from India, Concept Publishing Company, New Delhi, 2004, p. 41.
4. Kumar, K. N. K., In *Climate Change and Sustainable Food Security* (eds Shetty, P. K., Ayyappan, S. and Srivastava, H. S.), National Institute of Advanced Studies & ICAR, New Delhi, p. 321.
5. Challenge of food security and its management. NRAA, New Delhi, 2011, pp. 1–44.
6. Rajput, M. S., Biswas, P. P., Joshi, P. P. and Srivastava, K. C., *Indian J. Agric. Sci.*, 1989, **59**(3), 149–153.
7. Murovhi, N. R., Materechera, S. A. and Mulugeta, S. D., *Agrofor. Syst.*, 2012, **86**(1), 61–71.
8. Rathore, A. C. *et al.*, *Agrofor. Syst.*, 2013, **87**, 1389–1404.
9. Piper, C. S., *Soil and Plant Analysis*, Interscience, New York, 1967.
10. Gomez, K. A. and Gomez, A. A., *Statistical Procedures for Agricultural Research*, John Wiley, New York, 1984.
11. Bremner, P. M., *Aust. J. Biol. Sci.*, 1972, **25**, 653–668.
12. Buck, M. C., *Agrofor. Syst.*, 1986, **4**, 191–203.
13. Osman, A. N., Rabild, A., Christiansen, J. L. and Bayala, J., *Afr. J. Agric. Res.*, 2011, **6**(4), 882–891.
14. Quin, F. M., *Advances in Cowpea Research*, Sayce Publishing, Devon, UK, 1997.
15. Saroj, P. L., Sharma, N. K., Dadhawal, K. S. and Srimali, S. S., *Indian J. Soil Conserv.*, 2004, **32**(3), 231–234.
16. Pramila, S. C., M Sc thesis submitted to University of Agricultural Sciences Dharwad, India, 2008.
17. Singh, J., Randhawa, G. S. and Singh, J., *Acta Hortic. A*, 1988, **188**, 183–186.
18. Yadav, V. P. S., *Indian Agric.*, 1986, **30**, 1–2.
19. Swain, S. C., Dora, D. K., Sahoo, S. C., Padhi, S. K. and Sanyal, D., *Commun. Soil Sci. Plant Anal.*, 2012, **43**(15), 2018–2026.
20. Manna, M. C. and Singh, M. V., *Bioresour. Technol.*, 2001, **76**(2), 143–150.
21. Vitousek, P. M., Gerrish, G., Turner, D., Walker, L. R. and Dombois, D., *J. Trop. Ecol.*, 1995, **11**, 189–203.
22. Franzluebbers, K., Weaver, R. W., Juo, A. S. R. and Franzluebbers, J., *Soil Biol. Biochem.*, 1994, **26**(10), 1379–1387.
23. Korwar, G. R., Pratibha, G., Ravi, V. and Palanikumar, D., *Indian J. Agric. Sci.*, 2006, **76**, 457–461.
24. Laik, R., Kumar, K. and Das, D. K., *For., Trees Livelihoods*, 2009, **19**, 81–92.
25. Gupta, M. K. and Sharma, S. D., *Ann. For.*, 2009, **17**(1), 43–70.

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AVINASH CHANDRA RATHORE*
H. LAL
N. K. SHARMA
HARSH MEHTA
J. JAYAPRAKASH
O. P. CHATURVEDI

Central Soil and Water Conservation Research and Training Institute,
Kaulagarh Road,
Dehradun 248 003, India
**For correspondence.*
e-mail: rathoreac@gmail.com

Chemical weathering of biotite in the Ganga Alluvial Plain

It is conceived that the physical and chemical weathering processes of the Himalaya release huge amounts of sediment and dissolved load, which are transported to the Indian Ocean. This has affected the character of sea water during the last 40 million years[1]. The sediment eroded in the Himalaya comes to the Ganga Alluvial Plain, where it is stored over a reasonable length of time. Part of this sediment is preserved to make alluvial deposits of the plain, and part is moved to the Bay of Bengal. Sediments of the Ganga Alluvial Plain show much higher weathering indices than the sediments coming from the Himalayan source[2]. Recently, chemical weathering of the sedimets of Ganga Alluvial Plain has been highlighted[3,4]. In the present study, we describe the chemical weathering of biotite grains of the Gomati River sediments and release of various elements in dissolved load.

The interactions between minerals and water play an important role in geochemical processes, i.e. soil formation, elemental mobility, bio-mineralization, nutrient availability, etc.[5]. The study of chemical weathering processes of minerals in natural system is essential to estimate the release of various elements into solution. To understand the pattern of chemical weathering of the Ganga Alluvial Plain, the Gomati River Basin has been selected. The basin experiences humid sub-tropical climate, characterized by monsoon rainfall and large temperature fluctuations (2°C to 47°C) from winter to

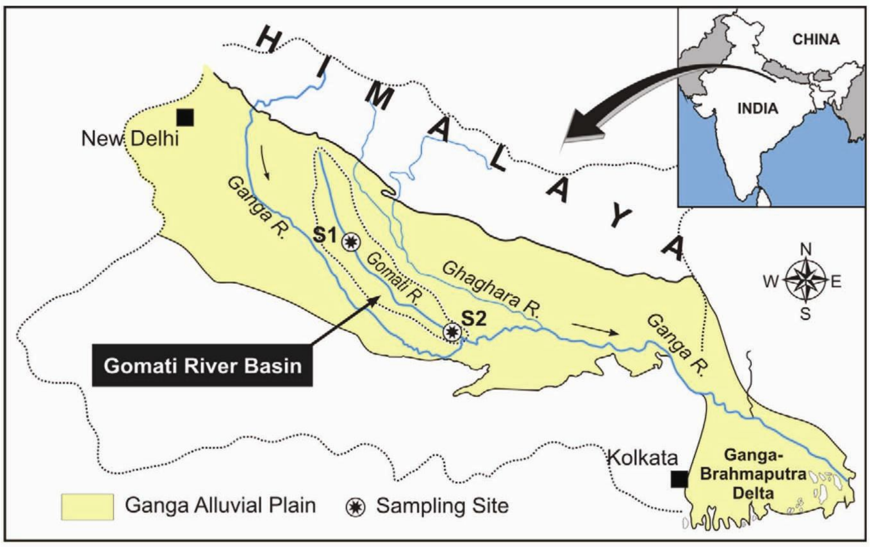

Figure 1. Map of the Gomati River Basin showing sampling locations of river sediment (S1–Naimeserayan) and river water (S2–Chandwak) used in the present study.

summer seasons. The Gomati River transports weathering products of the Gomati River Basin as bed load, suspended load and dissolved load to the Ganga River. High dissolved load (~400 mg/l) indicates prominent chemical weathering in its basin[6].

The Gomati River originates from the Terai belt of northern Ganga Alluvial Plain and joins the Ganga River. It flows for 900 km and drains about 30,437 sq. km area of the alluvial plain (Figure 1). It is a groundwater-fed river and receives water from many tributaries, which originate within the alluvial plain. The water discharge varies from 31.85 m^3/s in the summer season to 721.32 m^3/s in the monsoon season[7]. The Gomati River Basin receives its water and sediment discharges exclusively within the alluvial plain. There is no direct contribution of water and sediment discharges in this basin from the Himalayan region. Thus, the changes in sediment of the Gomati River are due to the results of physical and chemical weathering processes operating within the alluvial plain. The bed load sediments of the Gomati River are fine-grained sand and mineralogically made up of quartz (55%), mica (17%), feldspar (9%) and other minerals (19%)[8]. The large mica flakes (>500 μm) are abundant in the coarser fraction of the bed load sediments. The river water is hydrochemically characterized by Ca–Mg–HCO_3-type with mild alkalinity (pH = 8.0)[7].

We collected the bed load sediment samples ($n = 2$) at Naimeserayan (S1) from an active channel of the Gomati River. A total of eight mica grains were selected from these sediment samples. These grains were coated with carbon with the help of sputter coater and examined by scanning electron microscope (LEO 440). Chemical composition of core and margin of the biotite grain was determined using the Scanning Electron Microscope with Energy Dispersive X-ray (EDX) microanalyser. Water samples ($n = 36$) were collected every tenth day for a year (2009–10) at Chandwak (S2) location. This location represents contribution from the entire Gomati River Basin. These river water samples were filtered through Millipore filtering assembly using 0.45 μm filtering membrane and analysed by inductive coupled plasma mass spectrophotometer (ELAN DRC II Perkin Elmer SCIEX).

The scanning results show that the margins of biotite grain display a distinctive

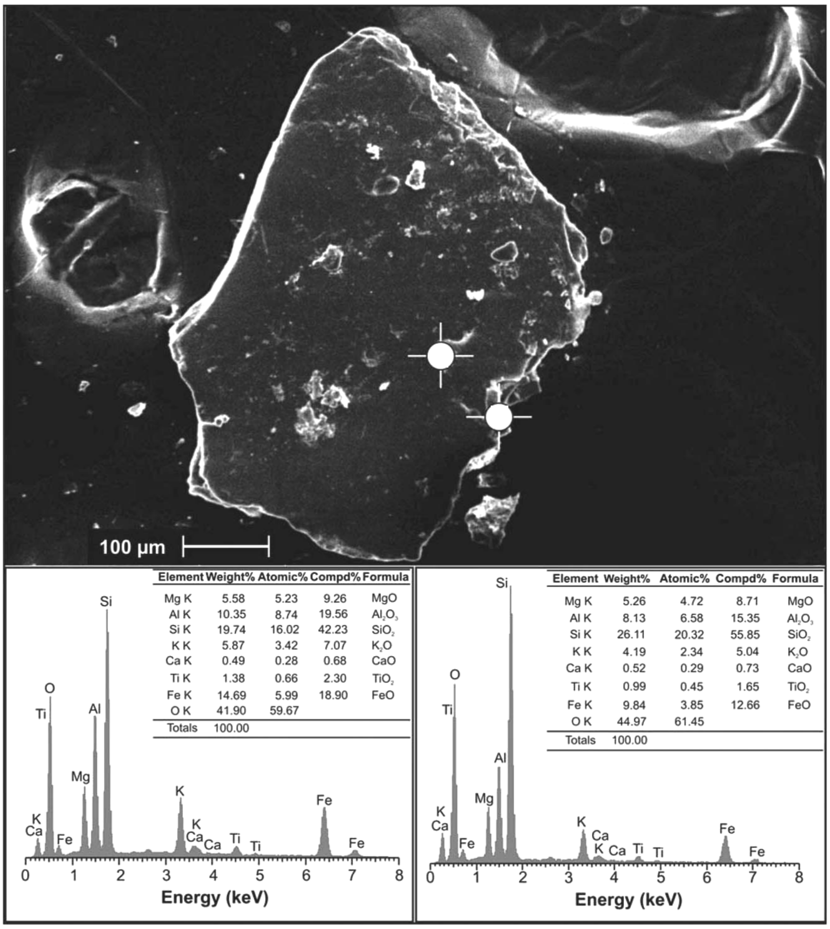

Figure 2. (Upper) Scanning electron photomicrograph of biotite grain of S1 sediment sample. The grain margin shows the effect of weathering as exfoliation and dissolution. (Lower) Results of Energy Dispersive X-ray (EDX) analysis of unweathered surface (***a***) and weathered surface (***b***) of the biotite grain. Peaks are levelled with the EDX line of the corresponding element and elemental data (in table) are presented in both weight and atomic per cent.

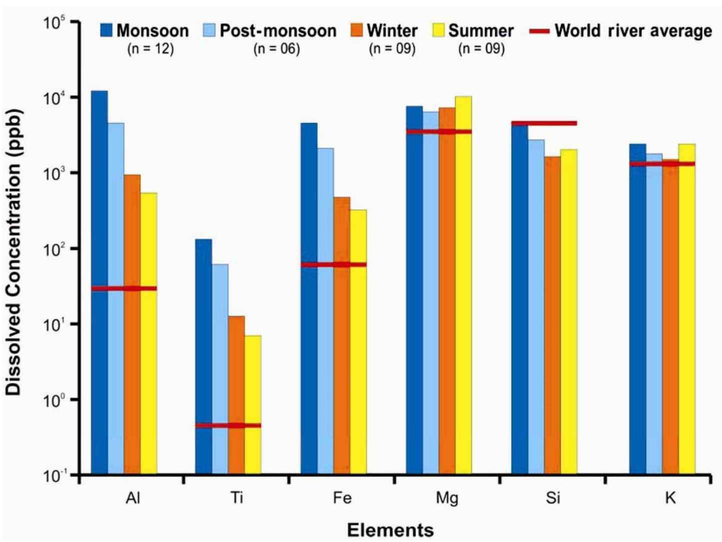

Figure 3. Bar diagram showing the average elemental composition of dissolved load of the Gomati River water during the monsoon, post-monsoon, winter and summer seasons. Note the concentrations of Al, Ti and Fe are ~10 to ~100 times higher than the average values of the world's river water. Release of these elements is due to the chemical weathering of mainly biotite mineral present in sediments of the Ganga Alluvial Plain.

tonal change due to the physical and chemical alteration (Figure 2). All the grains show prominent difference in the chemical composition of the core and the margin. Quantitatively, the margins of the grains show variability in the relative concentration of various elements. It has been documented that dissolution and deposition of elements during weathering go together and concentration of elements in weathered part depends upon flushing into moving water[9].

Biotite is a phyllo-(layer) silicate mineral and consists of octahedral (o-layer) sheet sandwich between two identical tetrahedral (t-layer) sheets producing the characteristic t–o–t layer. The tetrahedral sheets are occupied by Si and Al, whereas the octahedral sheets are usually inhabited by Fe, Mg and other cations. The interlayer site is typically resided by K[10]. Biotite quickly weathers into secondary minerals by solid-state alteration and dissolution processes[11]. Dissolution processes take place by replacement of K at the interlayer site, oxidation of Fe in the octahedral sheet, movement of other cations from the octahedral sheet into solution and neutralization of OH groups by H[12]. Generally, it is believed that mica minerals, particularly biotite, are prone to chemical weathering and release large amounts of major and trace elements to be moved into solution[13]. The chemical change in biotite can be represented as follows[14]

$$K_{0.65}(Al_{1.10}Ti_{0.15}Fe_{0.50}Mg_{0.55})(Si_{3.20}\,Al_{0.80})O_{10}(OH)_2 + 8H^+ = (Al_{1.71}Fe_{0.31}Ti_{0.03})Si_2O_5(OH)_4 + 0.65K^+ + 0.19Al^{3+} + 0.55Mg^{2+} + 0.19Fe^{2+} + 0.12Ti^{4+} + 1.2Si^{4+} + 3H_2O.$$

Figure 2 shows elemental composition of the central part and the margin of a biotite grain. The atomic per cent of Al, Fe, Mg, K and Ti at the core of the biotite grain is 8.74, 5.99, 5.23, 3.42 and 0.66 and decreases to 6.58, 3.85, 4.72, 2.34 and 0.45 at the margin respectively. Thus, it is reasonable to argue that along the margins of the biotite grain, silicate structure is broken during the chemical weathering to remove these elements into their dissolved phase.

Figure 3 represents seasonal variation in the average dissolved concentrations of Mg, Al, Si, K, Fe and Ti in the Gomati River water at Chandwak. Al, Ti, Fe and Si show maximum concentration during the monsoon season. The concentration of Al, Ti and Fe is ~10 to ~100 times higher than the average value of the world's river water[15,16]. The main source of these elements in the Gomati River water is essentially considered to be biotite mineral of the alluvial plain sediments. Sand and silt fractions of the Gomati River are rich in mica[8,17]. The contributions by other minerals, namely feldspar, seem to be subordinate.

We would like to argue that physical weathering in the Himalayan region is prominent, releasing huge amounts of sediment load to the Ganga River, with limited chemical weathering. Silicon concentration in the dissolved load of the Ganga River (~100 μmol/l) at Rishikesh is less than that of the Gomati River (~700 μmol/l) at Chandwak[18]. On the other hand, chemical weathering of the Ganga Alluvial Plain is significant, primarily due to high content of porous, mica-rich silty sediments[19], which are flushed by the monsoon rain, transferring the elements as dissolved load of the alluvial rivers into the Ganga River system.

These are the preliminary results of our study on chemical weathering in the Gomati River Basin. We are studying the chemical weathering of various minerals of the sediments, release of major and trace elements, transfer of these elements into groundwater and river water, and ultimately to the Ganga River system. This would provide insight into the pattern of chemical weathering of the alluvial sediments under monsoon-controlled, humid, subtropical climate.

1. Plamer, M. R. and Edmond, J. M., *Geochim. Cosmochim. Acta*, 1986, **92**, 11–26.
2. Singh, I. B., *J. Geol. Soc. India*, 2004, **64**, 431–454.
3. Rai, S. K., Singh, S. K. and Krishnaswami, S., *Geochim. Cosmochim. Acta*, 2010, **74**, 2340–2355.
4. Lupker, M. *et al.*, *Geochim. Cosmochim. Acta*, 2012, **84**, 410–432.
5. Putins, C. V. and Ruiz-Agudo, E., *Elements*, 2013, **9**, 177–182.
6. Gupta, L. P. and Subramanian, V., *Environ. Geol.*, 1994, **24**, 235–243.
7. Singh, M., Kumar, S., Kumar, B., Singh, S. and Singh, I. B., *Hydrol. J.*, 2013, **21**, 687–700.
8. Kumar, S. and Singh, I. B., *Senckenbergiana marit*, 1978, **10**, 145–211.
9. Putnis, C. V., Tsukamoto, K. and Nishimura, Y., *Am. Mineral.*, 2005, **90**, 1909–1012.
10. Deer, W. A., Howie, R. A. and Zussman, J., *An Introduction to the Rock-Forming Minerals*, Longman, England, 1966, p. 528.
11. Banfield, J. F. and Eggleton, R. A., *Clays Clay Miner.*, 1988, **36**, 47–60.
12. Feldman, S. B., Zelazny, L. W. and Baker, J. C., *Soil Sci. Soc. Am. J.*, 1991, **55**, 1629–1637.
13. Price, J. R. and Velbel, M. A., *Aquat. Geochem.*, 2014, **20**, 203–224.
14. Dong, H., Peacor, D. R. and Murphy, S. F., *Geochim. Cosmochim. Acta*, 1998, **62**, 1881–1887.
15. Faure, G., *Principles and Applications of Inorganic Geochemistry*, Macmillan Publishing Company, New York, 1991, p. 626.
16. Gaillardet, J., Viers, J. and Dupré, B., In *Treatise on Geochemistry* (ed. James, I. D.), 2003, vol. 5, pp. 225–272.
17. Ansari, A. A., Ph D thesis, University of Erlangen-Nuremberg, Germany, 1997.
18. Chakrapani, G. J., *Environ. Geol.*, 2005, **48**, 189–201.
19. Singh, I. B., Srivastava, P., Sharma, S., Sharma, M., Singh, D. S., Rajgopalan, G. and Shukla, U. K., *Facies*, 1999, **40**, 197–210.

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DHARMENDRA KUMAR JIGYASU[1]
ROHIT KUVAR[1,3]
SHAHINA[1,4]
PRIYANKA SINGH[2]
SANDEEP SINGH[2]
INDRA BIR SINGH[1]
MUNENDRA SINGH[1,*]

[1]*Centre of Advanced Study in Geology, University of Lucknow, Lucknow 226 007, India*
[2]*Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee 247 667, India*
[3]*Present address: Department of Applied Geology, Dr Hari Singh Gour Vishwavidyalaya, Sagar 470 003, India*
[4]*Present address: Geological Survey of India, Western Region, Jaipur 302 004, India*
**For correspondence.*
e-mail: smunendra@gmail.com