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GAS GEOCHEMISTRY STUDIES AT POAS VOLCANO, COSTA RICA MARCH 1992 AND JANUARY 1993 (PROJECT NO. 91/17)

by

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The remnants of Poas crater lake,
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GAS GEOCHEMISTRY STUDIES AT POAS VOLCANO, COSTA RICA MARCH 1992 AND JANUARY 1993

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1. SYNOPSIS

Volcanoes and earthquakes occur in many parts of the world. Primary phenomena are potentially catastrophic, whilst those of a secondary nature may be merely considered as *background* activity, or of sufficient intensity to cause long-term suffering to indigenous populations. The latter is the case at Poas volcano in Costa Rica, where increasing activity during the last decade has precipitated a change in the quiescent state of the volcano. Acid gases are *apparently* now being emitted more intensely than before, to the detriment of the health of people and domestic livestock living in the surrounding countryside; damage to crops and farm buildings is also comparatively serious.

A pilot study has been undertaken to determine the principal constituents of the gas emissions, the form in which they are most likely to be transported and the extent of the area within which they can be easily measured. In addition, the impact of the acid components, both gas and liquid (from the crater lake), on the composition of natural waters has also been considered.

The results obtained indicate that combined emissions of hydrochloric, hydrofluoric and sulphuric acids all contribute to the problems encountered, but seasonal changes and distance from the source also exert control. The acids appear to be variously transported as free acids, complexed species and aerosols, but the rate of transfer is heavily dependent on the prevailing atmospheric conditions. Rainfall effectively *scrubs* the acid gases during the wet season, thereby considerably ameliorating the immediate effects of the emissions. Continued longer-term monitoring is necessary to establish baseline information and recommendations for this are made.

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2. INTRODUCTION

This work was carried out under Project No. 91/17 (Environmental aspects of radon and other gases in geothermal areas) as part of the ODA/BGS Research and Development Programme forming part of the UK Government's Aid Programme to developing countries.

The importance of geothermal resources as a relatively inexpensive source of energy has long been recognised. Project No. 87/15 was established to investigate the application of soil gas geochemistry techniques to the exploration for geothermal power sources in developing countries, and work undertaken in Costa Rica was reported by Ball (1988). Exploitation of such resources is however costly in the first instance, and therefore needs to be carefully assessed in terms of source quality. Geothermal steam contains many impurities such as carbon dioxide, radon and acid gases, some of which are potentially injurious to health, whilst others can cause corrosion in power plant components. Radon is known to cause lung cancer, and its association with high temperature steam provenances has been investigated in Kenya, Costa Rica and the Philippines, under the present project. The project was then extended to consider other harmful volcanic gas emissions and their epidemiological effects, in collaboration with a consultant occupational health physician based at the University of Cambridge. After discussion with geophysicists at the Open University, who had experience of working on Poas volcano for many years, it was decided to concentrate research at this particular location in Costa Rica, where a subtle change in activity of a dormant volcano is presently causing health problems and financial difficulties (through the direct effects of the volcanic gases on crops and domestic livestock) for local communities.

Poas is a composite stratovolcano rising 1400m above its surroundings in the populated Cordillera Central of Costa Rica. The last major eruptions occurred in 1952/53, when phreatic activity resulted in the loss of the crater lake, and culminated in the growth of a 45m high pyroclastic cone, which subsequently became the focus of continuous fumarolic activity. A new lake formed in 1967 and maintained a depth of about 50m, circulating mildly acidic brines at about 40°C. Apart from minor fluctuations in level and temperature, and a brief period of geyser activity during 1978/79, the system appeared stable until early 1986 when a long-term decrease in the lake level commenced. Intense geysering again occurred from June 1986 to July 1987, and these events heralded the start of a new magmatic cycle, which has been studied by a variety of geophysical and geochemical techniques, such as those of Brown et al. (1989), Barquero and Fernández (1990) and Rowe et al. (1992).

However, the environmental hazards posed by the escape of high temperature volcanic gases and aerosols are only now beginning to be appreciated.

A preliminary visit to Poas volcano by BGS staff was undertaken in November 1991, after discussions with geophysicists from the Open University and a consultant epidemiologist from the University of Cambridge. During this visit, useful contacts were also established with local scientists (OVSICORI–UNA) responsible for the constant monitoring of Costa Rican volcanoes. Rain adversely affected the sampling programme, but nevertheless sufficient data were gathered, and the results obtained from both field and laboratory studies were reported by Nicholson et al. (1992). This earlier report contains some information not repeated here, and reference to the earlier text should be made if improved clarification of certain aspects is required.

Since completion of the 1992 report, two further periods of fieldwork have taken place. These occurred in March 1992 and January 1993, and were designed to monitor the changing characteristics of the volcano and its environs, particularly the gas plume and water catchments, under dry–season conditions. The application of statistical techniques by the School of Environmental Sciences at the University of East Anglia, to some of the crater lake data acquired during the preliminary field excursion, encouraged us to examine the possibility of condensing the aerosols formed in the gas cloud above the lake. Therefore during January 1993, condensate in the volcanic plume was sampled using a device suspended from a wire stretched across the crater above the lake.

The gradual decrease in crater lake water level over the last few years at last ensured that it was possible to collect condensate samples relatively safely, during the January 1993 visit, from one of the previously–submerged fumaroles. However, constant blockage of the sampling tube occurred, due to spattering by mud boiling inside the hardened mud–dome containing the open vent.

3. FIELD STUDIES, GAS MONITORING AND SAMPLE COLLECTION

3.1 General Considerations

The preliminary visit in November 1991 took place at the end of the wet season in Central America, and some of the proposed sampling activities were curtailed because of heavy rain, Nicholson et al. (1992). Poas volcano comprises few andesitic lavas separated by layers of unconsolidated materials, and during periods of exceptional rainfall some areas become liable to spontaneous collapse. Parts of

the crater area were therefore considered inaccessible for safety reasons, and it was decided to repeat the exercise when it could reasonably be expected that somewhat drier conditions would be encountered. This would also allow direct comparison of data for the chemical composition of both gas and water samples between wet and dry seasons.

3.2 March 1992

There was a marked difference between the conditions encountered on this occasion and those experienced during the earlier fieldwork. Little or no rain fell throughout the entire visit, only light precipitation from persistent afternoon cloud-cover caused any problems. However, acid fallout from the volcanic plume appeared to be more intense in the drier air, and brief interviews with local people confirmed this as typical of the dry seasonal effects of the volcano. In populated areas downwind, several kilometers from the summit, there was a definite *sulphurous* smell in the air, although the highest concentrations of sulphur dioxide measured, using an MEI personal toxic gas monitor, did not exceed 0.3 – 0.5ppm over periods of a few minutes (STEL – Short Term Exposure Limit 2.0ppm). Data subsequently obtained from long-term (600 hours exposure) diffusive gas samplers showed comparable values (see below).

Colleagues from OVSICORI-UNA were not available to accompany us to the crater immediately following our arrival due to commitments elsewhere, and therefore a preliminary visit to the volcano entailed a brief study of conditions on the upper rim only. On this occasion the wind was gusting to 8.0m/s from the NNE, but locally within the caldera the direction was variable. Sulphur dioxide was measured using the toxic gas monitor, the highest temporal concentration recorded being 34.5ppm, which necessitated the wearing of breathing masks for short periods. Stinging sensations, caused by acid precipitation on exposed skin, were pronounced. This was subsequently confirmed by collecting the acid-fallout on impregnated filter papers, and measuring the sulphate, chloride and fluoride contents. One of the OVSICORI-UNA rainfall sampling points is located on this rim (Borde Este).

The exposed western flank, approximately 1km downwind, is completely denuded of vegetation on the inner-facing slopes, and only supports low scrub elsewhere. This flank is also one of the monitoring points for rainfall (Pelon). Wind direction here was again variable, apparently blowing from all points of the compass within the space of a few minutes, but wind speeds were very low at zero to 4.0m/s. Low cloud

within the crater obscured the view, so that it was impossible to know when the volcanic plume was drifting towards the sampling area, but values of sulphur dioxide measured with the toxic gas monitor did not exceed 0.2ppm at any one time. However, Draeger short-term diffusion tubes emplaced above the open ground showed a total flux of 10ppm sulphur dioxide over a four-hour period, i.e. 2.5ppm per hour. There was no indication of the presence of either hydrogen chloride or hydrogen sulphide at this location, and it is assumed that both were below the detection limit of the diffusion tube method.

Similar studies carried out at the Mirador public viewing platform, which is much closer to the source but at right angles to the prevailing wind direction, gave zero concentrations for all three acid gases, even after five hours of exposure. The obvious signs of corrosion of metal objects in this area, such as the remains of the corrugated shelter previously used to house gas sampling equipment, indicates that this situation is not normal, and it is known that localised meteorological conditions drastically affect the circulation of air masses in the region of the crater. The Mirador viewing station is another collection point for rainwater.

On the volcanic dome in the bottom of the main crater, values of 2.5ppm for hydrogen chloride and 5.0ppm for sulphur dioxide were obtained with short-term diffusion tubes. There was no indication of hydrogen sulphide. During sampling of the low-temperature (85^{o}C) dome fumaroles, using the evacuated Giggenbach vessels, the atmospheric sulphur dioxide concentration frequently exceeded 20ppm, and occasionally reached 50ppm. The maximum value determined was 71ppm, which is three times higher than that previously recorded in November 1991. Within the crater the wind direction was highly variable, and although close to the source of the gases, it was often possible to work for prolonged periods without a breathing mask. It was not possible to approach any of the high-temperature fumaroles venting through the remnants of the crater lake, due principally to the presence of acid waters and thixotropic sediments. However, it was possible for staff from OVSICORI-UNA, who are familiar with the inherent dangers of the area, to collect lake water samples. These samples have been routinely collected on approximately a monthly basis as part of the continuing geochemical monitoring of the volcano.

Samples of acid-fallout within the crater were collected on 125mm filter papers impregnated with sodium formate and glycerol, and placed flat on a polyethylene sheet for one hour, and also by pumping 1 litre of air through 25mm filter papers contained in a filter holder. This latter experiment was repeated at approximately

quarter-hourly intervals over a period of four hours, at a point on the crater rim diametrically opposite to the Borde Este, during which time the atmospheric sulphur dioxide concentration varied between zero and 3.0ppm. Wind speed was relatively gentle and direction highly variable, there was also persistent light rainfall.

To confirm the earlier data obtained on acid precipitation at locations around the volcano, long-term diffusion tubes were again emplaced at sites near the summit, and also at distances of up to seven kilometers on the downwind side. These remained in place for almost one month, and were subsequently retrieved by OVSICORI-UNA staff and returned to the UK for analysis in the Department of Trade and Industry's Warren Spring Laboratory.

A few samples of decaying tree vegetation were collected from open land on a dairy farm near the summit. This farm frequently receives acid rain as wind direction varies, and was the location at which the highest concentration of sulphur dioxide had previously been measured using the diffusion tube technique.

Natural water samples were collected from a variety of provenances around the volcano, to determine the distribution of *normal* levels of cations and anions; sources included piped drinking waters and rivers. All the water samples remained unfiltered. Waters had previously only been collected from rivers known, or believed, to drain the summit crater region. By sampling more widely it was hoped to obtain a better overall understanding of the chemistry of the main catchments involved. The Rio Gata was blue when the sample was collected, but the reason is unknown as subsequent analysis was equivocal.

3.3 January 1993

Thermodynamic calculations in the School of Environmental Sciences at the University of East Anglia (UEA), on the chemical composition of the crater lake waters, showed that it was important to measure the composition of the aerosol droplets in the vapour cloud above the lake. A device to sample these droplets was designed and built in the BGS workshops (Plate1). The framework was fabricated from 316 stainless-steel and PVC, as it was thought that these materials would ensure rigidity combined with the inertness of the plastic components necessary to prevent sample contamination.

During the actual sampling, a 0.5km long by 1.6mm diameter stainless-steel cable was suspended between two sides of an upper ledge above the crater lake, across that part of the crater above the main area of fumarolic activity. The cone of the sampler was filled with crushed ice (transported to the crater in a vacuum flask), and the device deployed along the wire into the vapour cloud. Acid droplets condensed on the outside of the cold PVC cone and were collected in a polyethylene bottle; three samples of condensate were obtained for analysis. The temperature of the outside of the cone was probably just above freezing point, and therefore ideal for condensing the volcanic vapours; the ice/water mix remained cold sufficiently long enough to allow sampling for at least one hour on each occasion. Attempts to improve the rate of collection, through lowering the temperature still further by the addition of sodium chloride to the crushed ice, failed due to the build-up of a solid deposit of frost on the outside surface of the cone. The sampler was recovered along the suspended wire by the use of a reel containing a fifty pound breaking strain nylon fishing line. The strong winds experienced whilst sampling occasionally caused problems during retrieval due to the nylon line wrapping itself around the stainless-steel wire and ultimately breaking. It was then necessary to climb down into the bottom of the crater near the lake and lower the sampler until it could removed from the stainless-steel wire by hand.

Water samples were collected from many of the sites sampled in March 1992, in order to confirm the earlier analytical data, and note any major variations. The names of some of the previously unknown rivers and their tributaries were also substantiated. The Rio Gata again appeared blue (Plate 2), but no explanation for this phenomenon was offered by local counterparts, as there was apparently no known upstream source of contamination, other than the volcano. A series of rainwater samples, collected on a regular basis during 1992, from the Mirador (Public Viewpoint), Edificio (Visitor Centre), Botos (Extinct Crater), Borde Este (East Side of Upper Rim), Pelon (Western Flank) and Potrero (Near Entrance Gate), were sub-sampled for confirmatory analyses in the BGS laboratories. Similarly, samples of water from the crater lake collected between February 1992 and January 1993 were also returned to the BGS laboratories. Sample locations are indicated in Figure 1. One of the samples of lake water collected during this fieldwork was preserved with sodium tetrachloromercurate, to stabilise the dissolved sulphur dioxide as the disulphitomercurate complex, for subsequent spectrophotometric determination by the method of West and Gaeke (1956). All the water samples remained unfiltered.

As the crater lake water level has diminished over the past few years, it has gradually become easier to approach certain parts of the area around the lake with care, indeed OVSICORI-UNA staff have been undertaking sampling of the crater lake for many years on a routine basis. It was therefore encouraging to discover that it was at last possible to approach one of the higher temperature fumaroles (117^{o}C) relatively safely to sample the condensate for gas composition (Plate 3). However, only one sample was retrieved due to persistent blocking of the quartz sampling tube by mud boiling within the hardened mud-dome capping the volcanic conduit. Pressure within the mud-dome changed constantly during the sampling, and it was not possible to determine at this stage whether or not the sample had become contaminated by air.

Samples of acid-fallout, on the crater rim at the Borde Este rainwater sampling site, were collected on 125mm filter papers impregnated with (a) sodium formate and glycerol and (b) potassium hydroxide and glycerol. These papers were placed flat on a polyethylene sheet for one hour. Similar experiments were carried out by pumping 1 litre of air through much smaller 25mm filter papers contained in a filter holder. During the sampling period the atmospheric sulphur dioxide concentration varied between zero and 4.0ppm, indicating the variability of the wind direction about the point of sampling.

4. RESULTS AND DISCUSSION

Major and trace elements in the water samples were determined by inductively coupled plasma optical emission spectrometry, and the anions by a combination of ion chromatography, flow injection analysis, selective ion electrode and titrimetric techniques. All water data are shown in Tables 1 – 4. The major components of the gas confined above the condensate sample were determined by gas chromatography, and the anions by titrimetry and selective ion electrode. Anions absorbed on impregnated papers were dissolved using selective reagents and measured by spectrophotometry and selective ion electrode.

4.1 Water Chemistry

The pH of the lake water samples was not determined, as the strength of the acid had undoubtedly increased significantly with the fall in lake level. Previous investigations had shown that acid concentrations were generally high, with negative pH values (pH $\pm$ -0.5), knowledge of which are important for ion speciation studies.

Only three of the natural water samples indicated any tendency towards acidity, the Rio Agrio and Rio Desague having been noted previously, but the pH of 5.86 recorded on the Rio Gata perhaps indicated an additional escape route for summit drainage.

4.1.1 Crater Lake

Preliminary thermodynamic calculations of the state of Poas crater lake only considered those species with concentrations >0.1mol dm^{-3}. Hydrogen ion concentration was obtained from the charge balance, and in the absence of any very recent data a temperature of 85°C was assumed. All fluoride not complexed with Al^{3+} was presumed to be present as free hydrofluoric acid (HF), which is a logical assumption in such highly acidic waters.

The Pitzer (1973) thermodynamic model was used to determine speciation and ionic activities in the crater lake samples collected during 1991. Total ionic strengths and calculated partial pressures of hydrogen chloride (HCl) are shown in Table 5. In general, the dissolved acids (HCl and H_2SO_4) make up the bulk of the dissolved material; consequently the partial pressures of HCl and HF are functions of the total ionic strength.

Table 5

Date	**19Apr**	**6June**	**26July**	**23Aug**	**24Sept**	**1Nov**
Total ionic strength	3.70	1.69	3.34	3.00	4.18	4.53
Fraction due to acids (H^+, Cl^-, SO_4^{2-})	60%	73%	81%	79%	81%	80%
pHCl (10^{-5} atm)	7.0	2.0	13.3	8.3	22.0	28.0
cCa^{2+}	0.039	0.056	0.040	0.040	0.029	0.023
γCa^{2+}	0.077	0.122	0.130	0.130	0.140	0.140
cSO_4^{2-}	0.011	0.013	0.023	0.020	0.025	0.024
γSO_4^{2-}	0.120	0.073	0 037	0.047	0.037	0.038
Activity product of $CaSO_4/10^{-6}$	3.96	6.50	4.40	4.40	3.80	2.93

Calculations show that the HSO_4^- -SO_4^{2-} speciation in solution is an important influence on acid gas partial pressure by controlling the amount of free H^+ available. Typically 30% of total H^+ in the lake is present as HSO_4^-. Sulphate speciation also influences the concentrations of metal ions which have weakly-soluble sulphates. For example, the calculated activity product of calcium sulphate is relatively constant over all the samples, indicating that it is in thermodynamic equilibrium with the mineral phase.

It is recognised that temperature gradients exist within the lake, as localised heating undoubtedly occurs where fumarolic activity is maximal. Changes in temperature affect chemical equilibria, and have a marked effect on the partial pressures of HCl and HF, and therefore the amounts outgassed. A increase or decrease in lake temperature of 10^oC results in approximately a factor of two change in partial pressure for both gases, i.e. increasing temperature increases the partial pressures and vice versa. An HCl partial pressure of 7×10^{-5} atm implies an emission of 1500 tonne $year^{-1}$ km^{-2} from simple volatilisation of HCl from the lake water, assuming a transfer coefficient of 5×10^{-3} m s^{-1}. The fluoride is heavily complexed by Al^{3+} in solution and its partial pressure, although comparable to that of HCl, is likely ultimately to be much less. Gas release from the lake is therefore presumed to be highly variable over the entire surface, and greatly influenced by isolated hotspots.

From the above observations it was apparent that there were a number of interesting seasonal changes in the lake chemistry that merited further investigation. However, it was not clear whether the greater impact of aerosols in the dry season could be explained without further measurements, because it was impossible to distinguish between simple *volatilisation* of material from the lake and bubble-bursting processes. This distinction could be made if data were available on the composition of aerosol droplets above the lake, and as indicated above, the gas cloud was successfully sampled during subsequent fieldwork (see under gas geochemistry section for the results of these experiments).

Under such highly acid conditions it would be expected that any uncomplexed anionic species will be present as the free acids. Figure 2 shows the distribution of fluoride, chloride and sulphate in the lake waters throughout 1992, although difficulties in sampling from the same location on each occasion may have slightly affected the overall results. The much higher concentrations prevailing throughout

the drier months (Dec – April) indicate the gradual evaporation of the remnants of the lake, followed by dilution with rainwater, and eventual loss through drainage during the wet season. It is understood that rain was much heavier than usual during December 1992, and similar conditions were experienced during the January 1993 fieldwork. This obviously affected the concentrations of dissolved ions, which would normally be expected to start increasing as the lake waters disappeared.

The sample preserved by the addition of sodium tetrachloromercurate showed that there was approximately 70mg/l free SO_2 in solution. The presence of free unreacted gases such as SO_2 and H_2S is to be expected, since oxidation/reduction reactions of sulphur species will be a continuing process within the system.

4.1.2 Rainwaters

Figures 3 – 8 show the distribution of the same parameters in some of the rainwater samples collected during the 1992 wet season. However, it should be noted that the Botos sample is not strictly a rainwater, as it is taken from an extinct crater lake which is kept filled by rainfall, but which overflows constantly via a semi–permanent stream. All of these samples are generally recovered on a fortnightly basis, but localised meteorological conditions directly affect the amount of summit rainfall recorded. Therefore the dataset is always likely to be inconsistent, because sufficient sample is not necessarily obtained from every station on a regular basis.

There was an apparent *event* in September which dramatically affected the output of HCl and HF. Chloride and fluoride are high at the Mirador, Borde Este and Botos, and also increased slightly in Poas crater lake at the same time. This may have been caused by a minor increase in activity, but could also have resulted from a brief period of drier weather which allowed greater evaporation. Volatilisation of HCl and HF again increased significantly towards the end of the wet season, although this was not accompanied by a proportionate increase in SO_2 emission, probably due to the greater stability of sulphate ions in the lake waters. Botos lake was exceptional in December in that it showed a *decrease* in chloride content but a large *increase* in fluoride content; the reason is not known.

4.1.3 River and Drinking Waters

The distribution of trace elements in the natural waters is principally influenced by the composition of the main catchments, much of which is either primary volcanic

material or weathered products of volcanic origin. The majority of the rivers exhibit neutral to weakly alkaline characteristics, and the variation of trace element content between the two sets of samples collected in March 1992 and January 1993 is minimal, being affected by seasonal dilution effects only. All data are shown in Table 4. However, three of the samples are distinctly acid, those of the Rio Agrio (bitter river) and Rio Desague having already been noted from earlier work, but the acidity of the Rio Gata was not recognised previously, because samples were not collected during the November 1991 fieldwork. The very low pH value, and the high levels of major and trace elements in the Rio Agrio, are thought to originate from Poas crater. This is confirmed by the rate of loss of lake fluids during recent years, caused by evaporation through increased power output, and seepage through the crater walls, Brown et al. (1991).

According to Figure 1, the sources of the Desague and Gata are both on the same side of the volcano as the Agrio, and although the pH's are significantly higher (between 5 and 6), the possibility that some of the acid waters from the summit area are reaching tributaries feeding these two rivers cannot be ignored. The levels of dissolved halides and sulphate particularly are indicative of acid conditions, even though the absolute concentrations are much lower. The concentrations of fluoride, chloride and sulphate in the main catchments are shown in Figure 9, and the distinctly higher levels in the Desague and Gata are prominent. There are probably still some streams that have not been sampled due to their seasonal nature, but indications are that losses from the crater lake are confined to the WNW slopes i.e. towards the Bajos del Toro. The source of the drinking water supplied to this area is not known, but it may not be local as it is seemingly unaffected by the presence of acid river conditions nearby.

Apart from the small isolated community in the Bajos del Toro comprising farms, private dwellings, a school, a medical centre and shops and bars, the countryside is relatively devoid of human habitation. The area to the north of the community (several kilometers distant) is destined to be a major reservoir, and development work is already well underway. Because of its intended location this reservoir may ultimately be a catchment for some of the waters draining the NW slopes of Poas volcano. However, it is not known whether due account is being taken of the acid nature of the waters, and hence the implications for subsequent water quality.

4.2 Gas Geochemistry

4.2.1 Fumarole Gases

During the March 1992 fieldwork, low temperature fumarole (85°C) samples were collected from the top of the volcanic dome, using an inverted funnel buried in the ash. However, the oxygen and nitrogen content of the gases determined subsequently by gas chromatography indicated that the samples were contaminated by air, thereby confirming data obtained previously from an adjacent area.

As outlined above, in January 1993 it was possible to sample a higher temperature system near the crater lake, although the presence of boiling mud did cause problems with blockage of the quartz sampling tube. Only after return to the UK was it possible to establish that although apparently one good sample was collected, the headspace gas was again contaminated by atmospheric components. The oxygen content was 0.25% and the nitrogen content almost 20%, indicating that at least a quarter of the sample was probably air. A similar sample collected from the same fumarole in November 1992 by the University of Florence contained no oxygen and less than 0.1% nitrogen. Better sealing of the joint between the sampling tube and the sampling vessels, and an improved technique for flushing the connecting pipe are therefore necessary. Our sample also contained approximately 0.3% w/v chloride and 35% w/v sulphate, but poor reproducibility between determinations for total sulphur, prevented accurate calculation of the average oxidation state, and hence estimation of the individual proportions of SO_2 and H_2S. The reasons for the poor agreement are not fully understood, but interference from other species in solution is suspected, perhaps related to the presence of clay minerals from the boiling mud.

4.2.2 Condensate from the volcanic plume

The three samples of condensate had relative compositions of solute species that were very similar (Table 6). The differences in overall concentration can be explained in terms of condensation of variable amounts of pure water, leading to overall dilution or concentration. If the levels of metal ions are ignored, then the dilution is calculated to be a factor of about 0.005 – 0.05.