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REPORT**

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**Study of groundwater colloids and
their ability to transport radionuclides**

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Stockholm

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**STUDY OF GROUNDWATER
COLLOIDS AND THEIR
ABILITY TO TRANSPORT
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SUMMARY

The general aim of this investigation was to test if the two photon correlation spectroscopy equipments at the Institute for Surface Chemistry could be used to measure the colloid concentration in groundwater and also to measure the surface potential (zeta potential) of these colloids.

Groundwater colloids from Stripa, Kamlunge and Svartboberget have been investigated. Well characterized pure kaolin was used as a model colloid.

The equipment for dynamic light scattering at the Institute for Surface Chemistry was found to be sensitive for detection of colloids in groundwater down to 100 $\mu\text{g/l}$. The highest amount measured in real groundwater was 400 $\mu\text{g/l}$. In KBS-3 one assumed a content of 500 $\mu\text{g/l}$, this seems to be a good assumption.

The equipment at the Institute for Surface Chemistry for measuring the zeta potential is also based on dynamic light scattering, in combination with detection of a Doppler shift in the frequency of the scattered light in an electric field (Malvern Zetasizer). This equipment is less sensitive than conventional light scattering equipment and hence it is necessary to concentrate the groundwater between 200 and 1000 times.

The method gives a distribution curve for zeta potentials (surface charges). In principle, it should be possible to detect several particle types with different charges. In practice, this is possible only for well-defined model systems, where there are large variations in the particle size and refractive indexes.

The accessible equipment was found to be useful for the estimation of the colloid content in groundwater and also for the estimation of a mean value (with distribution) of the zeta potential of the colloides.

Due to the low concentrations of colloids, a very low content of multiple valent cations can drastically change their zeta potentials, which is illustrated by model studies with kaolin and Fe^{3+} . It could be possible to estimate the size of these changes on basis of the model of James and Healy for ion adsorption on mineral surfaces.

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1 INTRODUCTION

Natural occurring colloids in groundwater can adsorb and transport released radionuclides. In this work groundwater colloids has been investigated with zeta potential measurements and dynamic light scattering. The goal was

- i) to estimate the detection limits of the Institute's equipment for particle size estimation with dynamic light scattering and zeta potential with dynamic light scattering combined with estimation of Doppler shift in the scattered light frequency.
- ii) to examine several different groundwaters (Stripa, Kamlunge, Svartboberget).

The possibility to apply a theoretical adsorption model for interpreting the results is also discussed.

2 DETECTION LIMIT FOR THE ZETA POTENTIAL MEASUREMENTS

2.1 Measurement principle

The Malvern Zetasizer consists of a light scattering spectrometer and a digital autocorrelator coupled to a computer for statistical analysis of the measurement results. The amount of light which is scattered from a diluted particle suspension is analyzed as a stream of photons. The fluctuations in light intensity will show the changes in number and place among the particles in the observed suspension volume. These changes are due to the Brownian movements of the particles, which is directly proportional to their diffusion coefficient. By presuming a specified shape on the particles the diffusion coefficient is used to calculate the particle dimensions.

The fluctuation in intensity is measured by letting the detector capture photons within a couple of successive time intervals and store the registered amounts in the autocorrelator.

If the particles are charged and exist in an electric field the Brownian movement will be "overlapped" by a systematic movement in the field. The particle velocity is regulated by an electrical potential which the particle surface shows towards the surrounding solution in the shear plane of the solution to the particle surface. The movement of the particle in the field will give rise to a Doppler shift in the frequency of the scattered light proportional to the velocity of the particle. In the zetasizer, the zeta potential of the particles is estimated by the size of the Doppler shift.

The intensity of the scattered light is determined by particle size and concentration, the wavelength of light, the angle between the direction of the observed light and the incidence light, the difference in refractive indexes between particles and solution and the intensity of the incidence light.

In the zetasizer the non-particle dependent variables are fixed.

The primary quantity for the measurement is the electrophoretic mobility:

$$u = \frac{V}{E} \quad (1)$$

V = velocity ms^{-1}

E = electrical field strength, Vm^{-1}

which, if the particles have a sufficient size compared to the thickness of the diffuse layer of ions surrounding them, can be converted to zeta potential (ζ) according to

$$\zeta = \frac{\eta u}{\epsilon} \quad (2)$$

η = viscosity for the liquid, Ns m^{-2}

ϵ = dielectrical constant for the liquid F m^{-2}

2.2 Kaolin

Purified kaolin was used to estimate the detection limit of the Malvern Zetasizer, (Washing procedure, see Appendix 1). The specific area of the kaolin was (BET/nitrogen) = $9.43 \pm 0.02 \text{ m}^2/\text{g}$.

The following measurements were done:

Kaolin mg/l	pH	ζ -potential	countrate
1000	6.54	-34.8	207
100	5.96	-31.1	83
10	5.99	- 1.11	3.8

From these results the detection limit was set to 100 mg/l.

At 10 mg/l the countrate is too low to be separated from the signal of the background electrolyte. The ζ -potential value near zero also indicates that the signal mainly comes from noise.

2.3 Adsorption of Fe³⁺ on kaolin

When Fe(III)-ions are adsorbed on kaolin the ζ -potential changes towards more positive values. An investigation has been performed on the smallest contents of iron which will give detectable changes for the ζ -potential in the range $3 < \text{pH} < 7$. The results are presented in Figure 1 and they are valid for 100 mg kaolin/l. The experiments were carried out in such a way that the lowest added concentration of Fe(III)-ions was examined based on a surface area which at 100 mg/l is about $1 \text{ m}^2/\text{l}$ suspension. Such small total amounts of Fe(III) as $10 \text{ }\mu\text{mol}/\text{l}$ changes the ζ -potential markedly (rise 30 mV). A more complete investigation should of course be done with the aim to predict these kind of effects on basis of models for adsorption isotherms. One such model useful for mineral surfaces is presented below.

3 DETECTION LIMIT FOR DYNAMIC LIGHT SCATTERING

With the Institute's equipment for dynamic light scattering the particle size can be estimated by using the previously described principle for observation of the Brownian movement. The apparatus is furnished with a much stronger laser than the zetasizer, which promises a lower detection limit.

As for the zetasizer the composition of the reference water will determine the detection limit. We have used double filtrated water.

The countrate was determined as a function of kaolin content in the water. Every determination comprises 4-6 measurements on the same sample. On filtrated water, five different determinations with different water and cuvettes were carried out. The standard deviation is calculated from the five mean values.

Sample	Countrate · 10^{-3}	Standard deviation
Double filtrated water	0.13	0.02
100 $\mu\text{g}/\text{l}$ kaolin	0.28	0.03
1 mg/l kaolin	1.03	0.20
10 mg/l kaolin	11.2	0.9

The detection limit can be set to 100 $\mu\text{g}/\text{l}$.

4 ANALYSIS OF GROUNDWATER SAMPLES

4.1 General opinions

The original hope was that different groundwaters could be directly analysed with the zetasizer and that the pH of the isoelectrical point (iep) for colloids in groundwater could thereby be determined. It was found, however, that the colloid content in the groundwater is too low to permit measurement with the zetasizer without previously concentrating the sample.

Another expedition was the possibility to estimate the nature of the particles by using the zetasizer for detection of the isoelectric point. This possibility is limited, however, due to the possible presence of several different minerals with different iep and due to change in iep by specific adsorption.

In principle it should be possible to detect the occurrence of several particles with different ζ -potential. In practice the variation in size and refractive indexes is so dominating that discrimination based on ζ -potentials in mixtures is difficult.

The particle size can be determined by dynamic light scattering. The usefulness of this method for absolute measurements is restricted because the present theory is mainly applicable for particles <800 nm.

A particle size of about 2000 nm was estimated for groundwater sample KBS 345 from Kamlunge. The value is, however, uncertain due to the mentioned restriction in the theory.

The particle content can be determined by a semiquantitative method. The intensity of the scattered light from the particles is measured as a function of particle content. In this way a calibration curve (count-rate/particle content) can be produced. This is illustrated in Figure 2 for washed kaolinite as a reference substance. The content of particles in the groundwater can be estimated from these curves as "equivalent kaolinite units" = $K \cdot \text{count-rate}$ where $K = \text{slope for the line in Figure 2} = 0.95 \mu\text{g/l count-rate}$.

The problem is that one must know the particle content within the groundwater to obtain absolute results, since the light scattering is dependent also on particle size and refractive index. If the colloids in the groundwater is kaolinite with the same size distribution as the reference substance this technique can be applied. Filter analysis does, however, indicate that there is some clay in the groundwater.

The method could prove useful for the comparisons of various colloids.

4.2 Results of measurements on groundwater

The results from the measurements with dynamic light scattering is summarized below. The geographical locations from where the samples are taken are shown in Appendix 2.

Sample	Depth	Count-rate	Standard deviation	Samples taken from
Double filtrated water		129	17	-
Kaolin, 100 µg/l		283	27	-
Kaolin, 1 mg/l		1034	179	-
Kaolin, 10 mg/l		11160	931	-
KBS 471	514	316	28	Kamlunge
KBS 471		327	36	Kamlunge
KBS 339	445	137.5	12	Kamlunge
KBS 344	123	211	19	Kamlunge
KBS 345	123	209.5	10.5	Kamlunge
KBS 247	160	405	44	Svartboberget
E 1	360	182	18	Stripa
M 3	310	149	11	Stripa
V 21	969-1232	165	24	Stripa
V 22	960-968	110	7	Stripa
V 23	900-908	166.5	10.5	Stripa
V 24	812-820	144	23.5	Stripa

For countrate ≤ 283 corresponding to 100 µg/l the equivalent kaolinite amount can not be calculated, instead the sample is said to contain ≤ 100 µg/l.

For KBS 471 the equivalent kaolinite amount 305 µg/l is obtained. For KBS 247 this value is 385 µg/l. For the rest of the groundwater samples the equivalent kaolinite amount is ≤ 100 µg/l.

4.3 Analyses of the particulate material in deep groundwaters

Filtering procedures

The deep groundwater is pumped up from packed off sections of the boreholes through a plastic liner. The water samples are collected at the end of the line before the water has come into contact with the atmosphere. All the water samples are in-line filtered through a 0.45 micron filter.

For qualitative and quantitative determination of the particulate material in the groundwater a separate filtering technique is used. Instead of the normal in line filter, separate membrane filter holders are connected in series. These holders are equipped with 0.4, 0.2, 0.05 and 0.05 micron membrane filters respectively. If possible a volume of two litres is allowed to pass through the filters. The filter membranes are removed and sent for analyses.

X-ray fluorescence analyses

The contents of aluminum, iron, silicon, sulphur and calcium on the filters were determined by X-ray fluorescence. The samples were collected from different depths and the chemical composition of the water varied. There is no correlation between the amounts of the different components within the samples nor the distribution in size. It is not even possible to correlate the distribution of concentrations and size of the different elements to the composition of the water from which they have been filtered off.

Results from an experiment where oxygenated water was introduced into the reducing water in the rock showed that there was a drastic change in the composition and the concentration of particulate material after mixing, see Figure 3. In fact, the changes were greatest in the sulphur content, possibly due to an oxidation of sulphide to colloidal sulphur. There was also a great increase in the iron concentration while the aluminum content was fairly constant. These samples were from the borehole Fjällveden 2 at 468 m level.

5 ADSORPTION MEASUREMENTS

Due to the low concentration of colloids in groundwater it could be very difficult to detect the adsorption of different ions directly. It is, however, of interest to theoretical calculate the adsorption based on a model for adsorption, which can then be verified for more concentrated systems. A suitable model for ion adsorption on mineral surfaces has been developed by James and

Healy (1). According to this model the free energy of ion adsorption can be separated in 3 parts depending on the following:

- coulombic ion-ion-interaction
- changes in solvation at adsorption
- chemical interaction surface/ion

i.e.

$$\Delta G_{\text{ads}}^{\circ} = \Delta G_{\text{coul}}^{\circ} + \Delta G_{\text{solv}}^{\circ} + \Delta G_{\text{chem}}^{\circ} \quad (3)$$

Adsorption is calculated from $\Delta G_{\text{ads}}^{\circ}$ with Grahames equation

$$\Gamma_i = 2r_{\text{hyd}} \cdot C_o \cdot \exp\left(\frac{-\Delta G_{\text{ads}}^{\circ}}{RT}\right) \quad (4)$$

Γ_i = surface concentration, mol/m²

r_{hyd} = the hydrated ion radius, m

C_o = ion concentration in the solution, mol/m³

R = the gas constant = 8,314 J/K

T = temperature, K

This equation is based on the assumption that the adsorption sites are represented by cubes with the sidelength $2r_{\text{hyd}}$ in which the ions are re-bounded in a potential well with the depth $\Delta G_{\text{ads}}^{\circ}$. Immediately outside the well the ion has the same potential as in the solution, which is a rough approximation (Grahame (2)).

According to James and Healy for the ion i:

$$\Delta G_{\text{coul}_i}^{\circ} = z_i F \Delta \Psi_x \text{ joule mole}^{-1}$$

where

$$\Delta \Psi_x = \frac{2RT}{zF} \cdot \ln\left(\frac{(e^{zF\psi_o/2RT+1}) + (e^{zF\psi_o/2RT-1})e^{-kx}}{(e^{zF\psi_o/2RT+1}) - (e^{zF\psi_o/2RT-1})e^{-kx}}\right)$$

and

$$\begin{aligned} \psi_0 &= 2.3RT/zF(\text{pHpzc} - \text{pH}) \text{ volt} \\ k &= 0.328 \times 10^{10} (\text{I})^{\frac{1}{2}} \text{ m}^{-1} \\ x &= (r_{\text{ion}} + 2r_w) \text{ m} \\ z_i &= \text{the charge of the adsorbed ion} \\ z &= 1 \text{ (for 1:1 background electrolyte)} \end{aligned}$$

$$\begin{aligned} \Delta G_{\text{solv}_i}^{\circ} &= \left(\frac{z_i^2 e^2 N}{16\pi\epsilon_0} \right) \left(\frac{1}{r_{\text{ion}} + 2r_w} \right. \\ &- \frac{r_{\text{ion}}}{2(r_{\text{ion}} + 2r_w)^2} \left. \left(\frac{1}{\epsilon_{\text{int}}} - \frac{1}{\epsilon_{\text{bulk}}} \right) \right) \\ &+ \left(\frac{z_i^2 e^2 N}{32\pi\epsilon_0} \right) \left(\frac{1}{r_{\text{ion}} + 2r_w} \right) \left(\frac{1}{\epsilon_{\text{solid}}} - \frac{1}{\epsilon_{\text{int}}} \right) \\ &\quad \cdot \text{joule mole}^{-1}, \end{aligned}$$

using

$$\epsilon_{\text{int}} = \left(\frac{\epsilon_{\text{bulk}}^{-6}}{1 + (1.2 \times 10^{-17}) (\text{d}\psi/\text{d}x)_x^2} \right) + 6$$

and

$$\frac{\text{d}\psi}{\text{d}x} = -2k \frac{RT}{xF} \sinh \left(\frac{zF\Delta\psi_x}{2RT} \right) \text{ vm}^{-1},$$

ϵ = dielectricity constant

$\Delta G_{\text{chem}}^{\circ}$ values have to be experimentally determined.

There is a number of restrictions with James and Healy's adsorption theory:

It is only applicable to adsorption less than a monolayer.

It is only applicable to hydrolyzed ions and hydroxy complexes. It must be completed with adsorption measurements from which $\Delta G_{\text{chem}}^{\circ}$ may be calculated.

Calculation of the surface potential, ψ_0 , with Nernst' equation may give an erroneous value. In spite of these restrictions it may be interesting to theoretically study, with the help of an adsorption model, how the variation of different variables changes the adsorption.

Table 2 and Figures 4-9 show the changes in $\Delta G_{\text{ads}}^{\circ}$, $\Delta G_{\text{coul}}^{\circ}$ and $\Delta G_{\text{solv}}^{\circ}$ when different variables are changed. $\Delta G_{\text{chem}}^{\circ}$ is set to zero.

The following was chosen as basic conditions: The ion radius was set to 0.92 Ångström, this value represents roughly fourvalent actinoides. The ion charge was set to 1, which implies that the three hydroxy groups are bounded to the ion. The hydrated ion radius is 3.68 Ångström if one presumes that the ion only is surrounded by a primary waterlayer. Quartz was chosen as solid phase because the groundwater colloids are expected to contain quartz or have similar properties as quartz. Quartz has the dielectric constant 4.3 and zero point of charge 2.

A monovalent electrolyte at neutral pH with the ionic strength 10^{-3} M was chosen as waterphase. The temperature was set to 25°C, which gives the dielectricity constant 80.3 for the solution.

According to Table 1 and under the above mentioned conditions the following is obtained for the actinoid(IV) OH_3^+ ions:

$$\begin{aligned}\Delta G_{\text{ads}}^{\circ} &= - 8083 \text{ Jmole}^{-1} \cdot K = \exp \left(\frac{-\Delta G_{\text{ads}}^{\circ}}{RT} \right) \\ &= \exp \left(\frac{8083}{8.314 \cdot 293} \right) = 27.6\end{aligned}$$

So roughly the ions have about 30 times higher concentration in the surface layer than in the bulk solution.

The Grahame equation gives:

$$\Gamma_i = 2 \cdot 3.46 \cdot 10^{-10} \cdot C_{\text{bulk}} \cdot 27.6$$

which for a solution of $1 \cdot 10^{-2}$ mol m^{-3} gives

$$\Gamma_i = 2.9 \cdot 10^{-10} \text{ mol m}^{-2}$$

Table 2. Results obtained by using James and Healy's adsorption theory.

The basic condition

T = 293 K, $r_{ion} = 0.92 \text{ \AA}$, $r_{hydrated} = 3.68 \text{ \AA}$, $\epsilon_{bulk} = 80.3$,
 $\epsilon_{solids} = 4.3$, $z = 1$, $pzc = \text{point of zero charge-pH} = 2$, $I = 0.001$, $pH = 7$.

	ΔG_{coul}°	ΔG_{solv}°	ΔG_{ads}°
Basic condition	-18538	10455	- 8083
I = 0.01	-13455	10470	- 2966
I = 0.00001	-25726	10401	-15325
I = 0.01 pH = 2	0	10388	10388
I = 0.001 "-	0	10388	10388
I = 0.00001 "-	0	10388	10388
$\epsilon = 2$	-18538	23077	4539
$\epsilon = 10$	-18538	4198	-14339
$\epsilon = 20$	-18538	1838	-16698
pH = 3	- 5347	10388	5041
pH = 5	-14519	10401	- 4118
pH = 10	-19263	10478	- 8785
pzc = 4	-14519	10401	- 4118
pzc = 6	- 5347	10388	5041
pzc = 9	10366	10390	20757
$r_{ion} = 0.5 \text{ E-10}$	-19039	11831	- 7208
$r_{ion} = 1.5 \text{ E-10}$	-17920	9013	- 8908
$r_{ion} = 3.68 \text{ E-10}$	-16120	5944	-10176
charge = -3	55613	94094	147707
charge = -2	37075	41820	78895
charge = -1	18538	10455	28992
charge = 0	0	0	0
charge = 1	-18538	10455	- 8083
charge = 2	-37075	41820	4744
charge = 3	-55613	94093	38481

If the dielectrical constant of the solid phase increases, then the $\Delta G_{\text{ads}}^{\circ}$ value goes to $-18.500 \text{ Jmole}^{-1}$, see Figure 7, which gives a value of $K = 1987 \approx 2000$, and

$$\Gamma_i = 1.4 \cdot 10^{-8} \text{ mol m}^{-2}.$$

In these calculations the $\Delta G_{\text{chem}}^{\circ}$ has been neglected. If for example, the $\Delta G_{\text{chem}}^{\circ}$ is the same as for iron adsorption on quartz, -36 kJoule/mole then adsorption will increase 2.6 million times, according to this theory.

In Figure 4a the ionic strength is varied at $\text{pH} = 7$. $\Delta G_{\text{ads}}^{\circ}$ decreases with decreasing ionic strength.

In Figure 4b the ionic strength varied is at $\text{pH} = 2$. The adsorption is not affected by the ionic strength.

In Figure 5 the solid substance dielectricity constant is varied. The adsorption increases with increasing dielectricity constant.

In Figure 6 the pH is varied. The adsorption increases with increasing pH .

In Figure 7 the point of zero charge is varied for the solid substance. The adsorption increases with decreasing point of zero charge.

In Figure 8 the radius is varied. The adsorption is slightly increased when the radius increases.

In Figure 9 the charge is varied. An adsorption maxima is achieved for the ionic charge equal to $+1$.

6 DISCUSSION AND RESULT

In the KBS-3 report a groundwater colloid content of $500 \mu\text{g/l}$ was assumed. According to the measurements presented here there is no reason to decrease this content. To use the zetasizer it is necessary to concentrate the groundwater between 200 and 1000 times. One problem with concentrating the samples is the risk of coagulation colloids, and thereby change their properties. There are several alternative methods to characterize the groundwater colloids. One method is analysis of filter, which has been applied in the KBS groundwater chemistry program. The following elements were analysed Al, Si, S, Ca, Mn and Fe on filters through which groundwater was filtered. The filter size was varied between 0.45μ and 0.05μ . Nucleopore filters were used. By summarizing the amounts of the elements Al, Si, S in about 60 samples the following re-

sults were obtained: 510 μg Al, 255 μg Si, 393 μg S. This corresponds to 18.9 μmole Al, 9.1 μmole Si and 12.3 μmole S. The hypothesis is that the aluminum and silica comes from clays and the sulphur from iron sulphide. Iron occurs in great amounts in the filter analysis, probably originating from iron hydroxides and iron sulphide. The iron hydroxides are probably created by oxidation during sampling.

The relationship between Al and Si is $18.9/9.1 = 2.1 \approx 2$.

Kaolin has the formula $\text{Al}_4\text{Si}_4\text{O}_{10}(\text{OH})_8$, ref (3) and the Al/Si ratio is therefore not satisfied. The reason for using kaolin as a reference substance is that we have been working with this clay in a lot of other applications at the institute. Probably different clays occur in the groundwater. Silica could also come from quartz, SiO_2 .

The importance of characterizing the clays present is illustrated by the fact that montmorillonite has a BET-area of 800 m^2/g , illite 80 m^2/g and kaolinite 10 m^2/g , ref (4).

The detection limit for dynamic light scattering was determined to 100 $\mu\text{g}/\text{l}$.

Using a semiquantitative determination of particle concentrations in groundwater less than 100 $\mu\text{g}/\text{l}$ were found in 9 of the samples and 305 and 385 $\mu\text{g}/\text{l}$ in two of the samples.

In order to calculate the adsorption of ions on groundwater colloids with the James and Healy's theory the following must be known:

- 1) The water phase content of adsorbing ions, ionic strength and pH.
- 2) The point of solid charge for the solids and their dielectric constants.
- 3) $\Delta G_{\text{chem}}^{\circ}$

To decide on the content of ions in the water phase one should first know the content of ions in natural groundwater and then add the anticipated amount of released radionuclides.

To evaluate the point of zero charge and the dielectrical constant one must know the size distribution of the groundwater colloids.

To determine $\Delta G_{\text{chem}}^{\circ}$ one has to carry out experimental studies.

Actinoid(IV) OH_3^+ -complexes should according to the theory adsorb on quartz at neutral pH. The restriction on the adsorption measurements is that $\Delta G_{\text{chem}}^{\circ}$ is also dependent on the parameters used.

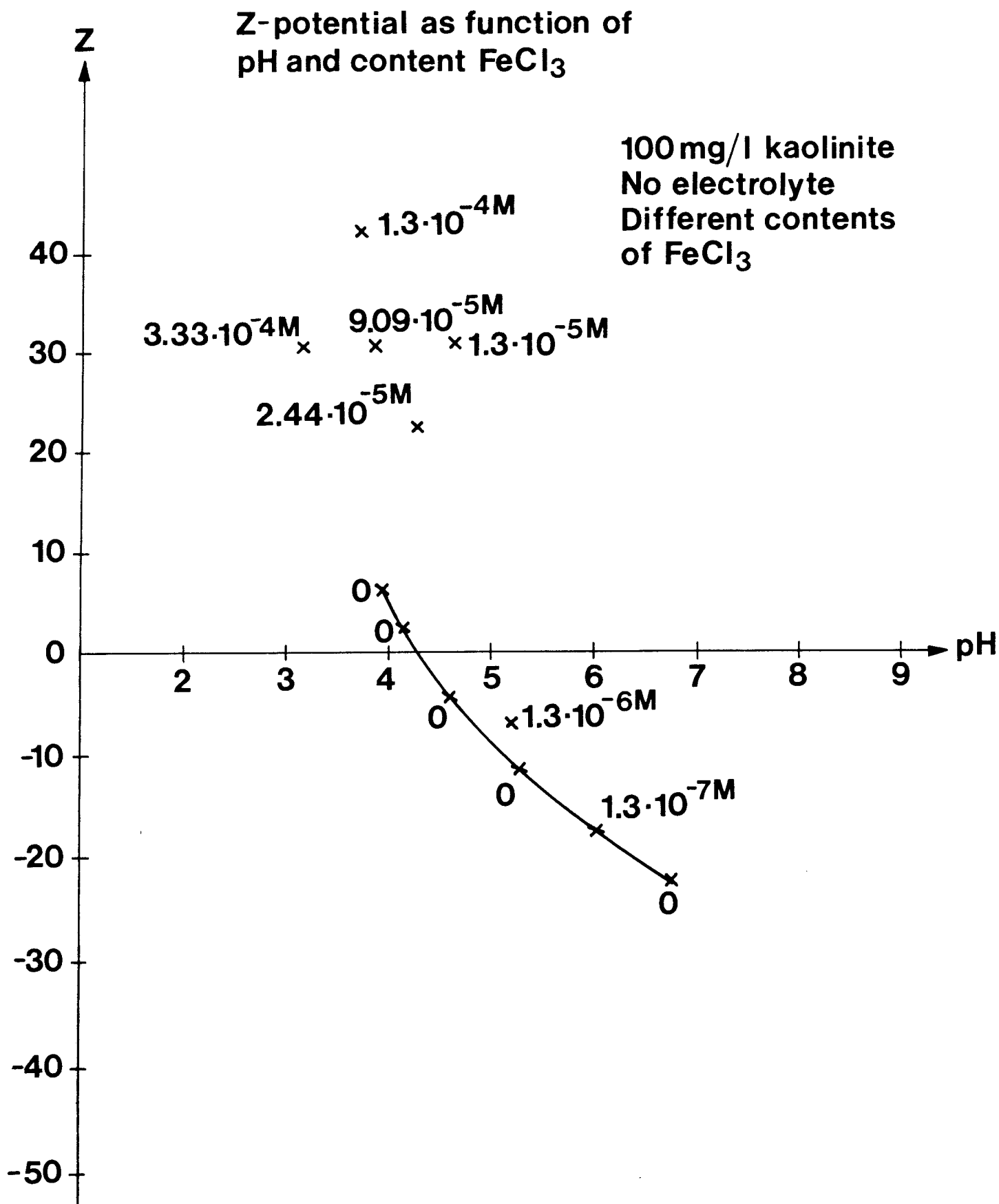
ACKNOWLEDGEMENTS

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Figure 1



**Dynamic light scattering
Countrate versus content
of kaolinite**

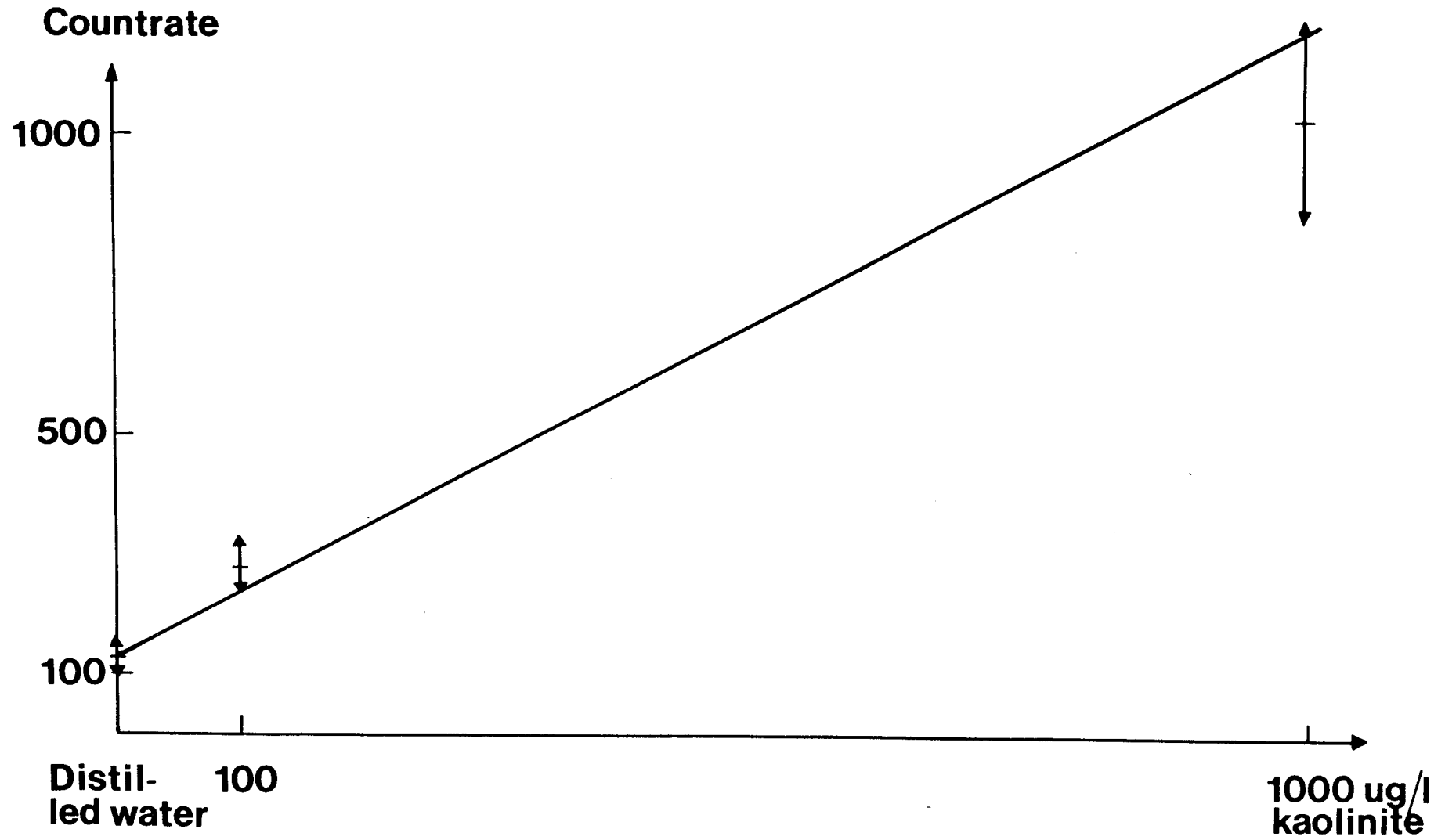
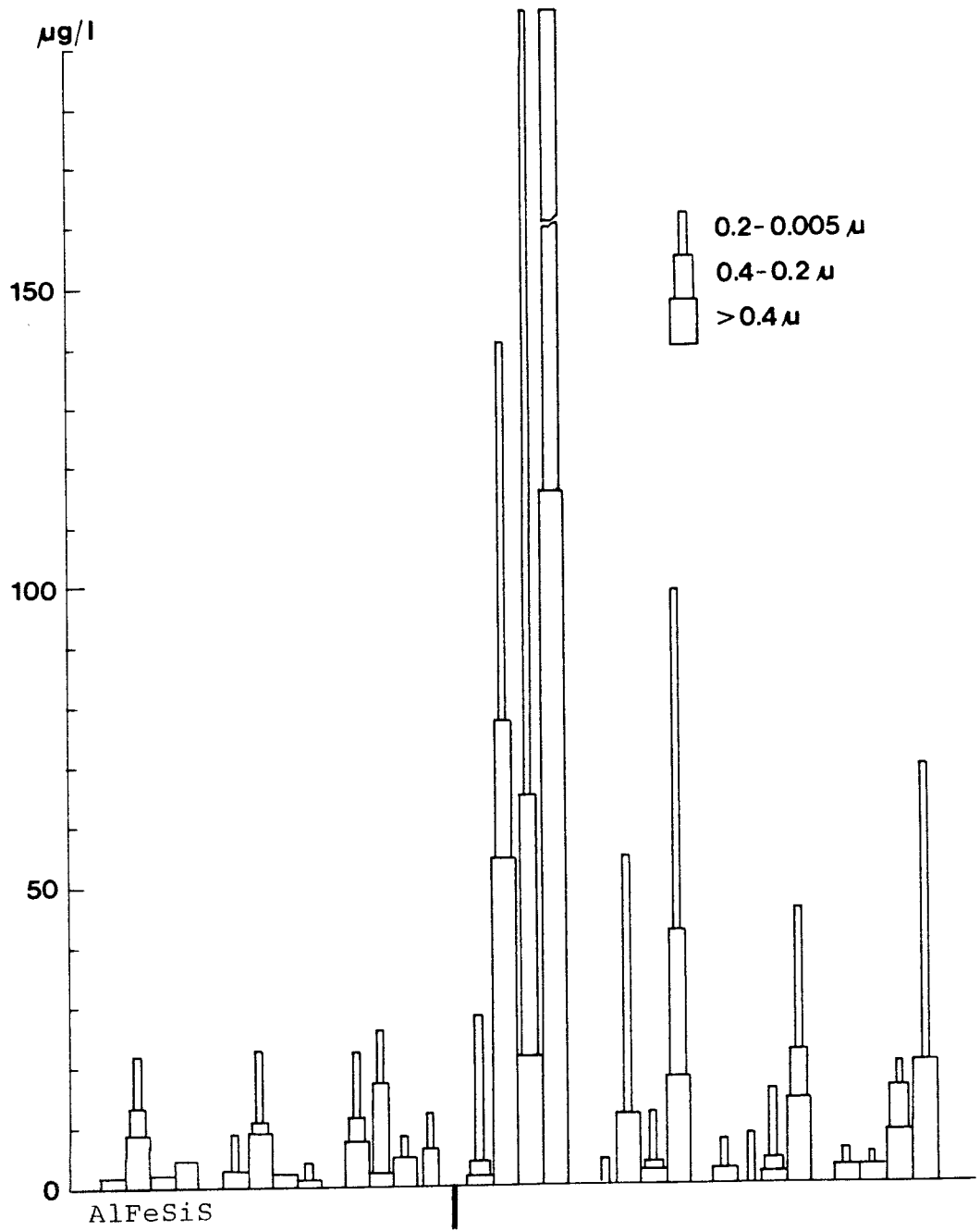


Figure 3



before mixing

after mixing

Theoretical adsorption energies

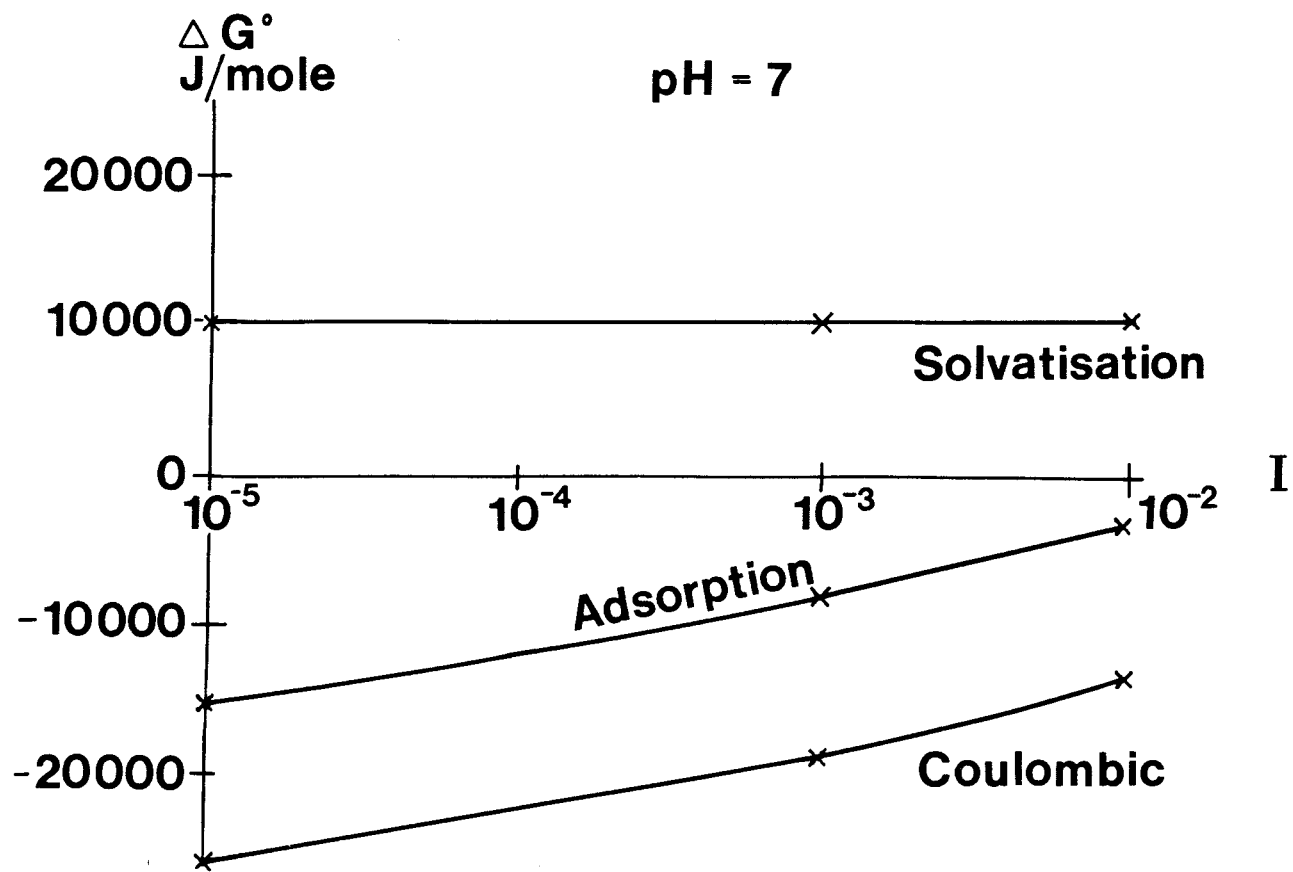


Figure 4b

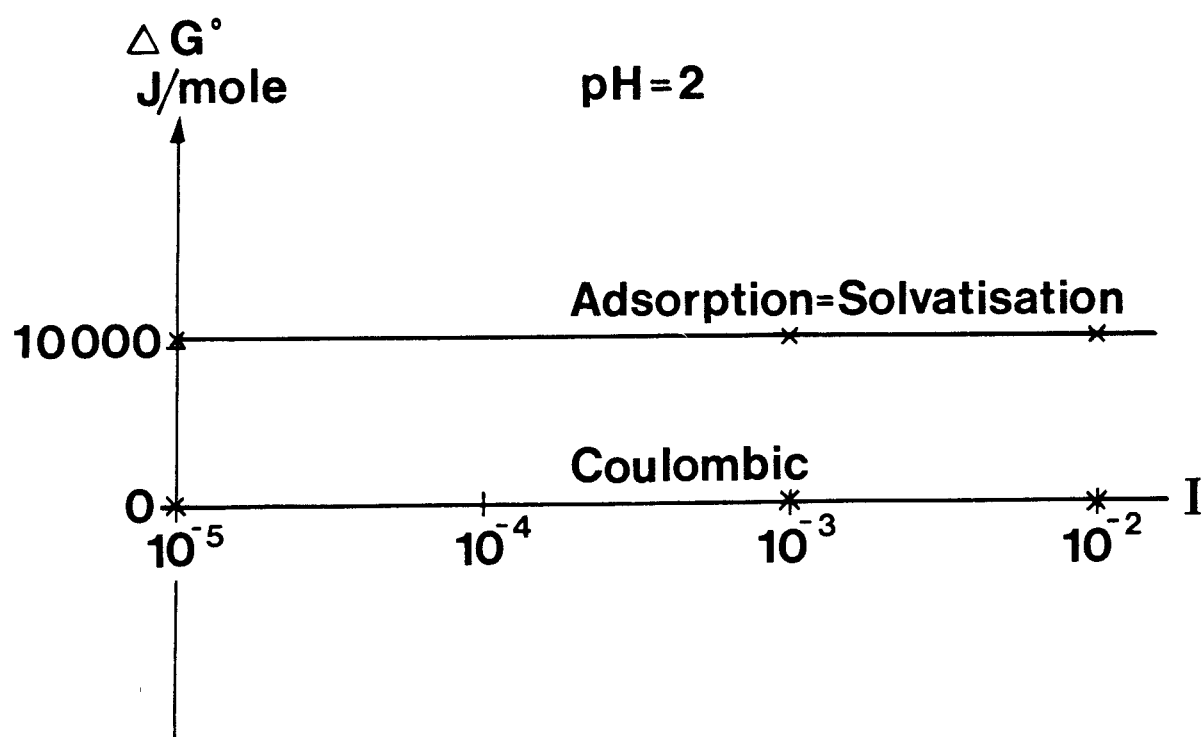


Figure 5

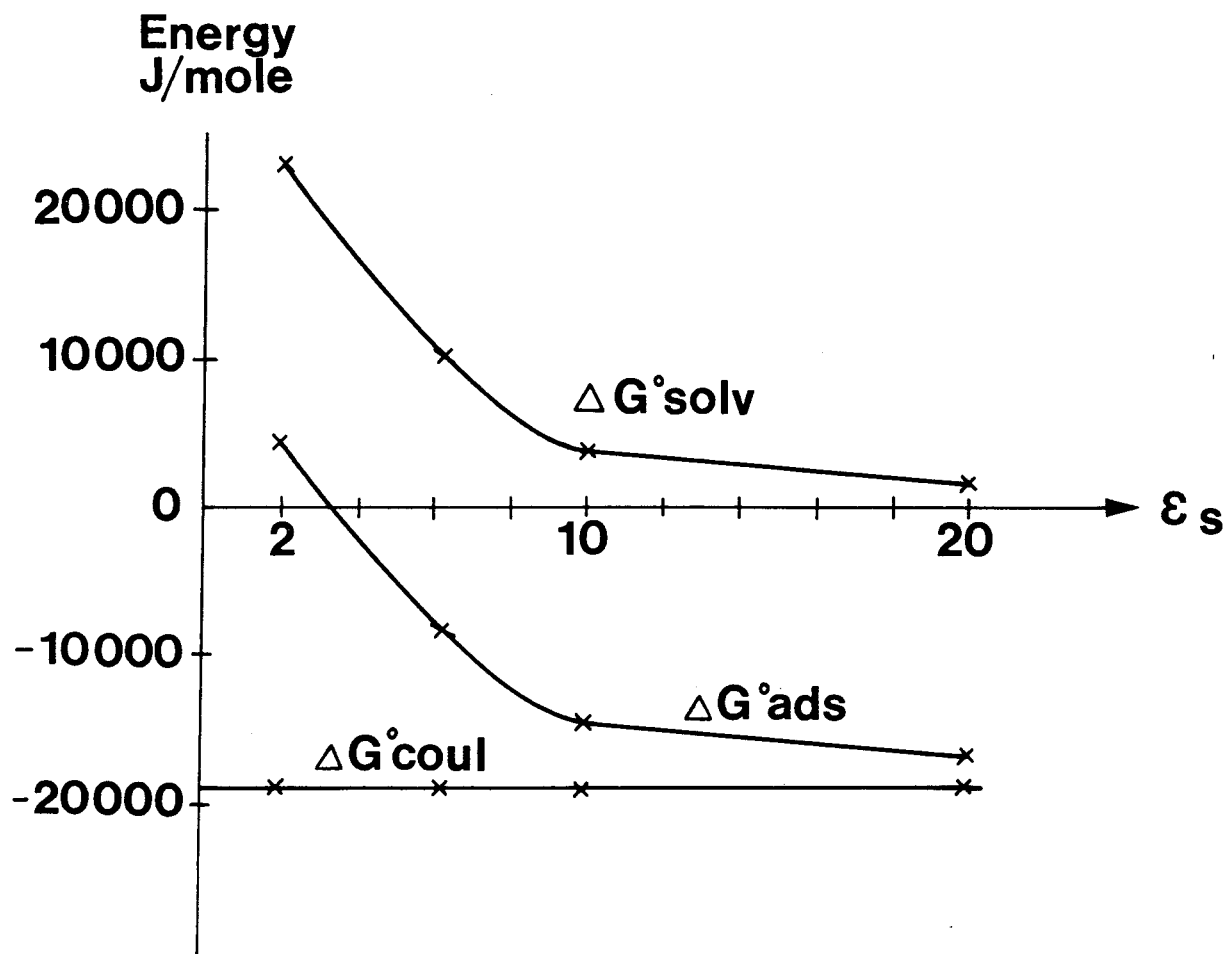


Figure 6

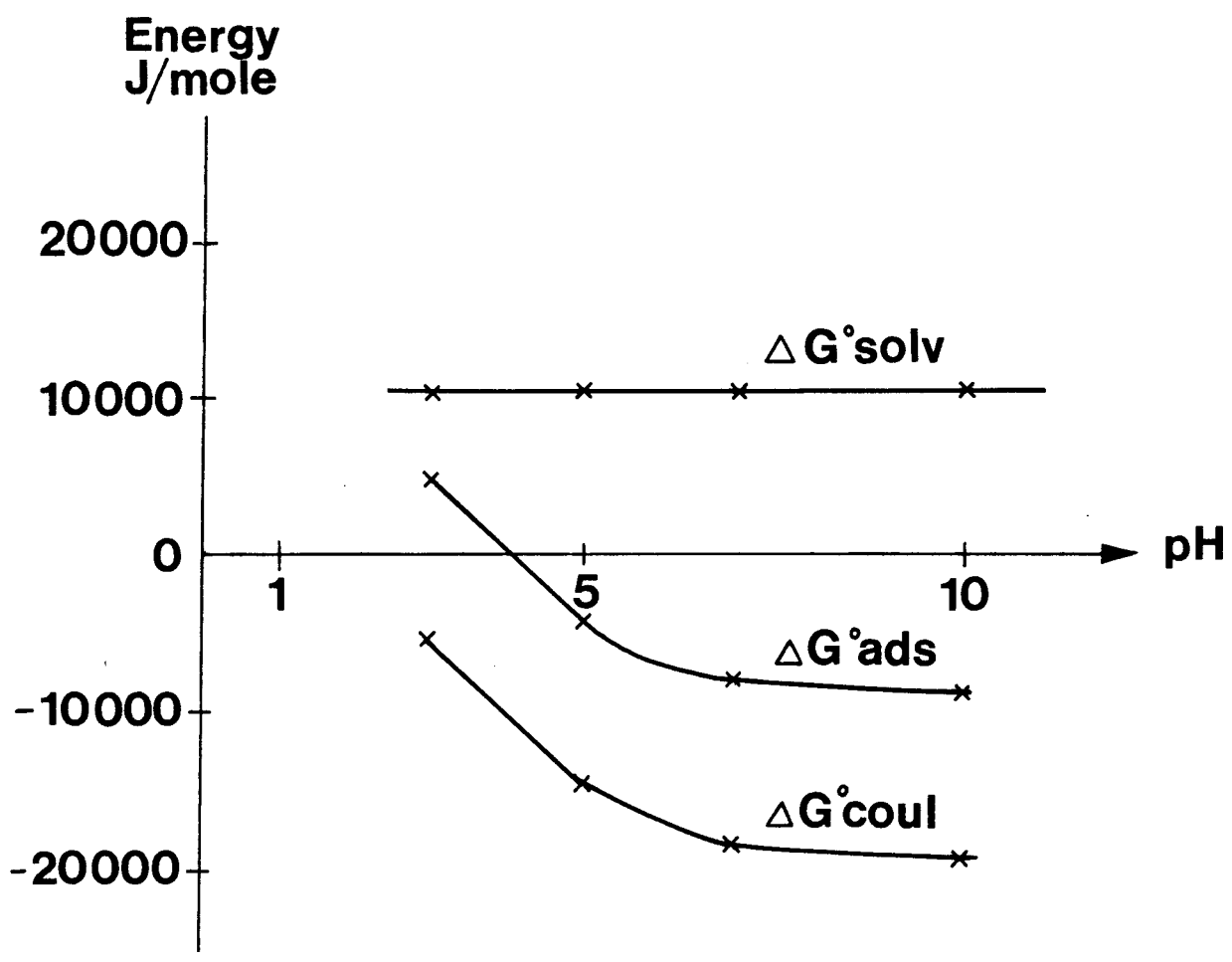


Figure 7

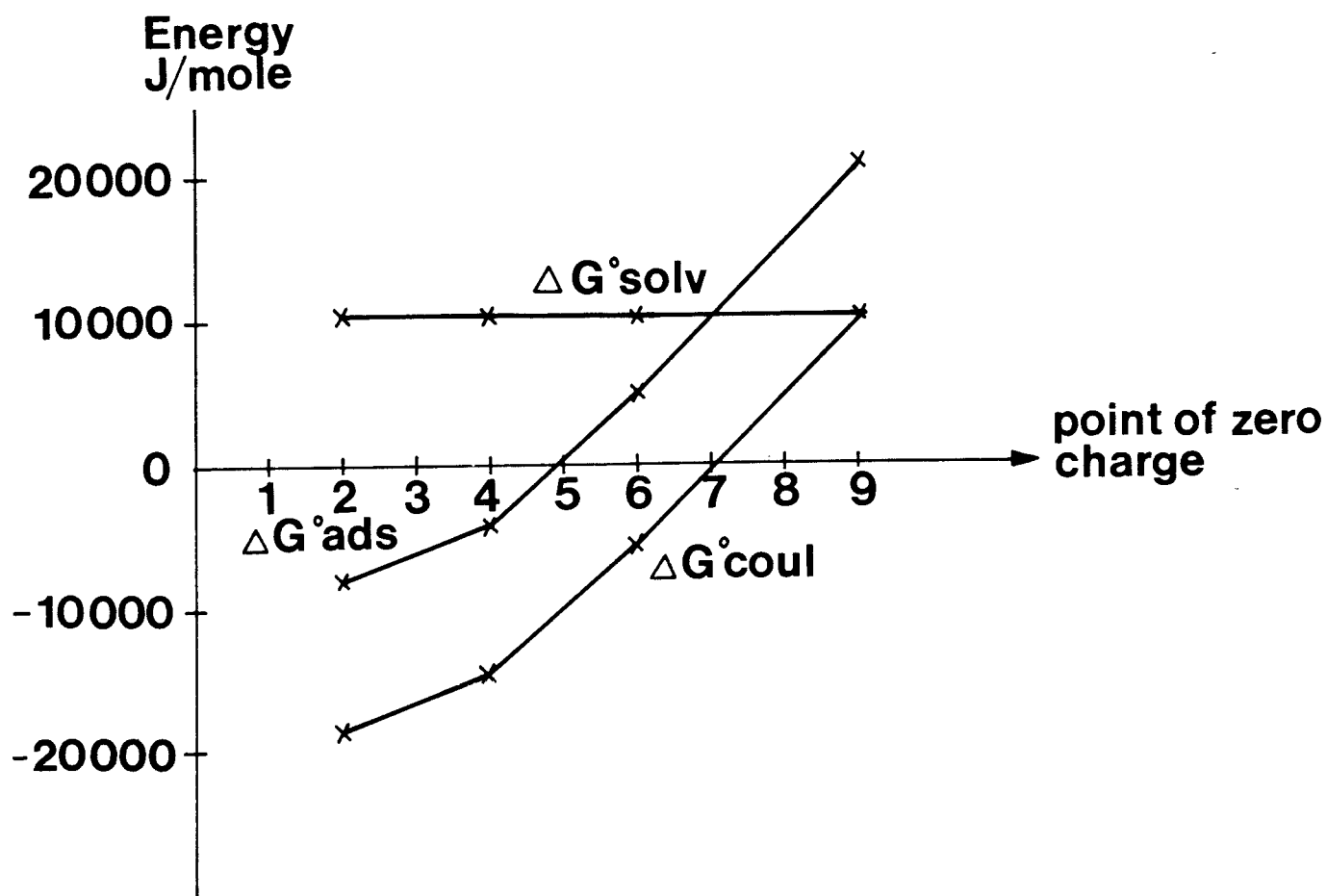


Figure 8

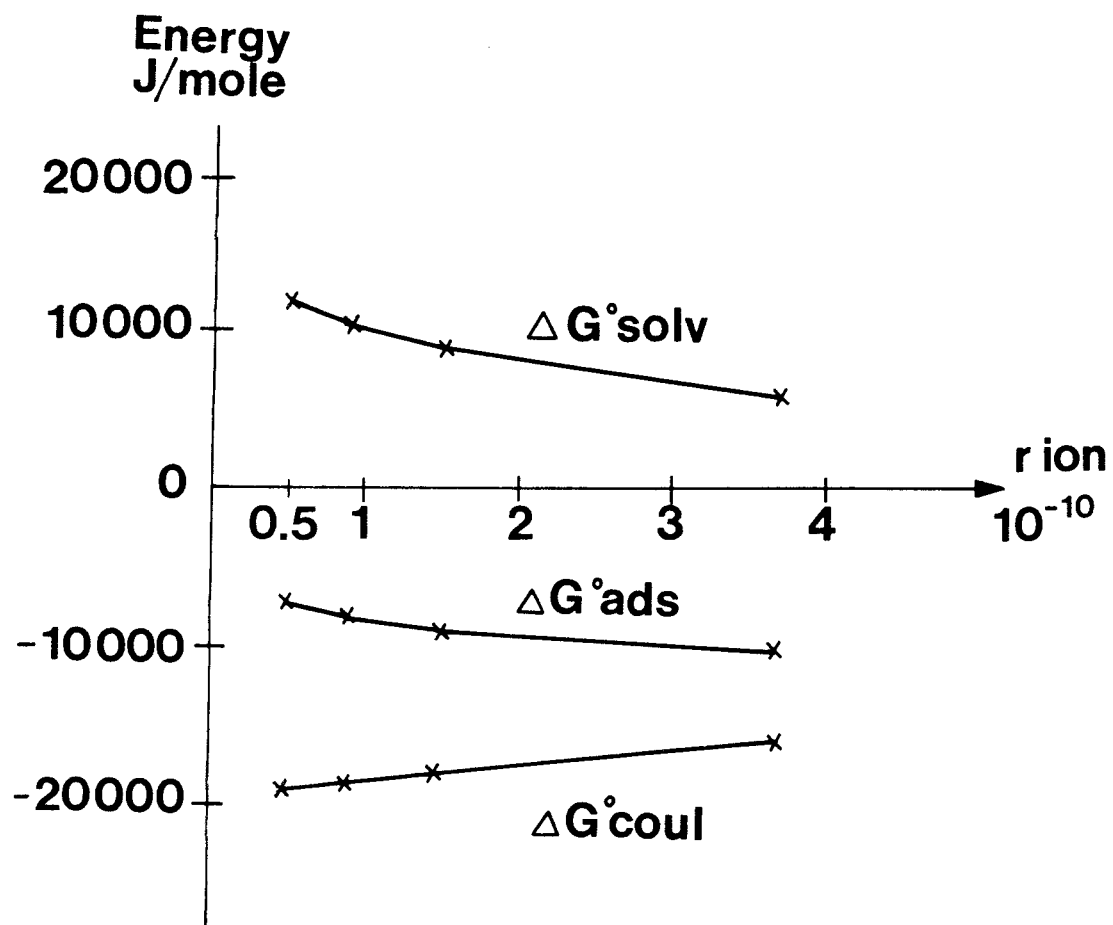
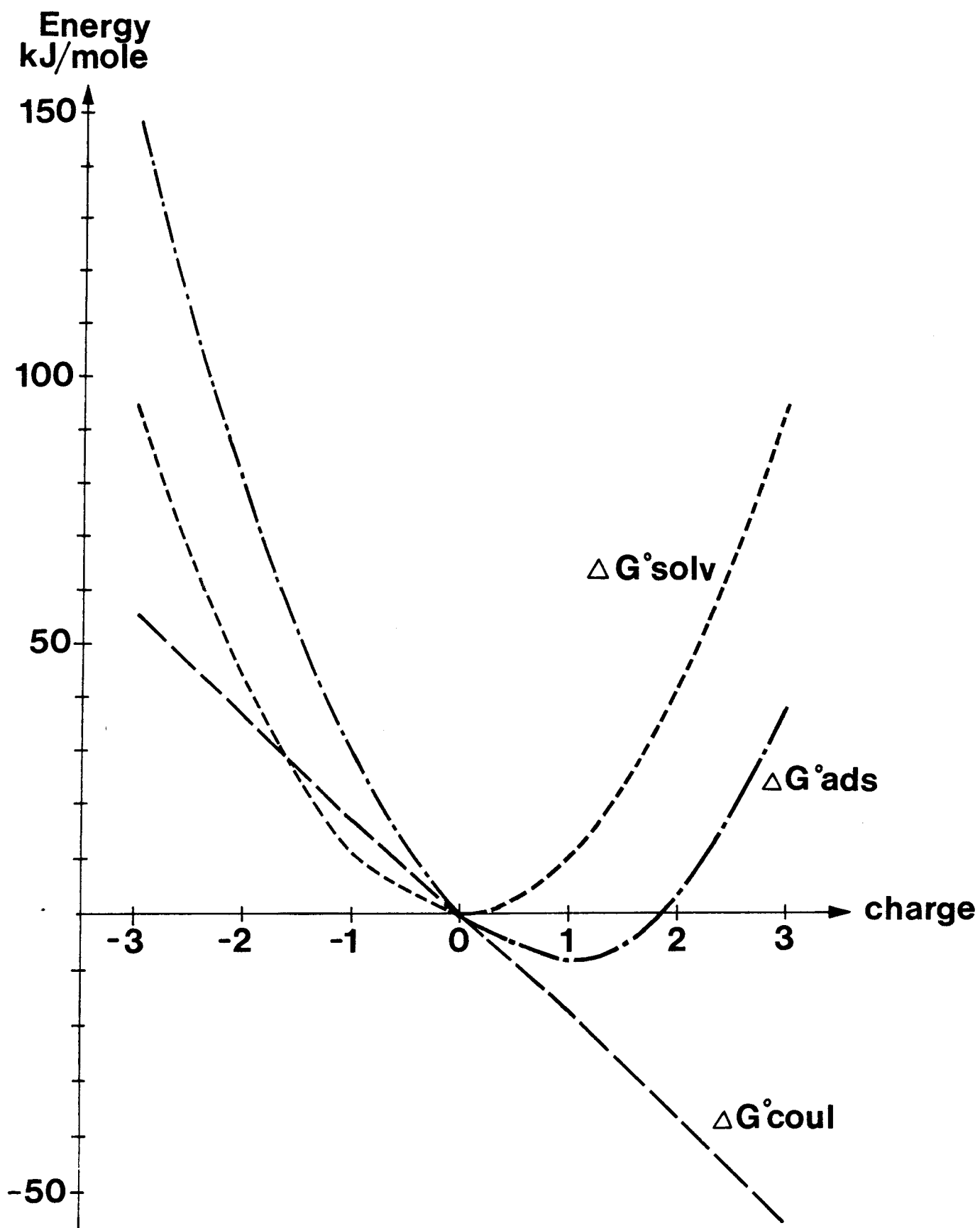


Figure 9



Appendix 2

Stripa

Samples were taken from the three boreholes M3, V2 and E1 in the Stripa mine. M3 and V2 are vertical, E1 is horizontal.

M3 starts at a depth of 310 m. Samples were taken 15 m down.

V2 starts at a depth of 410 m. Four samples were taken from this borehole.

V2:1 Depth 559-822

V2:2 Depth 550-558

V2:3 Depth 490-498

V2:4 Depth 402-410

E1 starts at a depth of 360 m.

Kamlunge

KBS 339 445 m depth

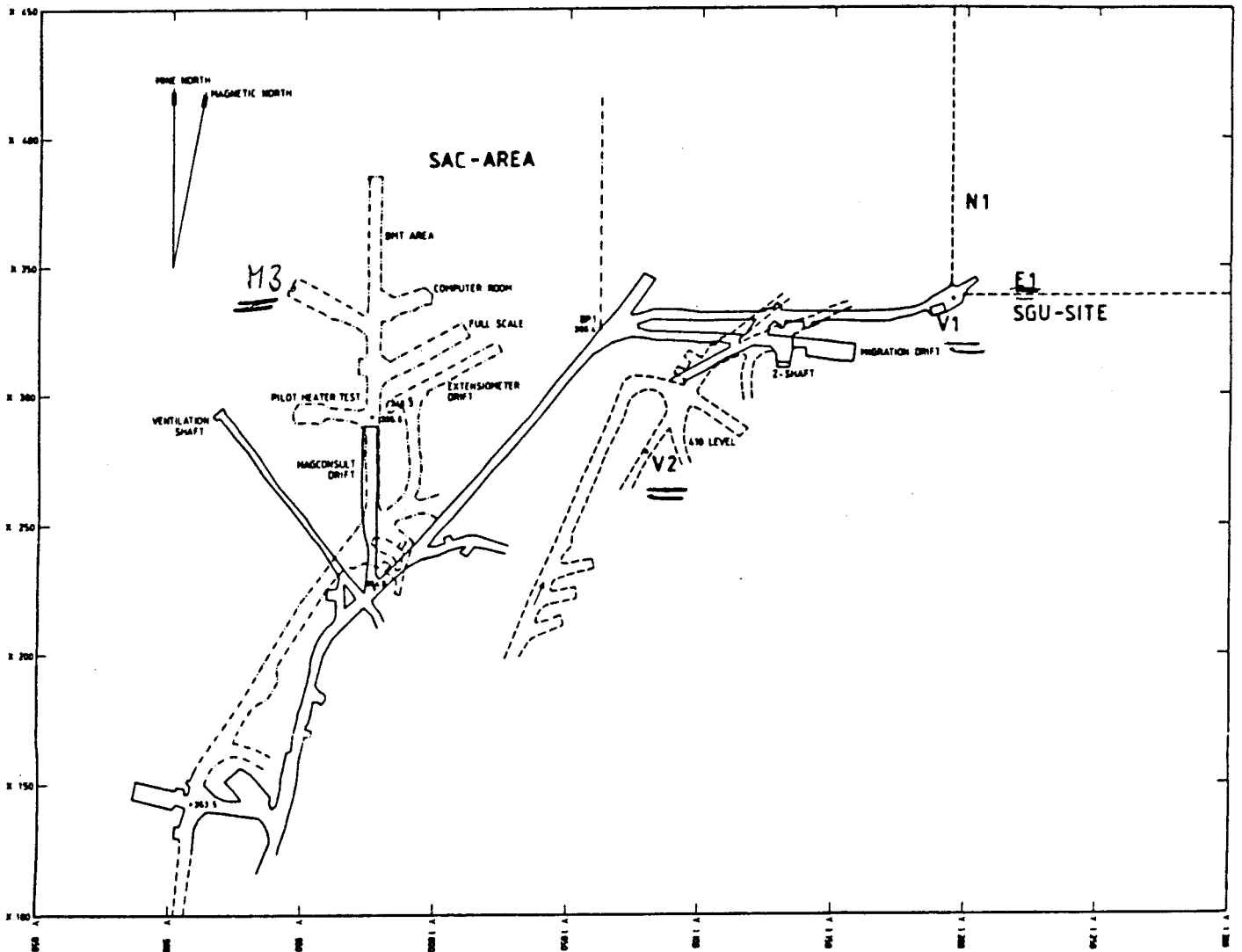
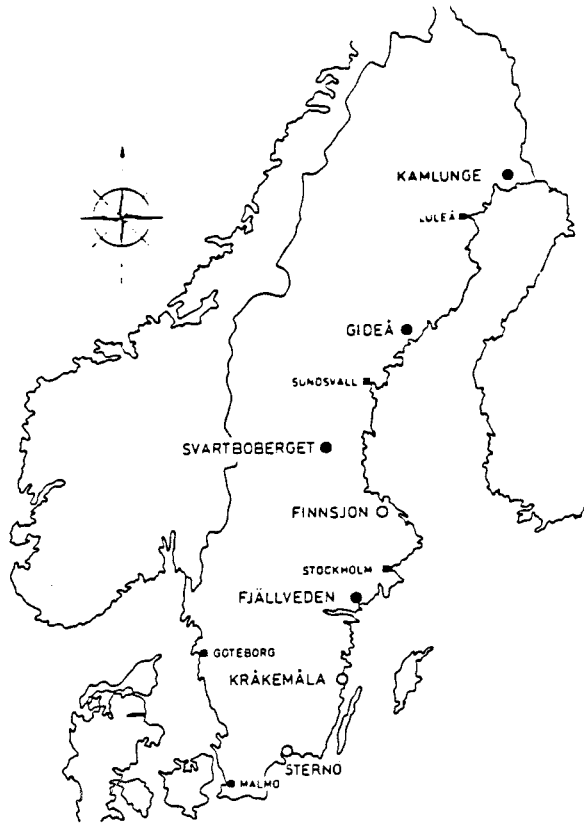
KBS 344 123 "-

KBS 345 123 "-

KBS 471 514 "-

Svartboberget

KBS 247 160 m depth



The investigations areas in the Stripa Mine with the boreholes used in the hydrogeological program.

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Radar measurements performed at the Klipperås study site

Seje Carlsten, Olle Olsson, Stefan Sehlstedt,
Leif Stenberg
Swedish Geological Co, Uppsala/Luleå
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Roy Forsyth
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Calculations on HYDROCOIN level 1 using the GWHRT flow model

Case 1 Transient flow of water from a
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aquifer

Case 3 Saturated-unsaturated flow
through a layered sequence of
sedimentary rocks

Case 4 Transient thermal convection in a
saturated medium

Roger Thunvik, Royal Institute of Technology,
Stockholm
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TR 87-04

Calculations on HYDROCOIN level 2, case 1 using the GWHRT flow model Thermal convection and conduction around a field heat transfer experiment

Roger Thunvik
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TR 87-05

Applications of stochastic models to solute transport in fractured rocks

Lynn W Gelhar
Massachusetts Institute of Technology
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TR 87-06

Some properties of a channeling model of fracture flow

Y W Tsang, C F Tsang, I Neretnieks
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