

**Arsenic in groundwater from mineralised Proterozoic basement rocks of
Burkina Faso**

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Applied Geochemistry, **22**, 1074-1092, 2007

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Abstract

This study describes the hydrogeochemistry and distributions of As in groundwater from a newly investigated area of Burkina Faso. Groundwaters have been sampled from hand-pumped boreholes and dug wells close to the town of Ouahigouya in northern Burkina Faso. Although most analysed groundwaters have As concentrations of less than $10 \mu\text{g L}^{-1}$, they have a large range from <0.5 to $1630 \mu\text{g L}^{-1}$. The highest concentrations are found in borehole waters; all dug wells analysed in this study have As concentrations of $<10 \mu\text{g L}^{-1}$. Skin disorders (melanosis, keratosis and more rare skin tumour) have been identified among the populations in three villages in northern Burkina Faso, two within the study area. Although detailed epidemiological studies have not been carried out, similarities with documented symptoms in other parts of the world suggest that these are likely to be linked to high concentrations of As in drinking water. The high-As groundwaters observed derive from zones of gold mineralisation in Birimian (Lower Proterozoic) volcano-sedimentary rocks, the gold occurring in vein structures along with quartz and altered sulphide minerals (pyrite, chalcopyrite, arsenopyrite). However, the spatial variability in As concentrations in the mineralised zones is large and the degree of testing both laterally and with depth so far limited. Hence, concentrations are difficult to predict on a local scale. From available data, the groundwater appears to be mainly oxic and the dissolved As occurs almost entirely as As(V) although concentrations are highest in groundwaters with dissolved-oxygen concentrations $<2 \text{ mg L}^{-1}$. The source is likely to be the oxidised sulphide minerals and secondary iron oxides in the mineralised zones. Positive correlations are observed between dissolved As and both Mo and W which are also believed to be derived from ore minerals and oxides in the mineralised zones. The discovery of high As concentrations in some groundwaters from the Birimian rocks of northern Burkina Faso reiterates the need for reconnaissance surveys in mineralised areas of crystalline basement.

Keywords: arsenic, gold, tungsten, groundwater, health, Burkina Faso, Africa

Introduction

Ore zones, particularly those bearing sulphide minerals, are often enriched in As and other potentially toxic elements. Remobilisation of the As has in several cases led to environmental problems. Some of these occurrences have proved directly detrimental to human health, especially through exposure to As from groundwater used for drinking (Chakraborti et al., 1999; Williams et al., 1996). Although there have been many studies of As in groundwater used for drinking in recent years, most of this attention has been focused on young sedimentary aquifers in alluvial plains and deltas. Comparatively few studies have been carried out on groundwater from areas of mineralised basement. This is especially the case in Africa. Much of Africa is composed of crystalline basement rocks, and several areas have been subject to metalliferous mineralisation. Some are also mined. Furthermore, groundwater constitutes a major source of drinking-water supply in many areas of crystalline basement in Africa, especially in arid areas. Hence, groundwater quality in these aquifers is of significance to human health.

Some environmental studies have been carried out in metal mining areas in Zimbabwe (e.g. Jonnalagadda and Nenzou, 1996; Williams, 2001) and Tanzania (Bowell et al., 1995) although these were not specifically concerned with drinking-water sources. Some local studies have also been carried out in areas of gold mineralisation and mining in Ghana (Amasa, 1975; Bowell, 1994; Bowell et al., 1994; Serfor-Armah et al., 2006; Smedley, 1996; Smedley et al., 1996). In Ghana, the gold occurs in quartz reefs along with primary sulphide minerals including arsenopyrite. Investigations have revealed high concentrations of As in some soils, surface waters and groundwaters, although these are highly localised and spatially variable. Bowell (1994) reported high As concentrations ($189\text{--}1025\text{ mg kg}^{-1}$) in soils above mineralised bedrock from the area around Ashanti mine in central Ghana. Amasa (1975) found concentrations up to 147 mg kg^{-1} in soils close to the roasting chimney at the processing plant. These values are much higher than the typical range of concentrations in soils of around $5\text{--}10\text{ mg kg}^{-1}$ quoted by Smedley and Kinniburgh (2002) and a median in soils of eastern England of 12 mg kg^{-1} (4609 samples, Rawlins et al., 2003). Smedley et al. (1996) found concentrations of As up to $175\text{ }\mu\text{g L}^{-1}$ in surface waters used for drinking in Ashanti Region though groundwaters from rural water-supply boreholes in the same area had a comparatively low maximum of $64\text{ }\mu\text{g L}^{-1}$. Smedley (1996) found concentrations of As up to $141\text{ }\mu\text{g L}^{-1}$ in groundwater affected by sulphide mineralisation from the Upper East Region of northern Ghana, again associated with local gold-sulphide mineralisation. However, the

borehole with this high concentration was not used as a drinking-water source. In the town of Prestea in Western Region of Ghana, Serfor-Armah et al. (2006) sampled streamwaters downstream or downslope of active gold processing sites and sediments close to mine shafts. They reported As concentrations in streamwaters in the range 900–8300 $\mu\text{g L}^{-1}$ and in sediments in the range 942–10,200 mg kg^{-1} (mean values). Groundwaters were not analysed in the study. None of these studies identified health problems that could be linked directly to As in drinking water, although high concentrations of As were recorded by Amasa (1975) in hair samples from Ashanti mineworkers and Obuasi townspeople. Adverse health effects have also been linked to As in food crops grown in mining-contaminated areas of Ghana (Obiri et al., 2006).

The gold-hosting rocks of Ghana are Birimian (Lower Proterozoic) meta-sedimentary and meta-igneous rocks that form part of the West African craton. Similar Birimian lithologies extend with a patchy distribution into parts of Burkina Faso, as well as Côte d'Ivoire, Mali, Guinea and Niger (Fig. 1). Mineralised zones within the Birimian sequence are relatively common though mining development is varied.

Few studies of groundwater quality in Burkina Faso have been published to date. In 1979, IWACO carried out an investigation of groundwater from three boreholes in a village close to Mogtédo in central Burkina Faso, some 80 km east of Ouagadougou, following reports of health problems there. Symptoms included skin lesions and fatigue of unknown cause (de Jong and Kikieta, 1981). The IWACO study found groundwater from the three boreholes having As concentrations in the range 200–1600 $\mu\text{g L}^{-1}$. No other analysed constituents had concentrations above WHO guideline values. The boreholes were closed and the population was moved from the village. The high As concentrations were concluded to be linked to sulphide (pyrite, chalcopyrite) mineralisation of the Birimian volcano-sedimentary aquifer and were thought likely to be of localised occurrence. The discovery predated the onset of artisanal gold mining in the region. The IWACO report was not widely accessible, though the study findings were mentioned indirectly by Appelo and Postma (1993).

This study describes the hydrogeochemistry of groundwater in the Ouahigouya area of northern Burkina Faso (Figs. 1, 2) where some high-As groundwaters have recently been found (COWI, 2004). Health surveys in the region have identified skin lesions in patients from three villages. Two villages are within the current study area, while a third is located in north-central Burkina Faso, 90 km north of Ouagadougou. The skin lesions are characterised by melanosis and keratosis; one patient presented with an ulceronecrotic tumour (COWI,

2005). While detailed studies have not been carried out to identify whether these symptoms are related to As in the drinking water, they show marked similarities with documented As-related symptoms from other countries (e.g. NRC, 1999).

Regional setting

The study area lies close to the town of Ouahigouya (population 70,000) in the provinces of Yatenga and Zondoma (Région Nord) of northern Burkina Faso (Fig. 2). The land surface is characterised by a broad peneplain with an elevation of around 250–300 m and an overall gentle southerly slope. As the area lies on the southern edge of the Sahel, the climate is arid with an annual rainfall generally less than 600 mm (Gamsonré, 2003). A distinct rainy season extends from May to September during which more than 80% of the rain falls. Vegetation consists of forested steppe and there are no permanent rivers in the area.

Land use is mainly rural; agriculture and cattle rearing are dominant components of the local economy. Cotton represents around 73% of export revenue (Collectif, 1998). Burkina Faso is rich in mineral resources and gold mining has expanded significantly since the 1980s following a drought that caused severe economic difficulties. Today, gold is the third most important export of the country, although almost all production is artisanal in nature (Gamsonré, 2003; Gueye, 2001).

Regional geology and hydrogeology

The geology of the study area consists mainly of Birimian (Lower Proterozoic, 2300–2150 Ma) volcano-sedimentary and plutonic rocks and later Eburnian (ca. 2150–2095 Ma) granite and alkali-granite intrusions. The Birimian formations consist of schist and graphitic schist with quartzite, andesite, metabasalt and tuff as well as intrusive tonalites (dated at 2194 ± 4 Ma), gabbros and quartz diorites (Gamsonré, 2003; Sattran and Wenmenga, 2002). Eburnian orogenic events resulted in regional deformation and metamorphism, generally to greenschist facies but to amphibolite facies close to the shear zones (Castaing et al., 2003). A major series of NNE-trending faults associated with the Houndé–Ouahigouya sinistral shear zone cross-cut the area (Fig. 2) (Gamsonré, 2003). The Birimian volcano-sedimentary rocks have been interpreted as an andesitic-basaltic island-arc system, intruded by extensive tonalites of calc-alkaline affinity. These are intruded by later granitoids and alkali granites.

Structural stresses during the Birimian and Eburnian periods also resulted in brittle fracturing and the emplacement of quartz veins. Many are associated with gold and massive sulphide

mineralisation and these occur almost exclusively within the Birimian volcano-sedimentary sequence. The associated sulphide minerals include pyrite, arsenian pyrite and chalcopyrite (Gamsonré, 2003) which are invariably highly altered. The host schists are themselves typically strongly kaolinised in the mineralised zones.

One of the best-developed zones of auriferous mineralisation in the study area occurs around Mogombouli–Nongfaéré–Margo (Fig. 2). Artisanal miners currently excavate this and other mineral veins. Hand-dug vertical or near-vertical mine shafts typically extend to depths of 30–60 m below surface. The gold extraction involves manual ore crushing, sluicing and panning. There is no evidence for the use of chemicals such as mercury compounds in the extraction procedure in this area, although chemicals are used elsewhere in Burkina Faso (Gueye, 2001).

The basement rocks are covered by a layer of weathered overburden of variable thickness. Large areas of the Birimian schist are capped by altered laterite which forms expansive upland plains. The lateritic cover typically consists of a saprolitic lower part, some 30–50 m thick with a highly altered mineral assemblage consisting largely of quartz with smectite, vermiculite and kaolinite as well as goethite and gibbsite. This is overlain by an altered clay layer, usually several metres thick, containing dominantly kaolinite and quartz, often with some iron-oxide staining. The surface layer above (cuiresse), around 1–5 m thick, consists of a highly altered assemblage of residual Fe-Al minerals (goethite, gibbsite, haematite), in places with a nodular texture (Gamsonré, 2003).

In the crystalline basement rocks, primary permeability is low and groundwater flow occurs along fractures. Some intergranular flow is possible in the weathered overburden but this is often clayey and so flow is limited. Groundwater levels are typically 10–20 m below ground surface.

Under the arid conditions in northern Burkina Faso, water resources are limited and communities are highly dependent on groundwater for water supply. Traditional sources of rural domestic supply are dug wells, usually less than 25 m deep, which intercept groundwater from the weathered overburden. As the overburden is usually clayey, groundwater yields from these are typically small. Many traditional dug wells are still in regular use for drinking-water supply and other domestic purposes. Some concrete-lined wells have also been installed in several of the villages.

Within the last two decades, new borehole-drilling programmes have been undertaken by various agencies and many of the villages now have boreholes with hand pumps (India Mark

II, Vergnet or similar) which abstract groundwater for domestic purposes. These are typically 50–120 m deep and most of the boreholes intercept groundwater from fractures in the basement. Only a small percentage of the boreholes abstract water from the overburden. Yields are typically around 1–4 m³/hour.

Groundwater sampling and analysis

Groundwater sampling in the Ouahigouya area was carried out during January–February 2005. Samples were collected from 45 water sources in total, 36 being from boreholes and 9 from dug wells. Of the well samples, 8 were from traditional wells and 1 was from a modern concrete-lined well. Sample sites were not chosen randomly: most sites had been sampled in a previous groundwater survey carried out under the PEEN (Programme Eau et Environnement – Région Nord) water-supply project (COWI, 2004). Samples were collected with a view to obtaining data from sources with a range of As concentrations.

On-site measurements included pH, Eh (redox potential), dissolved oxygen, specific electrical conductance (SEC, 25°C), water temperature and alkalinity. Where possible, the first three of these parameters were measured in an in-line flow cell to prevent aeration of the groundwater during measurement. Parameters were monitored until stable readings were obtained (typically 10–15 minutes). Eh measurements were corrected to the SHE using the calomel reference potentials. Site locations were determined by GPS (12-channel Garmin 12, UTM system), which is accurate to around 5 m.

Groundwater samples were collected in polyethylene bottles for subsequent laboratory chemical analysis. Three separate aliquots were filtered through 0.2 µm filters. One was acidified using 17% Aristar HNO₃ (1% v/v) for major cations, trace metals and SO₄, a second was acidified using concentrated Aristar HCl (1% v/v) for analysis of As species and total As concentration (McCleskey et al., 2004) and the third was left unacidified for analysis of anions. Additional samples were collected in chromic-acid-washed glass bottles after filtering with 0.45 µm silver-impregnated filters for analysis of dissolved organic carbon (DOC). Samples were stored where possible in refrigerators before analysis. All analyses were completed within 4 weeks of sample collection.

Major cations, SO₄, Si and Fe were measured by ICP-AES. A range of trace elements including As were measured by ICP-MS and anions (Cl, NO₃-N, F and Br) were measured by ion chromatography. Total As, along with inorganic As species (As(III) and As(V)), were also measured by hydride-generation AFS. Arsenic results are also available from the ICP-AES

analysis determined by direct aspiration, although these have a high detection limit of $50 \mu\text{g L}^{-1}$. Where concentrations were detectable by all three methods, average total concentrations were calculated and reported. Averages of the AFS and ICP-MS methods were calculated for lower-As samples. Sample batches had regularly interspersed standards and blanks. A field blank was also taken to check the purity of the acid. For As this had a concentration of $<0.5 \mu\text{g L}^{-1}$ and for most other trace elements, concentrations were below detection limits. Blank concentrations of Al ($19 \mu\text{g L}^{-1}$) and Cu ($3.1 \mu\text{g L}^{-1}$) were comparatively high; Pb ($0.21 \mu\text{g L}^{-1}$) and Zn ($8 \mu\text{g L}^{-1}$) were also detectable but at the low end of the sample ranges. However, the concentration of Sn ($0.72 \mu\text{g L}^{-1}$) was comparable to that in the samples. Hence, the detection limit for Sn has been given as $0.8 \mu\text{g L}^{-1}$ to reflect this high blank concentration.

Analytical charge imbalances for the groundwater samples from boreholes were in all cases less than 5%. Samples from dug wells usually had much lower concentrations of total dissolved solids and so absolute errors on individual ions mean potentially higher charge imbalances. The dug wells had imbalances mostly less than 5% but in the worst case was 11%.

In addition to the water samples, five samples of altered rock material were collected for analysis of As by XRF. These included four samples of clay-rich material extracted from artisanal mine shafts and one sample from a village mine-tailings pile. All chemical analyses described above were carried out at the BGS laboratories in the UK.

Groundwater chemistry

Major constituents

Results of chemical analyses reveal distinct differences between the groundwater from dug wells and boreholes. Summary statistical data for the groundwaters are presented in Table 1 and data for representative samples are given in Table 2. The sampled dug wells are shallow (25 m or less) and groundwater within them is likely to have been recharged recently and to have had little interaction with the weathered overburden from which they draw water. The groundwaters are typically acidic (pH 5.2–7.0, median 5.69) with low concentrations of dissolved solids (TDS 15–112 mg L^{-1} ; SEC 40–201 $\mu\text{S cm}^{-1}$), reflecting lack of sea salt in recharge and limited mineral dissolution. Ca-HCO₃ or Ca-Mg-Na-HCO₃ are the dominant ions but the well waters are all strongly undersaturated with respect to calcite, reflecting limited calcite occurrence in the shallow overburden. The groundwaters from dug wells are

invariably oxic with dissolved-oxygen concentrations of 1.4–4.5 mg L⁻¹; Eh values are in the range 142–440 mV.

Concentrations of dissolved organic carbon in the waters from dug wells are typically around 1 mg L⁻¹ but reach 7 mg L⁻¹ in one sample. This probably reflects input of pollutants from the surface. However, concentrations of nitrate (NO₃-N) are usually small, with a range of <0.05–5.5 mg L⁻¹.

The sampled boreholes are of the order of 50–125 m deep and so the groundwater abstracted from them is mostly from the fractured bedrock. Most sites were located on Birimian schist although some were on granitic rocks. Groundwater from the sampled boreholes has mostly near-neutral pH values (5.77–7.78, median 7.14) with higher concentrations of total dissolved solids (TDS in the range 34–1270 mg L⁻¹, median 281 mg L⁻¹; SEC in the range 54–1765 μS cm⁻¹, median 369 μS cm⁻¹) than occur in the wells. The chemistry suggests that these waters have undergone greater reaction with host aquifer minerals than the shallow dug-well waters and is consistent with their deeper circulation in the basement aquifer. The basement itself has also suffered less intense leaching than the near-surface overburden.

The groundwaters from boreholes are of Ca-HCO₃ or Ca-Mg-Na-HCO₃ type. Most samples are undersaturated with respect to calcite, but saturation is approached or attained in the samples with highest Ca concentrations.

Two comparatively saline samples with TDS concentrations around 1200 mg L⁻¹ are of Ca-Mg-SO₄ type, though these are exceptional. The compositions of most samples reflect the effects of silicate weathering but the high SO₄ concentrations in the two more saline samples (541 mg L⁻¹ and 657 mg L⁻¹) may have been derived from oxidation of sulphide minerals or possibly evaporites. The concentrations of SO₄ in most of the groundwaters are less than 30 mg L⁻¹.

Chloride concentrations are also very low, the maximum being 14 mg L⁻¹ with most concentrations being less than 6 mg L⁻¹. These low values reflect the inputs of low-Cl rainfall of continental origin and lack of Cl in the bedrocks.

The groundwaters from boreholes are also mostly oxic, with dissolved oxygen concentrations in the range <0.1–5.8 mg L⁻¹ (median 0.75 mg L⁻¹). Eh values are mostly around 300 mV or more (i.e. oxidising) but have a range of 97–447 mV (Table 1). As a result, nitrate is stable and present in many of the groundwaters (<0.05–21.7 mg L⁻¹, median 1.05 mg L⁻¹). Of the

analysed samples, 2 (5.5% of the borehole waters) exceeded the WHO (2004) guideline value for NO₃-N in drinking water.

Only two samples in the analysed batch have undetected dissolved oxygen (<0.1 mg L⁻¹) and a small number of samples had dissolved-oxygen concentrations close to the detection limit. This suggests that mildly reducing groundwater conditions occur in some areas, though they are not apparently widespread. Mildly reducing conditions are also reflected by a few samples having higher concentrations of Fe and Mn (up to 0.69 mg L⁻¹ and 99 µg L⁻¹ respectively; Table 1). However, concentrations of Fe and Mn in most samples from the boreholes are low.

One water sample (OG41; Table 2) with dissolved oxygen below the detection limit had a very high concentration of dissolved organic carbon (DOC, 37.6 mg L⁻¹). This sample was taken from a borehole which had been installed just a few months previously and the high concentration probably represents residual contamination as a result of sustained drilling difficulties experienced with the borehole. The contamination with DOC would explain the anoxic condition of the borehole water. Monitoring of the water quality and bacterial analysis has not been carried out to assess whether the source represents a health hazard to the users. The concentration of DOC in this sample is unusual and concentrations in most of the borehole waters are typically 1–3 mg L⁻¹.

Arsenic

The government of Burkina Faso has adopted a national limit for As in drinking water of 10 µg L⁻¹ (MAHRH/SG/DGRE, 2006), in line with the WHO (2004) provisional guideline value. In the 9 dug wells sampled, concentrations of As are in the range <0.5–6.1 µg L⁻¹ with a median of 1.45 µg L⁻¹ (Table 1). These are all less than 10 µg L⁻¹ and are consistent with observations from dug wells in several other high-As areas (Smedley, 2003; Smedley et al., 1996). The low concentrations are likely to be the result of the short residence times of groundwater within the shallow overburden, together with the probability that any remnant As not having leached from the surface horizons is strongly bound to secondary iron oxides under the ambient mildly acidic and oxic conditions.

In the groundwaters from boreholes, the concentrations of As are much more variable and samples in the analysed batch have a range of <0.5–1630 µg L⁻¹ with a median of 15 µg L⁻¹ (Table 1). The two highest concentrations (1630 µg L⁻¹ and 1620 µg L⁻¹) were from two boreholes spaced around 50 m apart, from a village where a significant proportion of the

population have visible skin lesions (COWI, 2005). The boreholes were each completed in 1997.

From the earlier PEEN project survey of around 200 groundwater samples from boreholes with hand pumps in the region (COWI, 2004), a range of concentrations from $<0.8 \mu\text{g L}^{-1}$ to $560 \mu\text{g L}^{-1}$ was observed. A statistical summary of the data from this earlier survey is given in Table 3. These summary statistics provide a better indication of the overall distribution of As concentrations in the groundwaters of the region as the sample population was larger and the samples were in most cases collected without prior knowledge of the groundwater As concentrations. Most of the samples in the 2004 dataset had concentrations of less than $10 \mu\text{g L}^{-1}$ with 32% being at or below detection limit. However, 13% were greater than $10 \mu\text{g L}^{-1}$ and 3.3% were greater than $50 \mu\text{g L}^{-1}$.

The groundwater sampling from the PEEN survey also revealed an As concentration of $1300 \mu\text{g L}^{-1}$ in a borehole from a second village where skin lesions (melanosis, keratosis) were identified among a proportion of the population (COWI, 2004). The borehole was completed and pump installed in 2003 but was closed in 2004 shortly after the discovery of the As problem. The villagers now use alternative low-As boreholes in the village and the affected patients have apparently recovered. No other villages visited during the PEEN project sampling campaign or for this study showed evidence of residents having visible skin lesions.

Spatial variations in groundwater As concentrations are shown in Fig. 2. Plotted data include the samples from both the present study and those from the PEEN survey that lie within the study area. The distribution indicates that high As concentrations in the sample set are almost entirely found in areas of Birimian volcano-sedimentary schist. There is also an apparent relationship between the location of high groundwater As concentrations and the locations of sites of known gold (and sulphide) mineralisation. A number of high-As boreholes are found in the Mogombouli–Nongfaéré–Margo–Pellé–Tanlili area (Fig. 2) where mineralisation and artisanal mining are well-developed. Nonetheless, there is a large spatial variability in this localised zone, with many low-As boreholes being located within a few hundreds of metres of high-As boreholes. Concentrations are low in many areas of volcano-sedimentary schist away from mineralised zones and in areas of granitic rocks (although there has been less detailed sampling in the granitic areas).

Variations with depth are shown in Fig. 3. Higher As concentrations are often found in groundwater from deeper boreholes, although the variation is large and the correlation is

weak. Fig. 3 illustrates clearly the much lower As concentrations found in groundwater from dug wells. The two boreholes with the highest groundwater As concentrations do not appear on Fig. 3 because the depths of the boreholes are not known.

A weak negative correlation is apparent between the concentrations of dissolved As and dissolved oxygen (DO). Highest As concentrations typically occur in groundwaters with a DO concentration of 2 mg L^{-1} or less (Fig. 4). However, the mobilisation of As does not appear to be controlled by reduction reactions as even in the high-As groundwaters, DO is usually present in small concentrations. The apparently polluted anoxic groundwater sample from borehole OG41 had a comparatively low As concentration of $14 \text{ } \mu\text{g L}^{-1}$. Likewise, there is no discernible relationship between dissolved As and dissolved Fe or Mn that might indicate mobilisation of As under reducing conditions; most of the groundwaters have low Fe and Mn concentrations. In addition, the As in the groundwaters is present almost entirely as As(V) (Fig. 5). It is therefore concluded that the weak negative correlation observed between As and dissolved oxygen is related to a general decrease in DO concentrations at deeper levels in the fractured basement aquifer where groundwater has potential for prolonged residence times and enhanced reaction with minerals and organic matter. Unfortunately, predicting the concentrations of DO in the groundwaters of the area is as difficult as predicting the As concentrations themselves and so the observed correlation provides little practical assistance for locating low-As groundwaters.

Groundwater with similar chemical characteristics to the high-As groundwaters observed has been found close to a gold-mining site in northern Ghana. Smedley (1996) reported groundwater from a borehole there (Nangodi Clinic) having a total As concentration of $141 \text{ } \mu\text{g L}^{-1}$, with As(III) of $4.4 \text{ } \mu\text{g L}^{-1}$ (i.e. dominated by As(V)), DO concentration of 1 mg L^{-1} and low concentrations of Fe ($<3 \text{ } \mu\text{g L}^{-1}$) and Mn ($4.5 \text{ } \mu\text{g L}^{-1}$). There too, oxidation of sulphide minerals was taken to be the primary source of the As. This suggests that the groundwater compositions observed in the study area of Burkina Faso are not isolated and that there may be other parts of the Birimian basement of West Africa similarly affected. At present the scale of the problem is unknown and requires further investigation.

Other trace elements

This study was restricted to the investigation of inorganic constituents in the groundwaters; no analysis of pathogenic organisms was carried out and so it is not possible to provide an assessment of the microbial content of the groundwaters. Likewise, no investigation of

parameters such as pesticides, solvents, $\text{NO}_2\text{-N}$ or CN was carried out as these were beyond the scope of the investigation. On the basis of available data for the inorganic constituents investigated, arsenic appears to be the most significant element of health concern in the groundwaters. Most other measured inorganic constituents of potential health concern are much lower with respect to international drinking-water standards and guidelines.

Of the trace constituents investigated, Mn exceeded the WHO (2004) guideline value of $400 \mu\text{g L}^{-1}$ in 2 samples (4.4%), both from dug wells. The highest concentration ($1450 \mu\text{g L}^{-1}$) was four times the guideline value. Molybdenum exceeded the respective guideline value of $70 \mu\text{g L}^{-1}$ in one sample, although the concentration of $76 \mu\text{g L}^{-1}$ was only just in excess. The highest concentrations were in groundwaters from boreholes.

Despite the fact that the aquifers of the area are crystalline basement rocks including granites, conditions often conducive to F mobilisation, the concentrations of F in the groundwaters are usually very low. The maximum observed in the wells was 0.22 mg L^{-1} and that in the boreholes was 0.85 mg L^{-1} (Table 1). Concentrations are in all cases well below the WHO guideline value for drinking water of 1.5 mg L^{-1} .

In the groundwaters from dug wells, concentrations of most trace elements are low (Table 1, 2), and trace elements that commonly accumulate in water through silicate-weathering reactions (notably Cs, F, Li, Mo, Si and Sr) are generally lower than are found in the groundwaters from boreholes. This reflects both limited interaction and the leached, Si-poor, nature of the overburden lithology. Some trace elements, such as rare-earth elements (e.g. La, Ce), Y, Co, Ni as well as Mn, have relatively high concentrations (Table 1, 2) as is typical under mildly acidic conditions.

Concentrations of U are $0.02 \mu\text{g L}^{-1}$ or less in groundwater from the dug wells and $<0.02\text{--}5.8 \mu\text{g L}^{-1}$ in groundwater from the boreholes. They show an overall increase with increasing pH and alkalinity (HCO_3) and are likely to be derived by desorption from iron oxides under the most alkaline conditions. U(VI) has long been known to form stable aqueous complexes with carbonate ligands such as UO_2CO_3^0 and $\text{UO}_2(\text{CO}_3)_2^{2-}$ (Langmuir, 1978). Concentrations in all the samples are less than the WHO (2004) provisional guideline value for U in drinking water of $15 \mu\text{g L}^{-1}$.

Antimony concentrations are usually very low in the groundwaters, the highest being $0.53 \mu\text{g L}^{-1}$ (Table 1). Antimony is often used as a pathfinder element in Au exploration and concentrations are often high in waters in Au-mineralised areas (Cidu et al., 1995). However,

variations are likely because of variable ore mineralogy and it is possible that the low concentrations in the Burkina Faso groundwaters are related to a mineral assemblage which is comparatively Sb-poor.

Concentrations of W are usually low (median $<0.02 \mu\text{g L}^{-1}$) but range up to $9.4 \mu\text{g L}^{-1}$ in some borehole waters. Tungsten is rarely detected in groundwaters and so the observed high concentrations are atypical. However, some studies have found W in groundwater in areas of metalliferous mineralisation (Grimes et al., 1995).

Concentrations of dissolved Au are in all cases less than the detection limit ($<0.05 \mu\text{g L}^{-1}$). This compares with the low concentrations of Au ($<2 \text{ng L}^{-1}$) found by Cidu et al. (1995) in surface waters and groundwaters from a gold-mining area of Sardinia and is expected given the low solubility of gold in water. Grimes et al. (1995) found concentrations of Au up to $4.7 \mu\text{g L}^{-1}$ in groundwater close to a Au-mineralised site in Nevada, USA, although the high concentrations were highly localised.

Discussion

Sources of arsenic and controls on distribution

It is often difficult to define the mineral sources of trace elements in water because of their presence in numerous minerals, the relatively small mass transfers necessary and the complexities related to mobilisation and transport in groundwater systems. Trace-element mobilisation is controlled by factors such as pH, redox conditions, mineral solubility, kinetics and surface reactions. These can lead to the development of correlations between elements that behave similarly but are from different sources and, conversely, the separation of elements derived from a common source. This may explain why few clear correlations are apparent between As and other solutes in the groundwaters of the study area.

One of the clearest links observed is between the distribution of high-As waters and zones of gold mineralisation within the Birimian volcano-sedimentary sequence. Lithological logs from several of the high-As boreholes reveal the presence of quartz veins within the borehole profile. Soil samples taken in the area for gold exploration also show regionally high As concentrations, often greater than 25mg kg^{-1} , with localised zones having in excess of 200mg kg^{-1} in the Margo–Nongfaéré mineralised area (Tecsult, 1999). Samples of altered clay-rich material taken from mine shafts in the goldfields and one sample from a village tailings deposit also have relatively high concentrations of As ($33\text{--}761 \text{mg kg}^{-1}$; Table 4).

Sulphide minerals, including in particular pyrite, arsenian pyrite and chalcopyrite, are present in the mineralised areas associated with gold in the quartz veins (Gamsonré, 2003). These are invariably partially oxidised. The reaction products of sulphide oxidation have not been well-studied in the region, but experience elsewhere suggests that these are likely to be dominated by Fe(III) oxides with possibly subordinate ferric arsenate and arsenic oxide minerals. Bowell (1994) listed limonite, amorphous Fe-Mn arsenates, pitticite, bukovskyite, kankite, scorodite, goethite, haematite and arsenolite among the secondary minerals found in the mineral assemblage of the Ashanti gold-mining area of Ghana. Scorodite ($\text{Fe(III)AsO}_4 \cdot 2\text{H}_2\text{O}$) is a relatively common oxidation product of primary As-sulphide minerals in ore zones (Welch et al., 2000). However, precipitation of scorodite is favoured under acidic conditions (<5) and the mineral is meta-stable at near-neutral pH, dissolving incongruently (Krause and Ettel, 1989) and transforming to Fe(III) oxide (Hering and Kneebone, 2002; Robins, 1987). Arsenolite (As_2O_3) is also relatively soluble (Linke and Seidell, 1958). Hence, these less common minerals are unlikely to be controlling the concentrations of As in the groundwaters; Fe(III) oxides are likely to be a more important control. Under the oxic and neutral to slightly acidic groundwater conditions, the mobility of As, especially As(V), is strongly restricted by adsorption to and co-precipitation with Fe(III) oxides (e.g. Hering and Kneebone, 2002; Wilkie and Hering, 1996). Aluminium oxides and clays may also be effective sorbents (Manning and Goldberg, 1996).

The association between high-As groundwater and auriferous mineral zones suggests that primary sulphide minerals and/or secondary metal oxides in the mineralised zones are the most likely sources of the As. The distribution of As in the unmineralised Birimian schists is likely to be much lower and these are not thought to be significant sources of the high As concentrations.

In general terms, a positive correlation between dissolved As and SO_4 might be expected if the two are released from a common primary sulphide source. However, no clear correlation between As and SO_4 exists in the groundwaters (Fig. 6). Sulphate concentrations reach up to 657 mg L^{-1} in the groundwaters but are mostly much lower and the two samples with the highest SO_4 concentrations have low As concentrations ($<5 \text{ } \mu\text{g L}^{-1}$). Hence, if sulphide minerals are the primary sources of the As, geochemical processes since dissolution must have decoupled the As- SO_4 association and carbonate and/or silicate dissolution reactions buffered the pH. Retardation of As by adsorption since dissolution is one possible process. The high affinity of As for iron (and Al) oxides is well known (de Vitre et al., 1991; Dixit and

Hering, 2003; Hiemstra and van Riemsdijk, 1999; Wilkie and Hering, 1996) and means that As would normally undergo much greater retardation by adsorption than SO_4 . If secondary oxides are the sources of the As in the groundwater, it is possible that the SO_4 released during the original sulphide oxidation may have been flushed from the aquifer long ago. However, it is also true that if the sulphide minerals present contain high concentrations of As which are typical of auriferous zones, only small amounts of As need to be dissolved to generate the concentrations observed in the groundwaters. Hence, a relationship with dissolved SO_4 may not be apparent. From the stoichiometry of minerals such as arsenian pyrite and arsenopyrite, it is evident that release of $\mu\text{g L}^{-1}$ quantities of As equates to $\mu\text{g L}^{-1}$ quantities of SO_4 . Sulphate is a major constituent in groundwaters and is normally present in mg L^{-1} proportions. Hence, such small additional contributions would be undetectable.

It is concluded that primary sulphide minerals and secondary iron(III) oxides (and possibly Al oxides) play a role in the cycling of As in the Birimian aquifer. The conditions are insufficiently reducing for iron oxides to be dissolved and for As co-dissolution to occur and the overwhelming dominance of As(V) in the groundwaters negates reduction of oxide-adsorbed As(V) to As(III) as a contributory factor in the mobilisation. As the groundwaters are mainly oxidic and of near-neutral pH, proximity to the As-bearing mineral sources must be a factor in the mobilisation since with increasing distance from the ore zone, the strong capacity of the Fe oxides to adsorb As(V) would be likely to limit the concentrations. Assuming that desorption of As(V) from iron-oxide surfaces is one important contributory process, it is easy to see how higher dissolved As(V) concentrations could be present in equilibrium with iron oxides having high sorbed-As(V) loads proximal to the sulphide mineral zones.

Arsenic appears to show some relationship with Mo and to a lesser extent W in the groundwater (Fig. 7). As noted above, concentrations of Mo range up to $76 \mu\text{g L}^{-1}$. Molybdenum is a constituent of the sulphide mineral molybdenite, MoS_2 , and is also an accessory element in several metal ores. Like As, it is also adsorbed readily to iron oxides (Goldberg et al., 1995; Stollenwerk and Kipp, 1990) and so these have an important impact on Mo mobility in water. In aerobic, neutral-pH conditions, it is stable in solution as the molybdate anion, MoO_4^{2-} (Kaback and Runnells, 1980). It is likely that the Mo in the groundwater is derived from the mineralised zones in a similar way to As.

The high concentrations of W observed in some of the groundwaters (up to $9.4 \mu\text{g L}^{-1}$) are also consistent with mobilisation of W from ore bodies. The principal W ore minerals are

wolframite ((Fe,Mn)WO₄) and scheelite (CaWO₄). The main form found in water is the hexavalent tungstate (WO₄²⁻). Occurrences of W in groundwater have not been reported widely, but concentrations in the range 1–260 µg L⁻¹ were found in groundwater from a Au-mineralised area of Humboldt County, Nevada (Grimes et al., 1995). The high concentrations correlated positively with As, as well as with Au and Sb. Concentrations up to 742 µg L⁻¹ have also been found in groundwater from the Carson Desert in Nevada (Seiler et al., 2005). The groundwaters of that area also have high As concentrations and the two elements were believed to be derived from geothermal fluids or by desorption from iron oxides in the sediments under high-pH conditions.

The associations between As and Mo and W in the groundwaters of study area further support the conclusion that As has been derived ultimately from As-bearing ore minerals in the auriferous zones. In the two samples from the mineralised area that had the highest As concentrations (around 1600 µg L⁻¹), concentrations of a number of other trace elements, especially Cs, Rb, Li, Ge and F were also high. These elements may also be preferentially concentrated in mineral veins in some areas as a result of past hydrothermal activity. There is not a general positive correlation between these elements and As in the groundwater samples however.

The observed spatial variability in groundwater As concentrations locally around the ore zones make it difficult to predict which boreholes are likely to have high concentrations. The spatial variability is probably a function of variable borehole depth and groundwater yield as well as heterogeneous distribution of water-bearing fractures and quartz veins. Variable borehole lithology is also a factor, as some boreholes in the Pellé–Margo area are located in granitic rocks (Fig. 2). The high spatial variability on this local scale means that it is essential that each borehole used for potable supply be tested for As.

Mining activity

Given the association between As in groundwater and mineralisation, the question arises whether mining activity (i.e. human intervention) has been responsible at least in part for the high groundwater As concentrations. Mining activity in the region is limited to small-scale artisanal operations, with vertical hand-dug shafts to depths typically of 30 m but in some cases up to 60 m deep. We saw no evidence during the field investigations for the use by the artisanal miners of chemicals such as mercury compounds to aid gold extraction. Indeed, none of the groundwater samples analysed contained detectable Hg (all had concentrations

$<0.1 \mu\text{g L}^{-1}$). The most significant effect that such mining activity could have on local geochemical conditions is increased aeration of the mineral zones by the development of the many mine shafts. However, this is likely to have had minimal effect on the aquifer conditions as the groundwaters are already predominantly oxidic. The hydrogeochemical evidence also suggests that As mobility is relatively low under the most oxidic conditions (Fig. 4). Most of the mines are situated several kilometres away from the village boreholes. The goldfield closest to any of the villages surveyed is at a distance of around 1.5 km from the sampled boreholes. The nearest goldfield to the village with the highest observed As concentrations (ca. $1600 \mu\text{g L}^{-1}$), is around 2 km distance. The closest goldfield to the village with the closed borehole that had an As concentration of $1300 \mu\text{g L}^{-1}$ is around 3 km from the village. Also, villages with boreholes having groundwater As concentrations of $379 \mu\text{g L}^{-1}$ and $153 \mu\text{g L}^{-1}$ are located some 10 km from the nearest mined area. A direct effect from the mining activity in these boreholes is therefore considered unlikely. Since mining in Burkina Faso is a recent phenomenon (mostly since the 1980s) timescales are also relatively short for an impact to be observed at distances of several kilometres from the mining activity. A similar conclusion must be reached for the Mogtédou area, east of Ouagadougou (Section 1). High As concentrations there were found in the late 1970s in groundwater from three boreholes averaging 40 m deep. Since the finding of high groundwater concentrations predated the onset of gold exploration in Burkina Faso, a natural cause of the high groundwater As concentrations is implicated.

The only direct evidence of mining contamination of drinking-water wells in the study area was from possible direct inputs of As-bearing waste to shallow traditional wells by the practice of tailings washing within metres of open wells. This was observed in a number of the villages. The tailings are sited close to some shallow dug wells as these supply sources of washing water for the ore. Many of the traditional dug wells are unprotected at the surface and washings containing both particulate and dissolved As may contaminate the well. The potential for contamination of modern dug wells is less as they have raised concrete rings at the surface and are usually used for domestic supply (drinking, cooking) rather than gold processing and so tailings are not located close to them. Inputs of tailings washings directly via the conduits of the hand-pumped boreholes is extremely unlikely as these are well-sealed with raised concrete aprons and in the case of the most recently-installed Danida-funded boreholes, have a surrounding retaining wall. Mobilisation of As from the tailings via the unsaturated zone to the water table is equally unlikely because of the strong binding capacity of Fe and Al oxides in the lateritic overburden and because of the long timescales involved in

As transport to the water table, given the likely retardation, relative to the duration of mining activity.

Other groundwater arsenic surveys

Since the instigation of this study, sampling of groundwaters for As in the Région Nord has been carried out by the government of Burkina Faso with funding from Danida (MAHRH/SG/DGRE, 2006). The survey of 1053 groundwater samples found 149 (14%) exceeding $10 \mu\text{g L}^{-1}$. This is close to the exceedance percentage found in the PEEN survey (COWI, 2004). The locations of boreholes with high As concentrations are also consistent with the earlier surveys and confirm that the worst-affected of the departments investigated are Ouahigouya, Namissiguima and Oula in Yatenga province.

A recent (2006) national survey of 296 water-supply boreholes carried out by UNICEF in collaboration with the Laboratoire National de Santé using field-test kits has found samples from only 7 boreholes (2.4%) with As concentrations in excess of $10 \mu\text{g L}^{-1}$. The samples were from a range of geological formations. While uncertainty exists over the accuracy of the field-test kit results, a linked health survey did not identify As-related skin disorders in populations from the investigated villages and supported the observations. The results encouragingly suggest that high groundwater As concentrations are not a widespread regional problem, although other as yet unidentified hotspots could exist, both in Burkina Faso and in neighbouring countries.

Arsenic mitigation

As water resources are scarce in many parts of northern Burkina Faso, groundwater is often the only water available and so villagers have little choice in their water supply. During the last two decades, relatively deep hand-pumped boreholes drilled into the fractured basement rocks have been the cornerstone of village water-supply programmes. Today, most of the villages have more than one hand-pumped borehole although dug wells abstracting water from the overburden still play a very important role in village water supply. The discovery of high As concentrations in some borehole waters is new and experience with arsenic mitigation in Burkina Faso is almost non-existent.

To date, three high-As boreholes in the Ouahigouya area have been closed and results from the recent investigations will most likely lead to the closure of several others. A number of the

high-As boreholes have been earmarked for replacement as part of a planned drilling campaign that is being orchestrated by the government and Danida.

Available data suggest that arsenic mitigation strategies need to be tailored to the local situation in each village. Boreholes completed in the overburden at shallower depths than those penetrated by the existing high-As boreholes could be considered as alternative supplies of drinking water. As the open shallow dug wells have generally low As concentrations, they also constitute a potential alternative source of drinking water for the villagers. However, problems may arise because of poor yields or drying out of wells in some areas in the dry season. Dug wells are also likely to have a much poorer bacterial quality than borehole waters. Hence, any promotion of dug wells as drinking-water sources will require improvements in sanitary conditions (e.g. concrete lining, surface enclosure, installation of hand pumps) around the wellheads. As for several years, the use of borehole water has been advocated and avoidance of dug-well water advised, the important role of health education and clear guidance is stressed.

Conclusions

Results of surveys of As in groundwater in the Ouahigouya area reveal a large range of concentrations. Most groundwaters investigated in this study have concentrations less than the WHO guideline value and national limit for As in drinking water of $10 \mu\text{g L}^{-1}$ although in borehole waters they reach extremes up to $1630 \mu\text{g L}^{-1}$. The high concentrations occur in zones of mineralised Birimian volcano-sedimentary rocks. Arsenic-bearing sulphide minerals and secondary iron oxides are considered the most likely sources.

National data from both groundwater and health surveys are still limited in Burkina Faso, although survey work is ongoing. The recent UNICEF/Laboratoire National de Santé national reconnaissance survey of 293 groundwater samples found that just 2.4% had As concentrations above $10 \mu\text{g L}^{-1}$. Although the distribution of the samples and the quality of the field-test kit data is uncertain, the survey suggests that high-As groundwater is not of widespread occurrence in Burkina Faso. Nonetheless, other As hot spots may occur. Birimian rocks cover an area of around $70,000 \text{ km}^2$ in Burkina Faso (Gueye, 2001) which constitutes more than 10% of the land area. Rich gold reserves are located in particular in the Belahouro, Bomboré, Bouda, Bouroum, Essakane, Goulagou, Inata, Kalsaka, Kerboule, Larafella, Nyafé, Poura, Taparko, Wona and Youga areas (Castaing et al., 2003). Birimian rocks also cover large areas of neighbouring Mali, Côte d'Ivoire, Ghana, Guinea and Niger. Parts of these

areas are also mineralised. Gold represents a significant export commodity for Ghana and was Mali's principal export in 2003. The distribution of As in groundwater in many of these areas is undocumented. Likewise, the trace-element chemistry of groundwater from other lithologies (e.g. granitoids) in West Africa has not been investigated in detail.

As further groundwater survey work in Burkina Faso is carried out by the government and aid agencies, the scale of groundwater arsenic problems nationally and in the Birimian aquifer in particular, will become increasingly apparent. This will provide the authorities with a better knowledge base with which to prioritise available resources.

As Burkina Faso is arid and groundwater is the only available water resource in the country, the options in affected areas for alternative low-As water supplies are limited. Siting of new boreholes may be possible in some affected villages but the uncertainties in spatial variation of As concentrations are large and the prospects of success uncertain. Doubtless, much is to be learned from new drilling programmes in the region. Dug wells offer some potential, either by improvement of existing wells or development of new ones. From limited available data, these appear to have usually low As concentrations ($<10 \mu\text{g L}^{-1}$), probably as a result of short groundwater residence times and the strong sorption of As to metal oxides under oxic, slightly acidic conditions. Dug wells are already widely used by many villagers in the Ouahigouya area and are the traditional sources of drinking water. However, their greater vulnerability to bacterial and other contamination and to drying out in the dry season in some areas make them potentially problematic. They could be of value as drinking-water sources, at least for parts of the year, provided their low As concentrations are assured, and they are of a sufficient depth and sanitary standard. Dug wells are being provided as low-As drinking-water sources in many high-As groundwater provinces across the world.

Acknowledgements

We thank Debbie Allen, Sally Bourliakas, Sarah Hannay, Dan Lapworth and Chris Milne (BGS, Wallingford) and Barbara Vickers (BGS Keyworth) for laboratory chemical analysis. We also thank laboratory staff of the Office National de L'Eau et de l'Assainissement (ONEA) in Ouagadougou for supplementary groundwater As analysis. We acknowledge Danida (particularly Jens Fugl) for provision of funding for the investigation and facilitation of project activities. Acknowledgements are also given to Thomas Riegel as well as to staff of the Direction Générale de l'Approvisionnement en Eau Potable (DGAEP), now the Direction de l'Approvisionnement en Eau Potable et de l'Assainissement (DAEPA), and the Direction

Régionale de l'Agriculture de l'Hydraulique et des Ressources Halieutiques du Nord (DRAHRH/N), Government of Burkina Faso, for assistance and provision of useful information. Additional funding for PLS was provided by the Natural Environment Research Council (NERC, UK). The paper benefited from reviews by the arsenic working group in Ouagadougou as well as David Kinniburgh, Russ Evans and an anonymous reviewer. This paper is published with the permission of the Executive Director, BGS (NERC).

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Figure Captions

Fig. 1. Simplified geological map of West Africa showing the location of Birimian volcano-sedimentary rocks and Eburnian granitoids.

Fig. 2 Geological map of the Ouahigouya area, Burkina Faso showing the concentrations of As in groundwater from sampled boreholes and dug wells (sample sites include the January–February 2005 survey and samples investigated by COWI from the 2004 survey).

Fig. 3. Variation of As concentrations with depth in boreholes and dug wells.

Fig. 4. Variation of As with dissolved oxygen (DO) in the boreholes and dug wells.

Fig. 5. Variation of As(V) with total As in groundwaters from the Ouahigouya area.

Fig. 6. Variation of As with SO₄ in the groundwaters from boreholes and dug wells.

Fig. 7. Variation of As with Mo and W in the groundwaters from boreholes and dug wells.

Table 1. Summary statistics for analysed groundwater samples from boreholes and dug wells (sample numbers: 36 boreholes and 9 dug wells).

Parameter	Units	Boreholes			Wells			WHO (2004) guideline value
		min	median	max	min	median	max	
Temp	°C	29.7	31.4	34.9	27.5	30.3	31.6	
pH		5.77	7.14	7.78	5.18	5.69	7.03	
DO	mg L ⁻¹	<0.1	0.75	5.8	1.4	3.3	4.5	
Eh	mV	97	302	447	142	325	440	
SEC	µS cm ⁻¹	54	369	1765	40	65	201	
Ca	mg L ⁻¹	2.96	25.1	171	1.79	3.56	11.7	
Mg	mg L ⁻¹	1.79	9.95	115	0.493	1.25	5.5	
Na	mg L ⁻¹	1.6	24.7	69.8	0.97	2.77	14.5	
K	mg L ⁻¹	<0.5	2.75	5.59	<0.5	1.07	3.97	
Cl	mg L ⁻¹	<0.5	0.79	13.8	0.65	1.44	4.62	
HCO ₃	mg L ⁻¹	25.5	191	346	6.6	10.7	47.5	
SO ₄	mg L ⁻¹	<0.2	6.76	657	<0.2	0.38	33.4	
NO ₃ -N	mg L ⁻¹	<0.05	1.05	21.7	<0.05	2.1	5.54	11
DOC	mg L ⁻¹	<0.1	1.97	37.6	0.68	1.52	7.11	
Si	mg L ⁻¹	8.52	22.7	44.9	6.92	8.5	12.6	
Ag	µg L ⁻¹	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	
Al	µg L ⁻¹	2.1	18	25	4.1	20	23	
As(III)	µg L ⁻¹	<1	<1	254	<1	<1	4.5	
As(V)	µg L ⁻¹	<1	17.1	1590	<1	<1	7.8	
As _T	µg L ⁻¹	<0.5	15.1	1630	<0.5	1.45	6.14	10(P)
Au	µg L ⁻¹	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	
B	µg L ⁻¹	<20	<20	<20	<20	<20	<20	500(P)
Ba	µg L ⁻¹	0.165	6.29	227	21.8	36	154	700
Be	µg L ⁻¹	<0.05	<0.05	0.578	<0.05	<0.05	0.124	
Bi	µg L ⁻¹	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	
Br	µg L ⁻¹	<5	11.4	82.6	8.3	14.5	45.5	
Cd	µg L ⁻¹	<0.05	<0.05	0.12	<0.05	<0.05	0.072	3
Ce	µg L ⁻¹	<0.01	0.01	0.072	0.01	0.021	0.165	
Co	µg L ⁻¹	<0.02	0.001	0.29	0.072	0.86	3.68	
Cr	µg L ⁻¹	<0.5	<0.5	4.65	<0.5	<0.5	<0.5	50(P)
Cs	µg L ⁻¹	<0.01	0.057	19.8	0.031	0.041	1.58	
Cu	µg L ⁻¹	0.31	1.14	5.78	0.41	0.93	2.17	2000
F	mg L ⁻¹	0.055	0.13	0.85	<0.02	0.042	0.22	1.5
Fe	mg L ⁻¹	<0.005	0.008	0.69	0.01	0.035	0.11	
Ge	µg L ⁻¹	0.062	0.20	1.21	<0.05	<0.05	0.12	
Hg	µg L ⁻¹	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1
La	µg L ⁻¹	<0.01	0.01	0.041	<0.01	0.01	0.12	
Li	µg L ⁻¹	1.2	13.9	231	0.21	1.45	10.9	
Mn	µg L ⁻¹	0.196	1.12	98.9	1.47	18	1450	400
Mo	µg L ⁻¹	<0.1	0.78	76.3	<0.1	<0.1	0.41	70
Ni	µg L ⁻¹	<0.2	<0.2	1.96	<0.2	0.93	7.44	20(P)
P	µg L ⁻¹	<20	26	282	<20	<20	35	
Pb	µg L ⁻¹	<0.1	0.1	2.3	<0.1	0.1	0.31	10
Rb	µg L ⁻¹	0.31	1.45	13.9	1.23	2.27	5.73	
Sb	µg L ⁻¹	<0.05	0.006	0.53	<0.05	<0.05	<0.05	20
Se	µg L ⁻¹	<0.5	<0.5	3.2	<0.5	<0.5	0.83	10
Sn	µg L ⁻¹	<0.8	<0.8	<0.8	<0.8	<0.8	<0.8	
Sr	µg L ⁻¹	35.4	303	980	18.6	32.8	111	
Tl	µg L ⁻¹	<0.01	<0.01	0.01	<0.01	<0.01	0.021	
U	µg L ⁻¹	<0.02	0.18	5.8	<0.02	<0.02	0.021	15(P)
V	µg L ⁻¹	<0.2	7.8	44	<0.2	0.21	0.72	
W	µg L ⁻¹	<0.02	<0.02	9.4	<0.02	<0.02	0.083	
Y	µg L ⁻¹	<0.01	0.021	0.124	0.01	0.031	0.176	
Zn	µg L ⁻¹	3.1	11	4610	5.4	10	21	
Zr	µg L ⁻¹	<0.02	0.021	0.73	<0.02	<0.02	0.021	

Temp: temperature; Eh: redox potential, SEC: specific electrical conductance, DOC: dissolved organic carbon, As_T: As total. (P) in the WHO guideline values: provisional.

Table 2. Chemical analyses of representative groundwater samples (boreholes and dug wells).

Sample	Units	OG1	OG4	OG6	OG14	OG21	OG32	OG36	OG41	OG42	OG11	OG43
Easting		0567938	0590692	0592266	0587169	0581335	0592097	0590157	0564466	0591046	0586599	0591090
Northing		1511168	1486853	1486731	1485371	1512671	1494784	1498583	1496863	1482084	1486085	1482130
Well depth	m	67	60.7		105	122		94	51		11.2	12.0
Well type		bh	bh	bh	bh	bh	bh	bh	bh	bh	well	well
O ³ burden thickness	m	56	43		48	18.3		39	37			
Yield	m ³ hr ⁻¹	2.0	3.5		2.2	0.9		2.1	2.7			
Completed	yr	2001	2003	1983		2002		2003	2004	1997		
Temp	°C	30.8	34.9	31.4	31.9	30.6	31.4	32.2	31	31.8	30.1	30.7
pH		7.23	7.36	5.77	7.72	6.44	6.91	7.2	7.4	7.33	5.18	5.42
DO	mg L ⁻¹	5.1	0.4	2.9	0.1	2.8	0.5	0.8	<0.1	0.1	2.6	4.2
Eh	mV	342	272	390	358	388	98	218	98	129	440	272
SEC	µS cm ⁻¹	162	612	54	296	174	646	489	397	349	75	65
Ca	mg L ⁻¹	8.88	46.3	2.96	20.6	15.4	43.5	22.4	28.2	17.4	3.56	4.32
Mg	mg L ⁻¹	8.99	27.2	2.7	3.33	5.51	32.8	17.6	11.8	2.8	1.61	1.51
Na	mg L ⁻¹	6.78	25.7	1.6	27.1	10.8	30.3	42.3	33.3	52.1	4.99	2.77
K	mg L ⁻¹	0.92	3.85	0.68	5.44	<0.5	3.8	0.98	5.59	3.95	0.64	1.97
Cl	mg L ⁻¹	0.62	10.2	<0.5	<0.5	1.22	1.06	0.66	0.58	<0.5	1.44	4.62
HCO ₃	mg L ⁻¹	83.5	237	25.5	170	76.2	320	247	218	186	6.6	6.7
SO ₄	mg L ⁻¹	0.82	5.04	0.2	3.11	5.94	53.5	14.3	9.9	13.6	<0.2	<0.2
NO ₃ -N	mg L ⁻¹	2.15	21.7	0.627	0.065	3.14	0.886	0.686	0.119	0.123	5.54	3.36
DOC	mg L ⁻¹	2.55	3.54	2.86	1.23	2.66	0.14	0.35	37.6	1.31	1.26	1.4
Si	mg L ⁻¹	22.1	25.2	14.7	23.8	10.1	22.3	19.4	35.4	22.7	12.6	7.74
Ag	µg L ⁻¹	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Al	µg L ⁻¹	21.7	17.6	17.6	19.6	19.6	2.1	3.1	2.1	2.1	22.7	5.2
As(III)	µg L ⁻¹	<1	<1	<1	20.9	<1	<1	<1	1.8	2.9	<1	1.8
As(V)	µg L ⁻¹	72.8	33.7	1.3	529	<1	178	49.6	14.1	1590	<1	7.8
As _T	µg L ⁻¹	62.6	26.1	1.44	519	7.61	162	47.1	14.2	1630	<0.5	6.14
Au	µg L ⁻¹	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
B	µg L ⁻¹	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Ba	µg L ⁻¹	0.165	57.3	0.795	38.8	11	1.73	3.4	78.1	5.51	55.7	36
Be	µg L ⁻¹	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.083	0.093	0.124
Bi	µg L ⁻¹	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Br	µg L ⁻¹	11.4	70.2	5.2	5.2	15.5	10.3	7.2	10.3	7.2	15.5	34.1
Cd	µg L ⁻¹	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.072
Ce	µg L ⁻¹	0.01	0.01	0.01	0.01	<0.01	0.01	0.01	0.041	0.01	0.062	0.021
Co	µg L ⁻¹	<0.02	<0.02	0.041	<0.02	0.041	<0.02	<0.02	0.114	0.052	3.68	0.95
Cr	µg L ⁻¹	0.93	<0.5	<0.5	<0.5	<0.5	0.93	<0.5	<0.5	<0.5	<0.5	<0.5
Cs	µg L ⁻¹	0.062	0.021	0.083	0.041	0.093	0.01	0.114	<0.01	10.7	0.031	1.58
Cu	µg L ⁻¹	2.79	1.34	4.34	0.31	1.14	0.62	0.83	0.62	0.72	2.17	0.72
F	µg L ⁻¹	272	167	55	71	112	59	74	0.298	724	<20	49
Fe	µg L ⁻¹	7.0	6.9	6.9	7.2	9.1	5.5	<5	0.107	76	79	15
Ge	µg L ⁻¹	0.155	0.196	0.155	0.176	0.145	0.269	0.093	0.186	0.682	<0.05	<0.05
Hg	µg L ⁻¹	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
La	µg L ⁻¹	<0.01	0.01	<0.01	0.01	<0.01	0.01	0.01	0.021	<0.01	0.041	0.01
Li	µg L ⁻¹	11.1	14.8	26.9	21.1	8.88	21	15	18.5	172	2.58	7.64
Mn	µg L ⁻¹	0.196	0.258	0.537	0.878	1.82	1.37	0.64	53.7	12.2	28.9	21.3
Mo	µg L ⁻¹	3.2	0.83	<0.1	9.09	0.72	1.45	5.58	12.1	55.9	<0.1	0.41
Ni	µg L ⁻¹	<0.2	<0.2	1.96	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	7.44	2.27
P	µg L ⁻¹	28	35	90	23	36	23	<20	<20	24	<20	<20
Pb	µg L ⁻¹	<0.1	<0.1	0.41	<0.1	0.21	0.21	0.1	0.21	0.1	<0.1	0.1
Rb	µg L ⁻¹	2.12	0.527	1.78	2.12	0.971	0.692	0.971	0.64	13.9	1.43	4.61
Sb	µg L ⁻¹	0.217	<0.05	<0.05	0.083	0.083	0.124	<0.05	<0.05	<0.05	<0.05	<0.05
Se	µg L ⁻¹	<0.5	1.14	<0.5	<0.5	<0.5	0.72	0.62	<0.5	3.2	<0.5	<0.5
Sr	µg L ⁻¹	36.7	502	35.4	486	180	396	572	231	238	32.2	42.8
Ta	µg L ⁻¹	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Tb	µg L ⁻¹	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Te	µg L ⁻¹	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

Th	$\mu\text{g L}^{-1}$	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
U	$\mu\text{g L}^{-1}$	0.041	0.609	<0.02	5.8	0.052	0.165	1.18	3.09	0.279	<0.02	<0.02	<0.02
V	$\mu\text{g L}^{-1}$	6.3	40.5	<0.2	8.78	4.34	12.2	2.38	21.4	8.06	<0.2	0.21	<0.2
W	$\mu\text{g L}^{-1}$	<0.02	0.083	<0.02	0.95	0.021	0.031	0.031	0.165	9.4	<0.02	0.083	<0.02
Y	$\mu\text{g L}^{-1}$	0.01	0.021	<0.01	0.021	<0.01	0.031	0.021	0.031	0.01	0.103	0.031	0.103
Zn	$\mu\text{g L}^{-1}$	5.68	5.78	12.2	4.03	25.1	9.09	8.88	7.75	30.5	8.37	20.7	8.37
Zr	$\mu\text{g L}^{-1}$	0.021	0.021	0.021	0.021	0.021	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Abbreviations as in Table 1; bh: borehole; completed: date of borehole/well completion

Table 3. Statistical summary of groundwater As data from the 2004 PEEN project survey (COWI, 2004) (samples with erroneous grid references excluded).

	Arsenic ($\mu\text{g L}^{-1}$)
Min	0.4
Max	560
Median	2.0
Arithmetic mean	8.9
Geometric mean	2.1
Number samples	185
% >10 $\mu\text{g L}^{-1}$	13
% >50 $\mu\text{g L}^{-1}$	3.2

Table 4. Arsenic concentrations in selected samples of altered rock material from the Margo–Nongfaéré goldfield.

Locality	Sample details	As (mg kg⁻¹)
Ramsa goldfield	Yellow clay, mine shaft extract	165
Margo Koyogo village	Red-brown silty clay, tailings deposit	193
Margo goldfield	Red-brown silty clay, mine shaft extract	761
Nongfaéré goldfield	Red-brown silty clay, mine shaft extract	33
Nongfaéré mine site	Kaolinitic clay, mine shaft extract	70

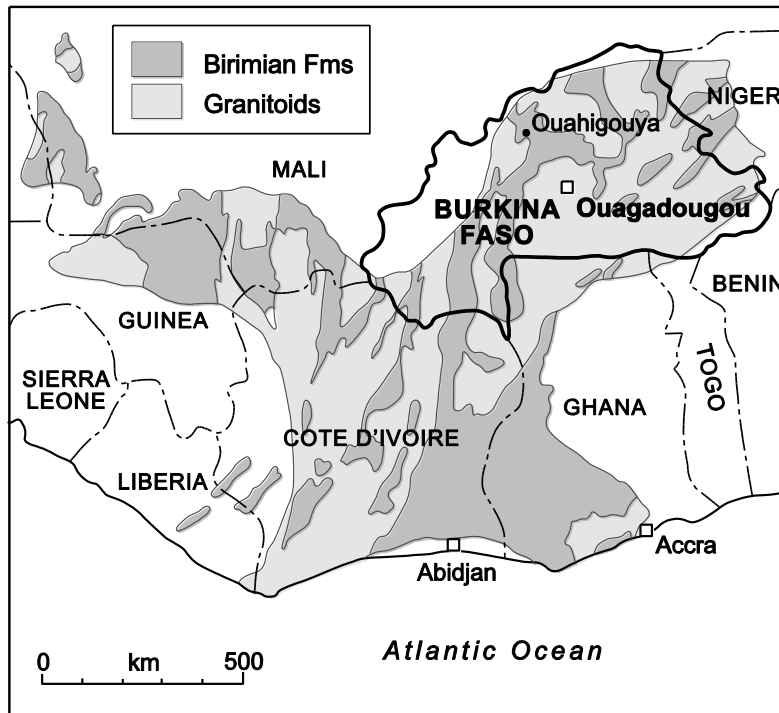


Fig. 1. Simplified geological map of West Africa showing the location of Birimian volcano-sedimentary rocks and Eburnian granitoids.

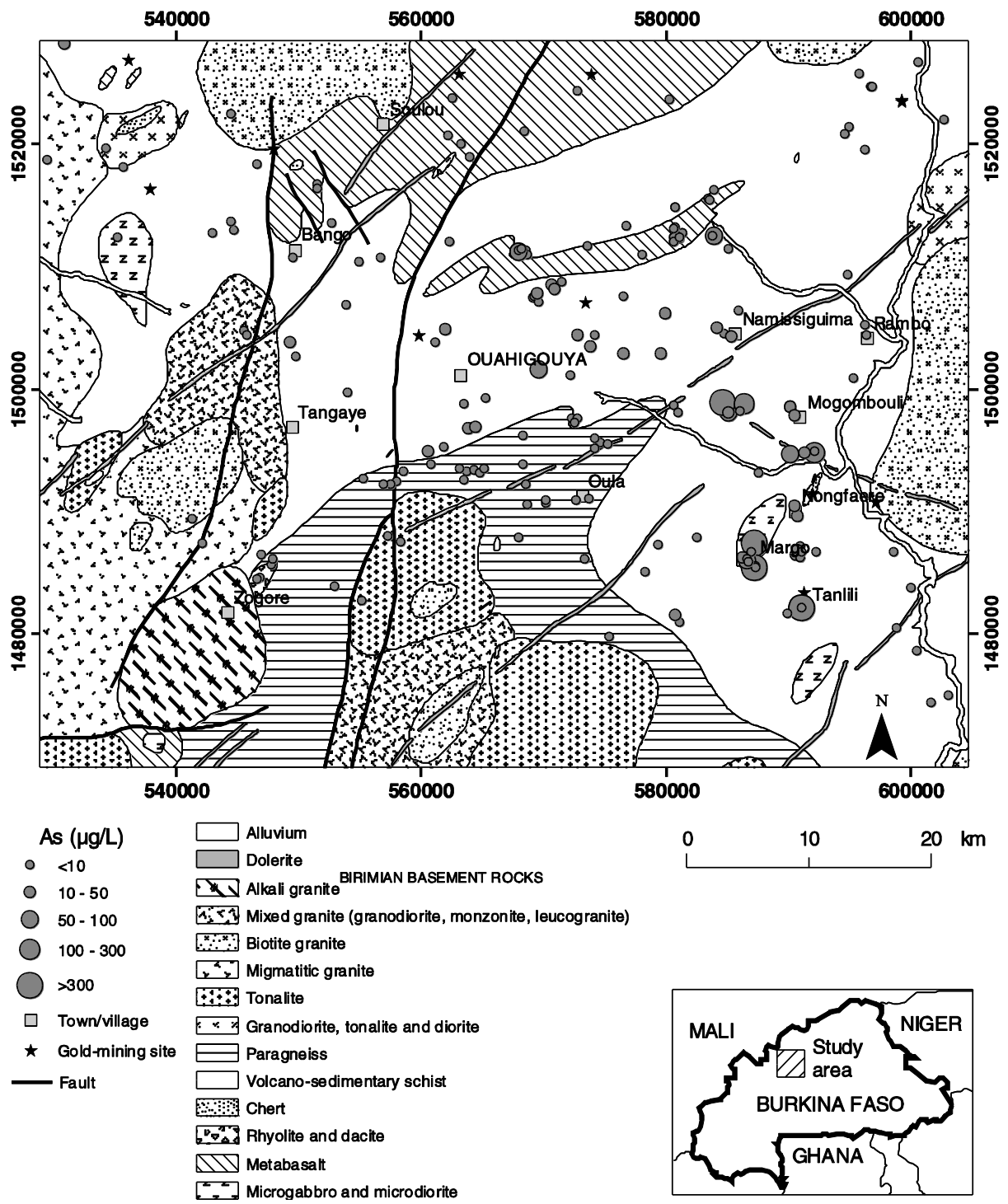


Fig. 2 Geological map of the Ouahigouya area, Burkina Faso showing the concentrations of As in groundwater from sampled boreholes and dug wells (sample sites include the January–February 2005 survey and samples investigated by COWI from the 2004 survey).

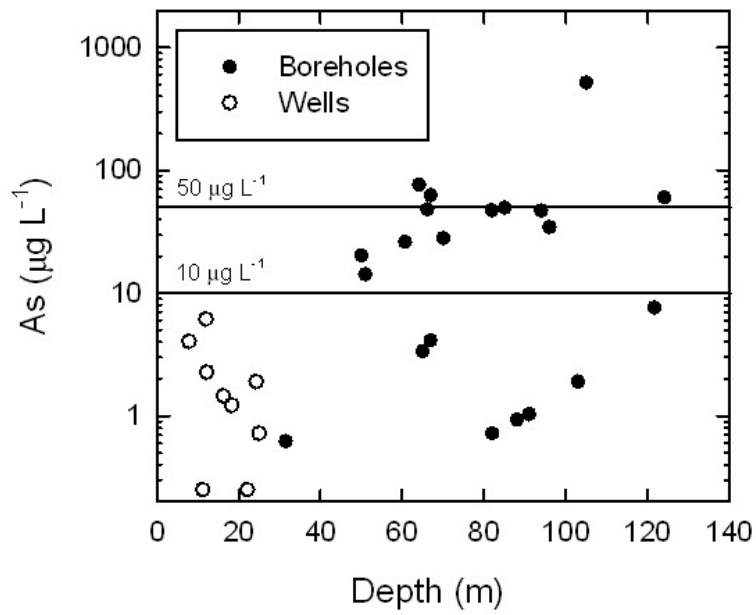


Fig. 3. Variation of As concentrations with depth in boreholes and dug wells.

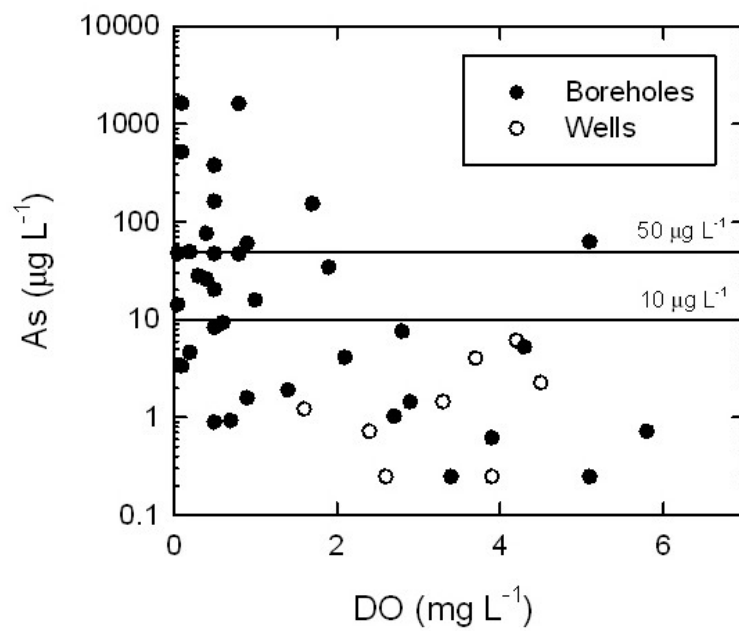


Fig. 4. Variation of As with dissolved oxygen (DO) in the boreholes and dug wells.

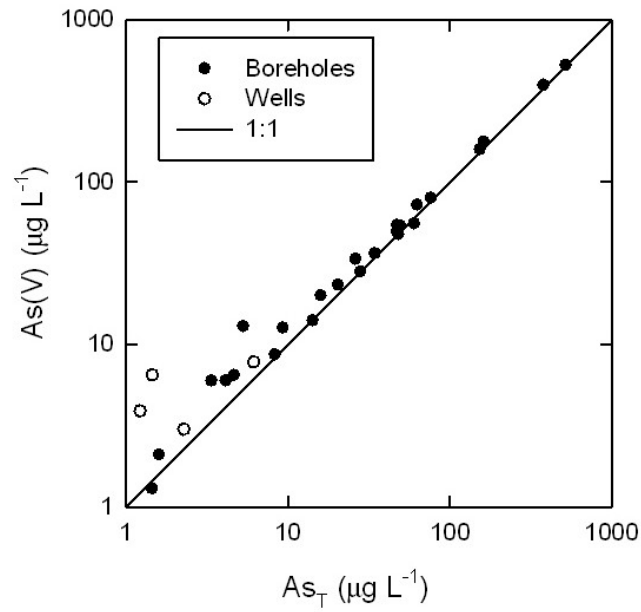


Fig. 5. Variation of As(V) with total As in groundwaters from the Ouahigouya area.

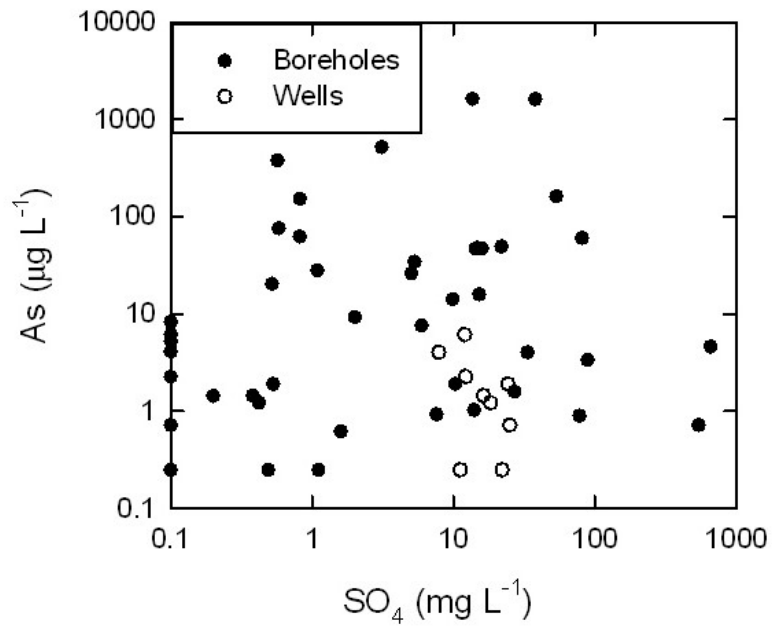


Fig. 6. Variation of As with SO_4 in the groundwaters from boreholes and dug wells.

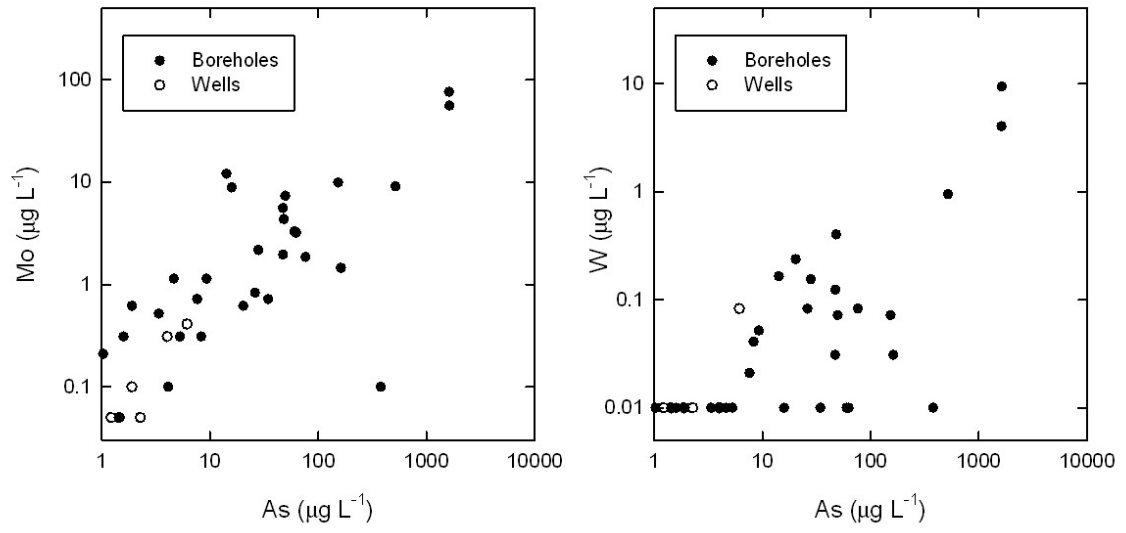


Fig. 7. Variation of As with Mo and W in the groundwaters from boreholes and dug wells.