

## Spatial variability in erosion in the Brahmaputra basin: causes and impacts

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**The rivers from the Himalaya supply large quantities of particulate and dissolved materials to the oceans. Among the various rivers, the Brahmaputra ranks highest in contributing to the sediment budget of the Bay of Bengal. The erosion rates among the sub-basins of the Brahmaputra vary over 1–2 orders of magnitude, the highest being in the Eastern Syntaxis basin which is eroding at an enormously high rate of  $\sim 14 \text{ mm yr}^{-1}$ , caused by the high stream power of the Siang river. These contemporary erosion rates are consistent with the time-averaged erosion and exhumation rates derived for  $\sim 100 \text{ ka}$  based on cosmogenic isotopes and geophysical methods. Both the Eastern and the Western syntaxes experience rapid erosion suggesting that the syntaxes, a characteristic feature of the collision belt, undergo rapid erosion under favourable conditions. The rapid erosion of the Eastern Syntaxis has caused important tectonic and geomorphological changes, such as the rapid uplift of this region resulting in the great peaks of Namche Barwa and Gyala Peri, and the nickpoint in the Tsangpo river bed prior to its entrance to the gorge. Further, the rapid erosion makes up about half of the particulate material transported by the Brahmaputra to the Bay of Bengal, an order of magnitude higher than its areal coverage. The high sedimentation rate in the Bay of Bengal over the past  $\sim 1 \text{ Ma}$  can be due to the high erosion rate of the Eastern Syntaxis. The mineralogical and isotopic composition of the sediments seems to suggest this inference.**

**Keywords:** Brahmaputra, Eastern Syntaxis, erosion, Himalaya, Sr–Nd–Os isotope systematics.

ORIGIN and evolution of the Himalaya–Tibet (HT) during the Cenozoic has not only changed the geomorphology of the earth, but has also influenced the global climate and geochemical and sedimentary cycles<sup>1–8</sup>. The rivers draining the Himalaya contribute  $\sim 25\%$  of the global sediment supply to the oceans. Among the various rivers draining the HT, the Brahmaputra alone supplies  $\sim 1000$  million tons of suspended material to the Bay of Bengal<sup>6–8</sup>. This estimate of sediment supply from the Brahmaputra would be doubled if bed load is also considered<sup>9</sup>. It has been shown<sup>9</sup> that the Brahmaputra basin erodes more rapidly compared to its western counterpart, the Ganga drainage, possibly because of higher run-off in the Eastern Himalaya. Recently, Singh and France-Lanord<sup>10</sup> observed that

there are significant variations in the erosion rates among the various sub-basins of the Brahmaputra.

This study aims to: (i) Quantify the contemporary erosion rates of the various sub-basins of the Brahmaputra system based on the sediment provenance<sup>10</sup> and available data on sediment flux. (ii) Compare the results of this study with the reported long-term exhumation rates and erosion rates from other regions<sup>11–14</sup>. This provides information on the temporal variability in erosion in selected regions of the Himalaya, (iii) Characterize the source of sediments contributing to high sedimentation rate in the Bay of Bengal over the past  $\sim 1 \text{ Ma}$ .

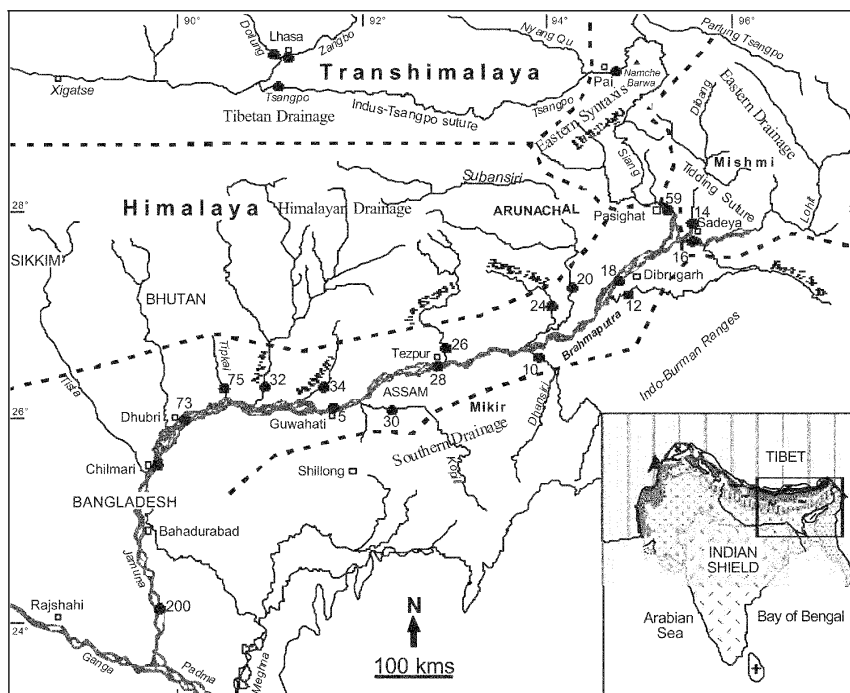
The Brahmaputra river has different names along its stretch of about 2800 km (Figure 1). It originates from the Kailash mountain in the northern slopes of the Himalaya and flows east of the Mansarovar lake. In Tibet, it drains  $\sim 1300 \text{ km}$  along the Indus–Tsangpo Suture and is known as the Tsangpo. After Pai, it enters the Eastern Syntaxis which houses the deepest ( $\sim 5000 \text{ m}$ ) gorge of the world and takes a U-turn. Near Singing, it turns south to enter Arunachal Pradesh (India), where it is known as Siang or Dihang. The Siang enters the Assam plain at Pasighat, downstream of which it meets with two eastern tributaries, the Dibang and the Lohit, before taking a turn in the WSW direction. In the whole stretch of the Assam plain, the river is known as the Brahmaputra. At the Indo-Bangladesh border, it turns south where it is known as the Jamuna. It meets with the Ganga at Aricha ghat, after which it is called the Padma until the Upper Meghna joins it and together they become the Lower Meghna, which drains into the Bay of Bengal through various distributaries.

In Tibet, the Tsangpo receives tributaries, the Doilung, Zangbo and Nyang Qu; and the Parlung Tsangpo in the gorge (Figure 1). It drains sedimentary rocks and gabbros, dolerite of the Trans Himalayan plutonic batholiths adjacent to the Indus–Tsangpo Suture and granites of the adjoining areas. The Eastern Syntaxis is made of gneisses and calc-alkaline plutons of the Trans Himalayan plutonic belt. Further downstream, in the Lesser Himalaya, crystallines and sedimentaries, quartzite, dolomite and limestone dominate the lithology. The tributaries joining from the Himalaya in the Assam plain, the Subansiri, Jia Bahreli, Manas, drain crystallines and sedimentaries of the Higher and Lesser Himalaya; the eastern tributaries drain the Mishmi Hills composed of calc-alkaline diorite-granodiorite-tonalite rocks of Trans Himalayan plutonic belt, whereas tributaries from the south drain the turbidites with ophiolites of Naga Patkoi ranges<sup>15</sup>.

Based on the lithology and climate, the Brahmaputra basin is divided into five sub-basins: (i) Tibet, (ii) Eastern Syntaxis, (iii) Eastern drainage/Mishmi Hills, (iv) Himalaya and (v) Southern drainage (Figure 1).

The climate of the Brahmaputra basin is highly variable. The Tibet drainage is cold and dry and has the lowest run-off among the various basins,  $\sim 0.3 \text{ m yr}^{-1}$ ; the Eastern Syntaxis region has the highest run-off,  $\sim 5 \text{ m yr}^{-1}$ . Run-off

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**Figure 1.** Brahmaputra river system. Sampling locations are shown by filled circles. Different sub-basins are delineated by dashed lines.

for the other basins falls between these two extremes, the eastern and southern basins have  $\sim 3\text{--}4 \text{ m yr}^{-1}$ , whereas for the Himalayan basin, it is  $1\text{--}2 \text{ m yr}^{-1}$ . Sediment contributions from the southern tributaries are insignificant<sup>16</sup> and hence this sub-basin is not considered for erosion rate calculations.

Sediment samples (both bed-load and suspended load) from the Brahmaputra main channel and from its major tributaries were collected from Pasighat to Dhubri (Figure 1). Sr and Nd concentrations and their isotope compositions were measured in silicate phase of the sediments and Os concentration and its isotope composition in bulk sediments<sup>10,17</sup>. Downstream variations in the isotopic composition of Sr, Nd and Os in the Brahmaputra mainstream and its major tributaries are shown in Figure 2. It is clear from Figure 2 that Sr, Nd and Os isotopic composition of the Brahmaputra mainstream sediments is nearly invariant between Pasighat and Dhubri, though the Brahmaputra receives sediments from the Himalayan tributaries which have distinctly different isotopic composition (Figure 2). Material balance calculations suggest that about half of the sediments at the Brahmaputra outflow is derived upstream of Pasighat. The ages<sup>18</sup> of detrital grains also support this inference; these results suggest about half of the sediments in the Brahmaputra is from the erosion in the Eastern Syntaxis region. Most of the sediments upstream of Pasighat are from regions around the Eastern Syntaxis, as contribution from Tibet are low due to low run-off, gentle slope and knick-point formation in the Tsangpo river prior to its plunging into the Eastern Syntaxis gorge<sup>19</sup>.

Based on material balance calculations, it is estimated<sup>10</sup> that the contribution from Tibet, Eastern Syntaxis, Eastern drainage/Mishmi Hills and the Himalayan sub-basins to the Brahmaputra sediments is 5, 45, 10 and 40% respectively. It is noteworthy that the Eastern Syntaxis, which occupies only an area of  $\sim 4\%$  of the Brahmaputra basin, supplies about half of the total sediments to the Brahmaputra. This disproportionately higher supply of sediments suggests rapid erosion in the Eastern Syntaxis region.

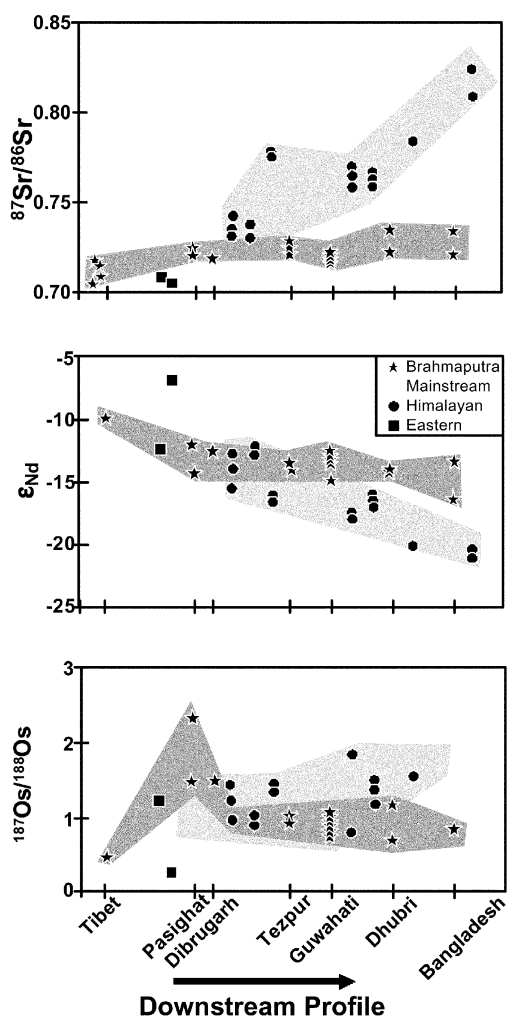
Estimates for the suspended load flux<sup>8</sup> from the Brahmaputra to the Bay of Bengal range from  $\sim 500$  to  $\sim 1600$  million tons  $\text{yr}^{-1}$ ; for erosion rate calculations a value of 1000 million tons  $\text{yr}^{-1}$  has been used. The total sediment flux of the Brahmaputra will increase to  $\sim 2000$  million tons  $\text{yr}^{-1}$  if the bed-load flux is considered equivalent to the suspended load flux<sup>9</sup>. Using a total sediment flux of  $\sim 2000$  million tons  $\text{yr}^{-1}$ , erosion rates for the various sub-basins have been calculated. These results are presented in Table 1 and Figure 3. (Uncertainties in the total sediment flux would not affect the relative erosion rates of various sub-basins.) A remarkable feature of these results is the high erosion rate for the Eastern Syntaxis basin (Figure 3),  $\sim 14 \text{ mm yr}^{-1}$ . This erosion rate is among the highest in the world; such as that reported for the tectonically active ranges of Southeast Alaska<sup>20</sup>. The lowest erosion rate  $\sim 0.2 \text{ mm yr}^{-1}$  is in Tibet, whereas the Himalayan and the Eastern basins are eroding at a rate  $\sim 2.2 \text{ mm yr}^{-1}$ .

Higher erosion rate in the Eastern Syntaxis is due to the higher run-off and higher relief of this area. The river loses its elevation of about 3000 m in  $\sim 300 \text{ km}$  stretch (Figure

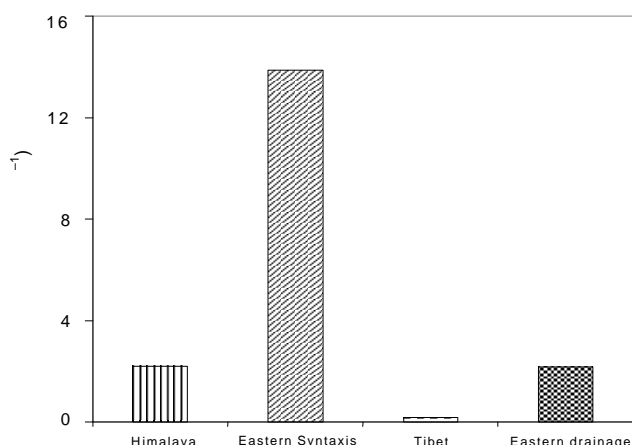
4), with an average gradient of ~30 m/km in the U-turn. The discharge in this section is also high, ~100 km<sup>3</sup> yr<sup>-1</sup>. Therefore, the stream power (gradient × discharge) of the

river in this section is high, causing intense erosion. The high erosion in the Eastern Syntaxis region and its causes discussed in this study are also supported by model calculations of Finlayson *et al.*<sup>21</sup>. This model<sup>21</sup> on Erosion Index (EI) based on the stream power and shear stress over the entire Himalaya, shows that EI is the highest for the Eastern Syntaxis region among the different basins.

The contemporary erosion rates derived above are compared with the available long-term (~over 100 ka) erosion rates determined using cosmogenic isotopes and also with exhumation rates of the other Himalayan–Tibetan regions (Table 1). The erosion rate in the Eastern Syntaxis zone, estimated in this study, is similar to the exhumation rate of ~10 mm yr<sup>-1</sup> reported<sup>22</sup> for this region during the last 3–4 Ma, and is also comparable to the erosion rate of ~9–12 mm yr<sup>-1</sup> for the Western Syntaxis<sup>13</sup>. The exhumation can be caused either by erosion or by tectonic denudation. The high exhumation rate for the Eastern Syntaxis region is considered due to the efficient erosion process<sup>23</sup>. The



**Figure 2.** Downstream variation of <sup>87</sup>Sr/<sup>86</sup>Sr, ε<sub>Nd</sub> and <sup>187</sup>Os/<sup>188</sup>Os of the Brahmaputra sediments<sup>10,17</sup>.

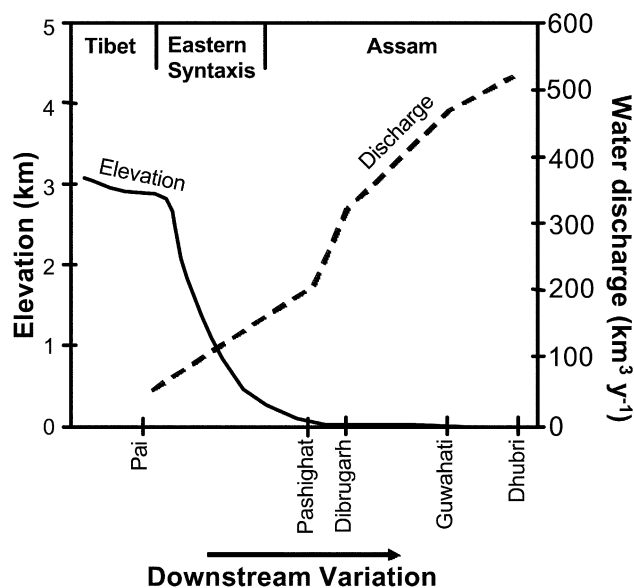


**Figure 3.** Weathering rates of various sub-basins of the Brahmaputra river system.

**Table 1.** Erosion/exhumation rates of various regions of the Himalaya

Sub-basin	Erosion rate (mm yr <sup>-1</sup> )		Exhumation rate* (mm yr <sup>-1</sup> )
	This study	Other studies*	
Tibet–Tsangpo	0.2	0.01–1.0	–
Higher Himalaya	2.2	2.7	1.6–3.0
Lesser Himalaya	–	0.8	0.6–1.3
Eastern Syntaxis	14	–	10
Eastern Drainage	2.1	–	–
Nanga Parbat–Indus	–	9–12	4–12

\*Data from Burg *et al.*<sup>11</sup>; Lal *et al.*<sup>12</sup>; Leland *et al.*<sup>13</sup> and Vance *et al.*<sup>14</sup>. Erosion rates are based on cosmogenic isotopes.



**Figure 4.** Elevation and water discharge of the Brahmaputra main-stream. In the Eastern Syntaxis region stream power (product of gradient and discharge) is high, resulting in higher erosion rate.

similarity of erosion rates between the Eastern and Western syntaxes indicates that the syntaxes, a distinctive feature of collisional belts, can erode rapidly under favourable conditions, such as high stream power. These results, therefore, suggest that the Eastern Syntaxis basin has been eroding at an extremely high rate of  $\sim 10\text{--}15\text{ mm yr}^{-1}$  for at least the past 3–4 Ma. It reduced to  $\sim 5\text{ mm yr}^{-1}$  in between at last  $\sim 2$  Ma, with the present-day erosion rate being the highest<sup>22</sup>.

The Bay of Bengal is a repository for sediments derived from the Himalaya. The signature of localized and high erosion in the Eastern Syntaxis seems to be recorded in the sediments of the Bay of Bengal<sup>18</sup>. Cochran<sup>24</sup>, and Derry and France-Lanord<sup>25</sup> have reported varying sedimentation rates in the Bay of Bengal during the last 20 Ma. These data show that the sedimentation rate, for the last 1 Ma, was significantly higher than those during 1–7 Ma. Comparison of properties of sediments during these two periods shows that the sediments of 0–1 Ma are characterized by more radiogenic Nd isotope composition and illite abundance. Contemporary Brahmaputra sediments have radiogenic Nd isotope composition and illite-rich clay composition<sup>10,26</sup>. The similarities in these signatures indicate increased contribution of sediments from the Brahmaputra to the Bay of Bengal since the last 1 Ma. Further,  $d^{18}\text{O}$  of the 0–1 Ma Bay of Bengal sediments shows decreasing trend<sup>25</sup> indicating material derived from high temperature metamorphic zone, such as the Eastern Syntaxis region, a zone known for high metamorphism<sup>22,23</sup>. Based on these evidences, it seems likely that the increase in the sedimentation rate in the Bay of Bengal during the last 1 Ma resulted from enhanced erosion in the Eastern Syntaxis during this time period.

The high erosion in the Eastern Syntaxis also seems to have an impact on the tectonics and geomorphology of the region. The intense erosion of this section has caused relatively higher uplift of this region because of isostatic rebound. This has resulted in high peaks of the Namche Barwa and the Gyal Peri. The uplift caused by the rapid erosion in this section has produced the knickpoint in the river bed of the Tsangpo just before the gorge<sup>19</sup>. The knickpoint has remained stationary despite the rapid erosion of the Eastern Syntaxis since the last 3–4 Ma, suggesting the sustained uplift of this region as result of the rapid erosion.

The erosion rates among the various sub-basins of the Brahmaputra show variability over 1–2 orders of magnitude. Among the various basins, the Eastern Syntaxis region is eroding rapidly with a rate as high as  $14\text{ mm yr}^{-1}$ , due to high stream power in the region. The contemporary erosion rates obtained in this study are similar to the reported longer term erosion and exhumation rates. Higher erosion and rapid exhumation of sediments from the Eastern Syntaxis region are contributing to the rapid uplift of this section due to isostatic rebound, resulting in the high peaks of Namche Barwa and Gyal Peri situated on

either side of the Eastern Syntaxis gorge. The erosion rate in the Eastern Syntaxis over the past  $\sim 1$  Ma seems to be the highest, and also responsible for higher sedimentation rate in the Bay of Bengal during this period.

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## A new record of calcareous algae from Shella Formation (Jaintia Group) of South Jaintia Hills, Meghalaya, India

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**The Shella Formation exposed in the southern part of Jaintia Hills comprises an alternate sequence of sandstone and limestone members. The limestones are fossiliferous with preponderance of benthic foraminifera, e.g. Nummulitids, Alveolinids, Discocyclina, etc. The foraminiferal assemblage suggests a Early Paleocene to Middle Eocene age for the Shella Formation. A rich assemblage of fossil calcareous algae (both non-geniculate and geniculate coralline red algae and halimedacean, udoteacean and dasycladalean green algae) has been recovered from the limestone. The non-geniculate corallines are represented by genera *Lithothamnion*, *Lithophyllum*, *Distichoplax*, *Sporolithon*, *Lithoporella* and *Spongites* and geniculate corallines are represented by the genera *Corallina* and *Jania*. A few green algae, viz. *Ovulites* (family Udoteaceae), *Halimeda* (family Halimedaceae) and *Actinoporella* (family Acetabulariaceae (Dasycladales)) have been recovered from the**

**study area. The overall algal assemblage indicates a shallow marine environment of normal salinity.**

**Keywords:** Coralline algae, green algae, Jaintia Hills, Palaeocene–Eocene, Shella Formation.

SIGNIFICANT contributions have so far been made on the study of fossil foraminifera from the Cenozoic sequence of Meghalaya shelf. Studies have also been made<sup>1–5</sup> on the calcareous algae from parts of the East Khasi Hills. However, lime-secreting calcareous algae from the study area (Figure 1) that forms part of the Meghalaya shelf are described here. Samples for the present study were collected from the Shella Formation (Jaintia Group) of South Jaintia Hills, Meghalaya (23°40′–25°9′N and 92°20′–92°35′E). Geologically, the area is part of the Meghalaya shelf, an extension of the Bengal Basin.

Excepting some impersistent exposures of Precambrian rocks, most of the area is covered by a thick pile of Tertiary sequences abutting against the Neogene clastics in the south and Precambrian metasediments in the north.

The Jaintia Group is subdivided into two broad divisions, i.e. the Shella Formation and Kopili Formation<sup>6,7</sup>. The Shella Formation is the lowermost lithounit of the Jaintia Group comprising three alternating sandstone and limestone members, viz. Lakadong Limestone, Umlatdoh Limestone and Prang Limestone respectively, in chronological order (Figure 2). The pinching out of some of the members and interfingering of limestone beds with sandstone and shale made them regionally impersistent.

From the lowermost member of the three limestone units of the Shella Formation, i.e. the Lakadong Limestone, calcareous algae (both geniculate and non-geniculate) have been recovered. Based on the foraminiferal assemblage, the age of this member is considered to be Early Palaeocene to Early Eocene. This member is found to be a regionally persistent horizon in the east and western Khasi Hills and has been equated with the Lakadong Limestone of Cherrapunji area. This member can also be correlated with the Khasian Stage of Kachchh<sup>8</sup>.

The middle limestone member designated as Umlatdoh Limestone is also highly fossiliferous. The red and green algae have been recovered from this unit in association with larger foraminifera. The age for the Umlatdoh limestone is considered as Lower Eocene to Middle Eocene based on foraminiferal assemblage. This unit is well developed in the Shella area but in west Khasi Hills and Garo Hills, this unit does not crop out. This limestone is considered as homotaxial to the Kakadian Stage of Kachchh<sup>8</sup>.

The uppermost of the three limestone members is designated as Prang Limestone in Khasi–Jaintia Hills and Siju Limestone in Garo Hills. This also occurs in Sylbhet, Delai and Koilapahar of Karbi Anglong district. The characteristic feature of Prang Limestone is the abundance of calcareous algae and larger foraminifera. The overall assemblage suggests a Middle Eocene (Lutetian) age for the

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