## Nature of arsenic pollutants in groundwater of Bengal basin – A case study from Baruipur area, West Bengal, India

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High incidence of arsenic in groundwater occurs as several small patches surrounded by zones with low arsenic in vast areas of West Bengal, India and adjoining Bangladesh. From the low- and high-arsenic groundwater zones, subsurface sediments have been analysed for mineral and chemical variations, in Baruipur, the worst arsenic-affected area in West Bengal. The Holocene sedimentary succession, in this part of Gangetic alluvium, shows a fining upward sequence from medium to fine sand, silt and finally to clay with occasional peat layer. The clay layer (As = 2-31 mg/kg) and peat layer (As = 9-40 mg/kg)contain higher concentration of arsenic compared to the silt layer (As = 2-6 mg/kg) and the sand layer (As = 1-7 mg/kg). It is inferred that the arsenic contamination in groundwater is related more with the components of sandy layer than others. Within the sandy layer, the components like (i) coated iron oxyhydroxides with residual magnetite and ilmenite (As = 14-112 mg/kg, (ii) illite (As = 10-40 mg/kg), (iii) iron hydroxide-coated sand grains (As = 30 mg/kg), (iv) chlorite (As = 5-31 mg/kg), (v) biotite (As = 9 mg/kg), and (vi) siderite concretions (As = 7-9 mg/kg) store most of the arsenic and are identified as the arsenic pollutants for groundwater in this part of Bengal basin.

Arsenic is introduced into the aquifer sediments in soluble state and get adsorbed on iron-rich clastic grains and on authigenic siderite concretions. Adsorption of the element on the sites and its consequent desorption to the groundwater are interpreted to be controlled by microbial activity in the aquifer sediments.

THE problem of arsenic contamination in groundwater in large areas of West Bengal and Bangladesh has been receiving wide attention because groundwater is the major source of drinking water in this part of the world. This vast area appears to be contaminated and also locally polluted and a large number of people in this densely populated region are likely to be affected by the menace.

Arsenic-affected areas in the Bengal basin are confined within the Ganges delta (Figure 1) mostly in the eastern part of Hooghly river (the lowermost western tributary of the Ganga). There are however, a few reports of arsenic contamination in the western part of the Hooghly river, in Bardhaman, Hooghly and Howrah districts of West Bengal<sup>1,2</sup>. But these are not well-defined yet. In Bangladesh, it extends from the Brahmaputra–Padma combined delta plain to the Sylhet basin and flood-delta plains of the Meghna river (Figure 1).

The sediments in these affected areas are composed of Recent floodplain and meander channel deposits with a stack of several fining upward cycles. The sandy to silty horizons in these cycles form the aquifers for ground-water in these areas. Arsenic is generally found<sup>2</sup> in water from the shallow aquifer (< 150 m bgl); the deeper aquifer (> 300 m bgl) has not so far been found contaminated, except for rare cases.

The source of arsenic in groundwater has been a subject debated since the identification of this particular problem. Different aspects of the problem, including the source of arsenic, are being investigated by several workers. Many alternatives have been suggested, dealing with the likely minerals contributing arsenic and also the likely processes responsible for release of the element into groundwater. Acharyya<sup>3</sup> opined that excessive withdrawal of groundwater induces oxidation of aquifer material, causing decomposition of pyrite and arsenopyrite and releasing of arsenic from them into the groundwater. Under such dewatered condition, the aquifer may also suck in arsenic liberated from adsorbed interbedded clay layers. According to Sinha Ray<sup>4</sup>, the aquifer in a reducing state allows the reduction of ferric iron in oxides and hydroxides, releases ferrous iron and adsorbed arsenic from the secondary iron and aluminium phases which subsequently get into water under alkaline condition during groundwater movement through porous media. Bhatta-



Figure 1. Arsenic-affected areas of Bengal basin with location of Baruipur area.

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charyya et al.<sup>5</sup> supported this hypothesis and opined that the source of arsenic is inferred to be volcanic rocks in eastern Bihar in the Chhotanagpur-Rajmahal hills and the anaerobic condition leading to reduction of ferric iron seems to be the most plausible mechanism for elevated dissolved arsenic in the aquifers of upper deltaic plains of West Bengal. Nickson et al.<sup>6</sup> are of the opinion that arsenic in aquifer is mobilized by the reduction of iron oxy-hydroxides forming a coating on sand grains in the aquifer. Acharyya et al.<sup>7,8</sup> have also supported the hypothesis of Nickson *et al.*<sup>6</sup> and inferred that arsenic appears to be adsorbed on iron-hydroxide-coated sand grains and clay minerals. Acharyya et al.<sup>8</sup> have suggested that arsenic was supplied by the Ganga-Padma river system and has been derived right from the source of the river. McArthur et al.9 suggested that the buried peat deposits supply arsenic to groundwater through microbial degradation. So far, there is no systematic study of the subsurface samples up to the aquifer depth to characterize the nature of arsenic pollutants for groundwater.

The present work has been carried out at Baruipur, the worst arsenic-affected area in West Bengal. From the pattern of arsenic content in groundwater, borehole sites have been selected and the subsurface sediments were collected from four boreholes, two each at high- and low-arsenic values in groundwater. A detailed mineralochemical study of subsurface samples collected from these boreholes has been carried out to identify the arsenic pollutants for this part of Bengal basin and to interpret the processes responsible for such high incidence of the element in groundwater.

The present study has been carried out at Ramnagar-Dhapdhapi block of Baruipur area, 24-Parganas (S) district of West Bengal (Figure 1), where people are suffering from arsenicosis and the groundwater is reported to contain greater than 0.05 mg/l arsenic. A ground survey for measuring arsenic values in groundwater has been carried out in this area. The arsenic values are either collected from already existing data from different agencies or measured by E-Merck arsenic determination kit. The values are then plotted on 1:400 scale (Figure 2). Arsenic plots in the groundwater of this block show distinct zonation of high (> 0.05 mg/l, arsenious zone)and low values (< 0.05 mg/l, safe zone) with two distinct clusters of low values (near Ramnagar Bazar and Padmajala) surrounded by a zone of > 0.05 mg/l. Again within the zone of high values, there are two characteristic clusters: one west of Ramnagar chawk and the other west of Padmajala. However, when the pattern is viewed for a larger area, surrounding the area covered in Figure 2, this cluster of high arsenic values is found to be enclosed by a larger area of low value (< 0.03 mg/l). The area under Ramnagar-Dhapdhapi block shows a flat topography, with a gradual down-slope towards south. The relief difference is only in the range of 0.58 m. The highest point is at Ramnagar and the lowest at Padmajala.

Four borehole locations (BH-1, BH-2, BH-3 and BH-4) for subsurface sampling have been selected, two each from high- and low-arsenic zones (Figure 2). Subsurface samples are collected from these four boreholes of 60 m depth. The undisturbed cores are logged and sampled at different depths. Raw samples at different depths are analysed for arsenic. Dry samples from sandy horizon are sieved successively through 60 (0.25 mm), 230 (0.0625 mm) and 325 (0.0039 mm) ASTM mesh. The (-60 + 230) size fraction is further separated into strongly magnetic (hand magnet), feebly magnetic (isodynamic separation) and non-magnetic parts; individual minerals from each part are then separated and analysed for arsenic content.

Magnetic separation of the sand size (-60 + 230) samples is made with a Frantz Isodynamic Separator (Model LB-1). Microscopic study of the sediments is made with an Olympus Stereo-binocular Microscope and the mineral phases are identified with an Automated Powder X-ray Diffractometer (Model PHILIPS APD 15). Arsenic content in sediments is analysed in an Atomic Absorption Spectrometer with hydride generator (VARIAN-Spectra 30). Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray analysis (EDX) of the selected grains are made in LEICA S440 model with 5  $\mu$ m beam diameter and 1 nA applied current. Electron Probe Microanalysis (EPMA) is made in a Cameca SX51 system with 1  $\mu$ m beam diameter and 12 nA applied current.



**Figure 2.** Arsenic map of Ramnagar–Dhapdhapi block, Baruipur area with the location of boreholes BH-1 to BH-4.

The Baruipur area and its surroundings are occupied by Recent floodplain and meander channel deposits of Hooghly river, forming part of the lower flood plains of Ganga–Hooghly river system. The sediments were deposited in the Late Holocene and Recent deltaic basin scoured by the Hooghly river. West of Hooghly river lies the early Holocene, older alluvial plane deposits overlain by alluvial fans of Damodar river. Part of the Damodar river fans are truncated by the younger delta plain of Hooghly river<sup>8</sup>. The lower level flood-delta plain of the Ganga–Padma river system is reported to be affected by arsenic contamination, but the bordering upland terraces and the Damodar fans are free from such contamination<sup>10</sup>.

The subsurface sediments encountered in the four boreholes up to 60 m, show a fining upward sequence. The constituents from top-downward are clay with occasional intercalatery thin peat bands, silty clay, silty sand, fine sand and minor medium sand (Figure 3). The sandy litho-facies is dominantly channel fill and the finer muddy litho-facies is over-bank levee deposit formed during floods. The top part of the sequence encountered in boreholes from the two zones shows a distinct difference. In the safe zone, the sand and silt layers are overlain by a 25–30 m thick top, comprising clays of



**Figure 3.** Lithologs showing fining upward sequence in boreholes BH-1, BH-3 (arsenious zone) and BH-2, BH-4 (safe zone) at Baruipur area.

different colours with occasional peat bands. In contrast, in the arsenious zone the top clay is either partially preserved or totally absent (Figure 3). Clay along with the peat in the upper part possibly represents a reducing, marshy environment.

Subsurface samples of the sandy aquifer are studied for mineralogical details along depth. The mineralogical constituents of the aquifer sediments in the two zones with different water quality are similar. However, the proportion of the mineral constituents shows distinct difference in the two zones. Underlying the clay, peat and silty layers, the sandy aquifer material in both arsenious and safe zones, is observed to consist of silt to sand-size grains (96.2–99.4%) and interstitial clay (0.6–3.8%). The coarser component consists of (a) non-magnetic fractions like stain-free quartz, feldspar, carbonate and lithic fragments constituting the bulk, and (b) minerals with variable magnetic intensity constituting 5.9 to 17.2%. The latter includes (i) strongly magnetic phases like iron oxyhydroxide with residual magnetite and ilmenite, and (ii) feebly magnetic phases like illite, biotite, iron oxyhydroxide-coated sand grains, siderite concretions, muscovite, garnet, hornblende, tourmaline, rutile, anatase, kyanite, sillimanite, epidote, apatite, staurolite, zircon, calcareous concretions, etc. The finer interstitial clay fraction (- 325 ASTM) contains quartz, feldspar, kaolinite, illite, montmorillonite, chlorite, etc. Arsenic-bearing clastic phases like arsenopyrite, arsenious pyrite, etc. are totally absent. The pyrites found in these sediments are framboidal in nature (Figure 4) and indicate an authigenic growth during diagenesis under reducing condition.

Samples from boreholes BH-1 (arsenious zone) and BH-2 (safe zone) are studied to determine the proportion of different fractions in the coarser component and to determine the arsenic content in each of the fractions. Mineralo-chemical data of these two boreholes are presented in Table 1. In the arsenious zone, the nonmagnetic fraction in the aquifer varies between 69.0 and



Figure 4. Colonized framboidal pyrite from the aquifer sand indicating organic growth during diagenesis in a reducing environment.

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83.9%. In contrast, in the safe water zone this fraction is always higher, varying between 83.63 and 89.14%. Both strongly magnetic and feebly magnetic fractions are consistently higher in the arsenious zone. A group of magnetic minerals, designated Assemblage-A (Table 1), are found to contain no arsenic and therefore, are not responsible for contaminating groundwater. In both the zones Assemblage-A minerals constitute a substantial

	BH-1 (arso	enic in ground water > 0	0.05 mg/l)		BH-2 (arsenic in ground water < 0.05 mg/l)				
Borehole depth (m)	Magnetic fractions	Minerals	Abundance (%)	Arsenic (mg/kg)	Borehole depth (m)	Magnetic fraction	Minerals	Abundance (%)	Arsenic (mg/kg)
00.32		Clay zone		3	00.32		Clay zone		33
07.00		Silty sand zone		6	06.31		Peat band		9–40
	HM		0.5	112	20.32		Clay zone		11
		Biotite	5.4		27.32		Silty sand zone		6
		Illite	1.7			HM		0.25	40
		Chlorite	1.9				Biotite	0.7	
10.00	IDS	Siderite concretions	0.4				Illite	0.6	
		Fe-coated grains	4.1				Chlorite	0.22	
		Subtotal	13.5	6.61	28.00	IDS	Siderite concretions	4.01	
		Assemblage-A	10.5				Fe-coated grains	1.14	
	NM		75.5	< 1			Subtotal	6.67	12
	HM		0.2				Assemblage-A	4.84	
		Biotite	5.7			NM		88.24	
		Illite	1.5			HM		0.18	29
		Chlorite	3.6				Biotite	1.81	
22.00	IDS	Siderite concretions	0.1				Illite	3.28	
		Fe-coated grains	2.5				Chlorite	0.53	
		Subtotal	13.4	5.5	35.00	IDS	Siderite concretions	1.06	
		Assemblage-A	12.4				Fe-coated grains	1.49	
	NM		74.0	< 1			Subtotal	8.17	17
	HM	<b>D</b>	0.3	14.6			Assemblage-A	2.51	
		Biotite	6.1			NM		89.14	1
		Illite	3.7			HM	D	0.19	32
27.00	ma	Chlorite	4.3				Biotite	0.97	
27.00	IDS	Siderite concretions	0.1				Illite	3.25	
		Fe-coated grains	2.7	5.62	41.00	IDC	Chlorite	0.32	
		Subtotal	16.9	5.63	41.00	IDS	Siderite concretions	0.54	
	NIM	Assemblage-A	13.8	. 1			Fe-coated grains	1.4	12
	INIM		69.0	< 1				0.48	15
						NIM	Assemblage-A	4.35	× 1
	uм		0.5	20.5				00.90	< 1
	<b>FINI</b>	Piotito	0.5	20.3		пм	Diotito	0.19	
		Illite	2.8				Illite	3.20	
		Chlorite	17				Chlorite	0.35	
36.00	IDS	Siderite concretions	0.5		47.00	IDS	Siderite concretions	0.35	
50.00	105	Fe-coated grains	1.2		47.00	105	Fe-coated grains	1.69	
		Subtotal	7.0	10.26			Subtotal	6.85	12
		Assemblage-A	8.7	10.20			Assemblage-A	4 91	12
	NM	rissemonage ri	83.8	1.9		NM	1 lose line lage 11	88.04	< 1
	HM		0.1	41		HM		0.23	28
		Biotite	1.7				Biotite	1.17	
		Illite	1.0				Illite	3.81	
		Chlorite	1.2				Chlorite	0.44	
51.00	IDS	Siderite concretions	0.2		53.00	IDS	Siderite concretions	1.76	
		Fe-coated grains	1.7				Fe-coated grains	2.64	
		Subtotal	5.8	8			Subtotal	9.82	7.5
		Assemblage-A	10.2				Assemblage-A	4.87	
	NM	•	83.9	1		NM	, i i i i i i i i i i i i i i i i i i i	85.07	1
	HM		0.2			HM		0.22	28
		Biotite	3.0				Biotite	0.96	
		Illite	1.0				Illite	1.93	
		Chlorite	2.4				Chlorite	0.64	
60.00	IDS	Siderite concretions	0.6		60.00	IDS	Siderite concretions	1.61	
		Fe-coated grains	2.8				Fe-coated grains	3.22	
		Subtotal	9.8	7			Subtotal	8.36	11.5
		Assemblage A	10.2				Assemblage-A	7.78	
	NM		79.8	2		NM		83.63	< 1

Table 1. Comparative mineralo-chemical analysis of BH-1 and BH-2, Baruipur area, West Bengal

HM, Hand magnet fraction (magnetite, ilmenite, iron oxy-hydroxide, magnetite inclusion in quartz); IDS, Isodynamic separates; NM, Non-magnetic fraction (quartz, feldspar, carbonate, etc.); Assemblage-A, Muscovite, garnet, hornblende, tourmaline, rutile, calcrete, etc.

Sl no.	Sediment layer	Magnetic fraction	Mineral fraction	Abundance (%)	Arsenic content (mg/kg)
1	Clay layer			0–38	2-31
2	Peat layer			0-1	9-40
3	Silty sand layer			0.5-19	2-6
4	Sand layer			52-83	1–7
4a	·	Hand magnetic fraction	Iron oxide/hydroxide with residual magnetite and ilmenite	0.09-0.5*	14–112
4b			Illite	0.6-3.7*	10-40
4c			Iron oxy-hydroxide-coated grains	1.2-4.6*	30
4d		Feebly magnetic fraction	Chlorite	0.2-4.3*	5-31
4e			Biotite	0.7 - 6.1*	9
4f			Siderite concretions	0.05 - 4.01*	7–9
4g		Non-magnetic fraction		69-84*	$\leq 1$
4ĥ		Interstitial clay		0.6-3.8**	2.6 - 8

Table 2. Summarized data showing arsenic-rich phases in the sedimentary column

\*Out of 100% (- 60 + 230) fraction of sand.

\*\*Out of 100% sand.



**Figure 5.** Globular authigenic siderite concretion, grown within the aquifer sand during diagenesis.



Figure 6. Stacks of rhombohedral crystal faces of siderite concretions.

percentage, but the pattern of distribution along the depth of the sequence is erratic. The other magnetic minerals are included under HM and IDS fractions and these analyse high arsenic values (Table 1). In the arsenious zone, the concentration of these components is higher at shallow depths up to 30 m and shows a sudden decrease below that depth. In the safe zone, it shows an almost constant value. It is also observed that the HM fraction containing magnetite and ilmenite is always significantly less in the safe zone. Samples of HM from both the zones have been analysed for arsenic and they show comparable values, except that at the depth of about 10 m bgl, the HM fraction in the arsenious zone, shows a value of 112 mg/kg, compared to the average value of 20-40 mg/kg. In contrast, arsenic value in the IDS fraction from the arsenious zone is low up to a depth of ~ 28 m, after which it drastically increases and remains constant up to 60 m. In the safe water zone, IDS fraction has lower values in both the shallower and deeper parts of the aquifer. In the intermediate part it has higher values, comparable to that in the arsenious zone.

The arsenic concentration in different magnetic fractions of sandy layers and in the overlying clay layers are analysed and presented in Table 1. It is observed that clay layers are the richest in arsenic content. The sandy layer, however, contains comparatively lower arsenic concentrations. Different fractions in the sand layer depict that the strongly to feebly magnetic part contains higher arsenic and the non-magnetic part is almost free of any contamination. Magnetite, ilmenite and iron oxide/hydroxide with residual magnetite and ilmenite constitutes the strongly magnetic fraction, whereas biotite, illite, chlorite, siderite concretions, iron oxy-hydroxide coated grains and other minerals (designated as Assemblage-A in Table 1) constitute the feebly magnetic fraction. The said strongly to feebly magnetic clastic grains, except the Assemblage-A are found to store most of the arsenic in sandy aquifer. The analysed arsenic values are in the following range: iron oxide/hydroxide with residual magnetite and ilmenite (14.6-112 mg/kg), illite (10-41 mg/kg), chlorite (31 mg/kg), iron-coated quartz and other grains

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Figure 7. Scanning electron microscopic images showing growth of siderite concretions on the surfaces of clastic arsenic pollutants a, Iron oxy-hydroxide; b, Illite; c, Iron-coated sand grains, and d, Chlorite.



Figure 8. Back scatter image of siderite concretion showing spheroidal growth with numerous quartz (Qtz) and potash feldspar (K-Fs) nucleii.

(30 mg/kg), siderite concretions (7-9 mg/kg) and biotite (9 mg/kg). In addition, the interstitial clay also contains arsenic in the range of 2.6–8 mg/kg.

The abundance and arsenic content of these phases are summarized in Table 2. It is evident that the sandy layer is more abundant in the sedimentary column up to the depth of consideration (60 m). Peat and clay layers show higher concentration of arsenic, but the abundance of peat layer is very low (< 1%) or absent, at places. It will be discussed later that the peat and clay layers probably

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Figure 9. Colonized aggregate of siderite concretions on clastic substrates.

do not release arsenic to the groundwater. Within the sandy layer, only the magnetic phases show higher concentration of arsenic and are, therefore, considered to be the arsenic pollutants.

These arsenic-rich phases, except the siderite concretions, are of clastic nature. The siderite concretions are globular objects (Figure 5) with varying sizes and may grow up to about 100  $\mu$ m. SEM study reveals surfaces are ornamented by tiny rhombohedral crystals (Figure 6). These have grown on the iron-rich clastic phases like iron-coated sand grains, illite, biotite, chlorite and iron oxy-hydroxide (Figure 7) which could later fall apart as individual concretions (Figure 5). EPMA pictures show nucleii or capture of quartz and potash feldspar within concretions (Figure 8). The concretions always grow as a colony on the clastic substrates (Figure 9) and are commonly associated with colonized framboidal pyrites (Figure 10). All these features point towards authigenic origin of the concretions in a reducing environment.

The arsenic concentration in groundwater shows clusters of high values (arsenious zone) in close spatial association with distinct patches of safe groundwater zones. Such a pattern can be explained either by the difference in subsurface lithology or by the selective dissolution of arsenic from the sediments to the groundwater. The subsurface sediments in both arsenious and safe zones, however, show similar lithology. The only marked difference is that for the safe zone, the thickness of the overlying clay layer is always high and may reach up to 30 m. McArthur et al.9 interpreted that the arsenic pollution in Bangladesh is driven by microbial degradation of the buried peat. The present study confirms the higher content of arsenic in the peat bands and clay layers for the subsurface samples of West Bengal, but the groundwater associated with peat and thick clay layers, always shows very low arsenic value (< 0.03 mg/l). This denotes that the clay and peat layers probably do not release arsenic into the groundwater and contradicts the hypothesis of McArthur et al.<sup>9</sup>.

The incidence of high arsenic in groundwater in this part of Bengal basin is patchy. Similar pattern is also reported from Bangladesh<sup>9</sup>. Within these patches high arsenic and low arsenic tube wells occur side by side. Mobility of arsenic in groundwater is slow and only those aquifer materials occurring in close vicinity of the affected wells are responsible for the contamination. Detailed mineralo-chemical analysis of the aquifer materials reveals that the iron-rich clastic phases and the authigenic siderite concretions are the carriers of arsenic. These are therefore identified as the arsenic pollutants for the study area. From the experimental study of earlier workers<sup>11–13</sup> and because of close affinity of arsenic with iron,<sup>6,7,14</sup> these pollutants are considered to have arsenic adsorbed onto their surfaces.

The absence of any primary arsenic phases and mineralomorphological evidences that arsenic is present in an adsorbed state over clastic grains, lead to the conclusion that arsenic was introduced into the aquifer in soluble state, possibly when the sedimentation was going on. The subsurface sediments, in the affected areas, represent an alluvial deposit of Ganges delta, which is a product of the river system of Ganga-Brahmaputra-Meghna. Analysis of the clastic sediments (sand, silt and clay) of Hooghly river deposited during the flood of September-October 2000, shows arsenic values in the range between 4 and 19 mg/kg. The separated grains of chlorite + biotite and illite + chlorite from the flood sediments yield arsenic values of 40 and 31 mg/kg, respectively. It is therefore, apparent that this arsenic is contributed by the bed rocks, having high arsenic values, encountered by the river system along their courses, right from the Himalaya to the lower part of the delta.

The growth of authigenic siderite concretions is considered to be biogenic and controlled by the activity of microbes<sup>15</sup> present in the subsurface sediments (Figure 11). It is therefore likely that microbes play an important role for entrapment of arsenic on the pollutant grains.

Carrillo and Drever<sup>13</sup> have suggested that at pH = 7-9, iron oxy-hydroxide adsorbs maximum amount of arsenic, but desorbs at higher pH. Under reducing condition, iron oxy-hydroxide would dissolve and contribute its adsorbed arsenic to groundwater<sup>6,7,14</sup>. Again at pH < 7 the siderite concretions would dissolve, as observed in BH-1 samples (Figure 12), with consequent release of arsenic



Figure 10. Colonized framboidal pyrite in association with concretionary growth of siderite.



Figure 11. Presence of tubular, worm-shaped microbes in association with siderite concretions.



Figure 12. SEM images showing effect of carbonate dissolution on siderite concretions.

to the groundwater. It is, therefore, suggested that pH of the natural environment would promote growth of these concretions, which together with iron-rich clastic phases like iron-coated minerals, illite, chlorite and biotite would capture the arsenic, thus becoming potential pollutants for contamination of the groundwater. With subtle changes in conditions, these arsenic pollutants would either release the adsorbed arsenic or themselves dissolve to increase the arsenic level of groundwater.

The local release of arsenic into the groundwater from the sediments with overall high arsenic values, is probably related to the local changes in Eh-pH condition. From the studies of sediments from Bangladesh, Nickson et al.<sup>6,14</sup> and McArthur et al.<sup>9</sup> have suggested that release of arsenic into groundwater is related to the degradation of organic matter. From the present study in parts of West Bengal, and ongoing study in other parts, it is proposed that the subsurface sediments, by and large, are similar in nature throughout this Gangetic delta and are richer in arsenic content. Compounded with the minor variation in local lithology and subsurface mineralogy, local development of anoxigenic acidic environment, due to degradation of organic matter present in the aquifer material by the microbes, might trigger the process of release of arsenic into the groundwater at favourable sites and result in an erratic disposition of arsenic pollution of groundwater. Such a disposition pattern demands a systematic study of groundwater to define safe zones for potable water. The present study conducted in this line indicates that the shallow aquifer of the study area, underlying a thick clay layer of about 30 m or more, appears to be safe.

The arsenic pollution of groundwater in this part of Bengal basin, is a geological problem. The shallow subsurface sediments are rich in arsenic and the shallow groundwater shows arsenic pollution at several small patches. There are safe zones of groundwater in the shallow aquifer. Such safe zones always have a thick clay cap, which should be used as deciding criterion for locating future shallow tube wells in these areas. There are reports of new incidence of high arsenic in groundwater from adjacent areas of this basin. This is not because the arsenic contamination is spreading rapidly, but because of emergence of new data, increased awareness and more wells being tested. Arsenic was present in the sediments of geological past and it continues to be present. The arsenic pollutants are identified to be the iron-rich clastic grains and the authigenic iron-rich carbonate (siderite). Release of arsenic from these pollutants into groundwater is incidental and possibly related to microbial degradation of organic matter. Since the microbes activate more at the air-water interface, the sediments having higher porosity in the top of the sedimentary column, will be the ideal sites for their proliferation. Such activities will eventually release arsenic faster than the sedimentary column starting with an impervious layer. This is the reason why the groundwater below a thick clay cap is safe. Excessive withdrawal of groundwater results in gradual lowering down of the water table, which exposes more sediment surfaces for microbial reduction. This, in effect, results in release of more arsenic into the groundwater and accentuates the problem of arsenic pollution.

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