–20 mm/yr and T_s ranges from 1087–1109°C, in the case of Garhwal and Kumaun the convergence rate ranges from 10–18 mm/yr and their T_s ranges from 1087–1115°C. Along the main frontal thrust the convergence rate is 21±1.5 mm/yr and the T_s shows 1097–1118°C (Bollinger et al. 2006). Overall convergence of 10–20 mm/yr occurs in the 2500 km stretch of the Himalayan arc from Kashmir to Arunachal and the convergence rates vary from west to east and their related top of the slab temperature T_s vary from 1087–1116°C. In general, the rate of convergence between Indian subcontinent and Eurasia over the period since initial collision was roughly 50 mm/yr. However, the possible long-term rate of convergence within the Himalaya is considerably less, i.e., 15–20 mm/yr, a fraction of the total convergence (Johnson et al. 2001). Avouac et al. (1998) and Wesnousky et al. (1999) quoted rate of 21±1 and 13±3.6 mm/yr respectively, for slip on the active Himalayan Main Frontal Thrust.

An approximation to the 50 mm/yr plate convergence rate is achieved by adding shortening rates in regions north of the Himalaya (Tibet, Tien Shan, Kun Kun etc., Dewey et al. 1988). The problem with this is that it assumes that distributed shortening by thrust /Z fold tectonics has operated since the time of collision. But we know that is not true. For example, the Tien Shan is a Neogene (post 24 Ma) orogen (Hendrix et al. 1994). The inferences are

either that the shortening rate in the Himalaya was much higher before the Miocene or that strike slip faulting operated over wide area of South East Asia.

After plotting convergence rate of corresponding region along the Himalayan subduction zone it is shown that the slab temperatures are slightly varied (Fig. 3). The maximum slab temperature is observed in Lhasa which is far away from the MBT and the minimum slab temperature is observed at Eastern plateau in Pakistan.

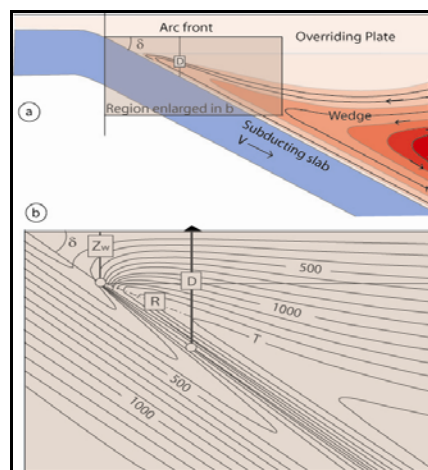


Figure 2. (a) Idealized cross-sections of a subduction zone. Two plates converge at a speed V , with the slab of Indian plate (lithosphere) being subducted at an angle δ beneath the overriding plate. (b) Enlargement of temperature structure of the rectangle in a: Isotherms are shown at intervals of 100°C. A schematic isotherm, labeled T , has its closest approach to the wedge corner (its 'nose') immediately beneath the volcanic front, at a distance R from the corner (black circle).

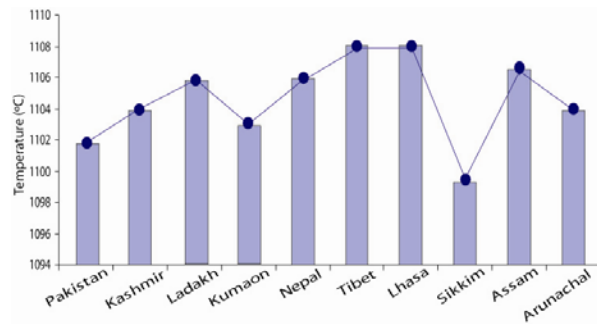


Figure 3 Maximum slab temperature distributions at the top of the slab along the Himalayan Range (in Line and in Histogram).

After plotting maximum slab temperature of corresponding places along the Himalayan subduction zone it is shown that the slab temperature is comparatively higher in central region (except Sikkim) than the Eastern and Western sides of the Himalayan region (Fig. 3). Comparatively low T_s value in Sikkim area may be the reflection of De and Kayal (2004) observation. They observed no remarkable seismic activity along NNW-SSE trending large Gangtok lineament (which indicate locally this area seismically less active).

Discussions and Conclusions

The results of the arc front temperature and geological data demonstrate a profound effect on the rock strength, that melt-weakening strongly influences the tectonic style of mountain belts that resultant weak partial-melt zones and magma arc present within large modern orogens. Both modern and ancient orogens belts display the protected interaction among melting deformation and crustal flow.

The analysis of the results gives the value of temperature structures (mantle wedge and slab) in Himalayan subduction zone, where maximum temperature in the mantle wedge, T_r is 1420°C. This result in the study area doesn't depend upon the changes of convergence rates, depth to the mantle wedge and the top of the slab, and the angle of the subducting slab, whereas temperature at the top of the slab in the study area, T_s , ranges from 1081.3–1119.5°C, which depend upon the changes of convergence rates, depth to the mantle wedge and the top of the slab, and the angle of the subducting slab. The mean value of the slab temperature is about 1103.3°C (Standard deviation is $\pm 10.7^\circ\text{C}$).

According to Kelemen et al. (2003), thermal structure in the mantle wedge beneath arcs is almost 1450°C. So, the result suggests that there might have a great possibility to develop volcanic arc in the studied mantle wedge, where the temperature is 1420°C. The

maximum temperature in the mantle wedge which is achieved in the study is consistent with Tohoku subduction zone, 1400°C in Northeast Japan (Honda 1985), Kamchatka subduction zone, 1450°C in Mexico (Manea et al. 2004).

From the analysis it is shown that the mantle wedge temperature along the Himalayan range is almost uniform whereas result of T_s shows slightly variable pattern (Grujic et al. 2006). It is remarkable that the slab temperatures variations are not so much high. The maximum slab temperature is 1119.51°C which is found in Lhasa, a great distance apart from MBT and the minimum slab temperature is 1081.25°C which is found at Eastern plateau in Pakistan. Generally plate convergence at rates of 10–50 mm/yr initially forms small cold orogens with back to back wedges consisting largely of low-grade sedimentary and volcanic rocks (e.g., Willett et al. 1993). As these orogens grow along the orogenic main sequence thickened crust heats up by radioactive decay on timescales of ca 20 Ma (Jamieson et al. 2011).

From overall observation, the study shows that the slab temperature in Central Himalaya (except Sikkim) is comparatively higher than Eastern and Western Himalaya. High compression and seismic activity characterize the entire tectonic boundary along both the eastern and western sections of the thrust. As a result there might be great possibility to form volcanic front and generate earthquake. For example, active collision along the northwestern boundary at the foothills of the Himalayan Mountains have already caused the destructive October 8, 2005 earthquake of magnitude 7.6 (Mw) in Pakistan (Pararas-Carayannis 2005) and June 15, 1897 earthquake of magnitude 8.7 (Mw) in Assam, India (Mahapatra and Mohanty 2009). Again, according to Bilham et al. (2001) the convergence has been responsible for many large earthquakes along the Himalayan arc in the past and could likely to creep up large earthquakes in the future.

So, this result may help to explain the complex details of geometry, rheology, heat transport and petrological processes of Himalayan subduction zone. These data are also helpful about the processes governing the location of volcanic arcs which is controlled by a strongly temperature dependent process taking place either at the top of the slab or in the wedge of mantle beneath the arcs (England and Wilkins 2004). Generally a temperature dependent process in the mantle wedge is responsible for the focusing of volcanic activity at the sharp fronts to the arcs. So, this study may also provide strong constraints in petrological modeling of the generation of arc margins.

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