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Bachelor's Thesis

Experimente zur Untersuchung von Konvektion von Salzwasser in porösen Medien

Experiments for the investigation of convection of salt water in porous media

prepared by

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Abstract

In Salzwüsten lassen sich an der Oberfläche in der Salzkruste polygonale Strukturen erkennen. Die Vermutung ist, dass Konvektion von Salzwasser unterhalb der Kruste für dieses Muster verantwortlich ist.

Um eine Idee davon zu bekommen, wie die Dynamik des Salzwassers aussieht und mit der Krustenbildung zusammenhängt wurden für diese Arbeit experimentelle 3D-Modelle verwendet.

An diesen Experimenten wurden verschiedene Messungen durchgeführt. Die Verdunstungsraten wurden gemessen, die Bildung von Krusten konnte beobachtet werden, durch Färbung des einlaufenden Wassers wurde die Dynamik des Wassers sichtbar gemacht und die Salzkonzentration an verschiedenen Stellen im Experiment wurde bestimmt.

Mit diesen Messungen ließ sich zurückschließen, dass in den Experimenten Konvektion aufgrund von Dichteunterschieden (wegen der unterschiedlichen Salzkonzentrationen) stattfindet und die Struktur der Kruste beeinflusst.

Abstract

Salt crusts at the surface of salt deserts have a specific polygonal structures. Those structures probably form due to convection of the salt water below the surface.

To get an idea how the dynamics of the salt water are and how they influence the structure of the salt crust experimental 3D models of salt deserts were used for this thesis.

With these experiments several different measurements were performed. The evaporation rates were measured, the forming of crusts was observed, with coloring the incoming water the dynamics of it were made visible and the salt concentration of the water in the sand in different parts of the models was measured.

With those results it was found that there is convection due to density differences (because of different salt concentrations) and that the convection influences the structure of the salt crust.

Contents

1. Introduction

The picture below shows the Bonneville Salt Flats in Utah. It is a salt desert or salt pan. Other salt deserts can be found in Namibia, Death Valley, USA or the largest one is in Bolivia. Salt deserts occur in areas, where evaporation exceeds precipitation, so in particular arid regions.
Characteristic for these salt deserts is that salt accumulates at the surface and crystallizes into a salt crust at the surface with a polygonal pattern, which can also be seen in the picture.

Figure 1.1.: Bonnneville Salt Flats in Utah (source: nhmu.utah.edu)

Even though the salts accumulate at the surface, the reason for these patterns to form is probably the dynamics of the groundwater below the surface. The theory is that convection happens and has an direct influence on the formation of the crust.

The main subject of this thesis are experimental 3D models to help to understand the dynamics of salt water in salt and how it influences crust formation.
At first the theoretical principles for fluid flow through porous media and groundwater flow of salt water are described. The setup for the model and the idea behind it are explained.
The different measurements on the experimental models include measuring the evaporation rate, coloring the incoming water, observing that water at the surface, as well as dissecting the experiment into layers and taking samples to measure the salt concentration in different parts. Moreover crusts that formed were observed.
The results of these measurements are discussed and compared.
Moreover an experiment to measure permeabilities of different sands was performed.

2. Theoretical principals

2.1. Darcy's Law

Darcy's law describes how fast fluids flow through a porous medium. It gives the volume flow rate per unit area q ($[q] = \frac{\mathrm{m}}{\mathrm{s}}$) and depends on the permeability κ of the medium, the pressure gradient ∇p inside the medium and the viscosity of the fluid μ

$$q = -\frac{\kappa}{\mu}\nabla p. \tag{2.1}$$

2.2. Definition permeability

The permeability κ is a property of porous media and describes how fast fluids can flow through it.
With Darcy's law and assuming the fluid flows only in one direction the permeability of a porous medium can be described as

$$\kappa = \frac{-q\mu}{\frac{dP}{dx}} \tag{2.2}$$

with $[\kappa] = m^2$. It should ne noted that the permeability is a property of the traversed medium and therefore does not depend on the fluid. That is given, since $q \cdot \mu$ is constant.

2.3. Salt deserts

Salt deserts are mostly found in arid regions. They form when the evaporation rate is locally higher than precipitation rate.
Even when the groundwater table is shallow, so that it does not reach the surface, fresh water gets to the surface due to capillary effects.

At the surface the water evaporates and leaves salt behind, which increases the salinity in near surface regions and eventually accumulates at the surface.
The evaporation causes an upflow of the groundwater. At the same time diffusion wants to compensate the built concentration gradient. In general salt transport due to diffusion is much slower than transport by fluid flow. That can be indicated by the Péclet number $Pe = \frac{advection}{diffusion} = \frac{Lu}{D}$ (L characteristic length, u characteristic velocity, D mass diffusion coefficient).
Therefore there is a steep salt concentration gradient near the surface which means there is a steep density gradient. The gradient is only significant in a boundary layer near the surface. That layer can be either stable or unstable. Instability leads to convection of the dense saline water back into the ground. In the stable case it remains near the surface.

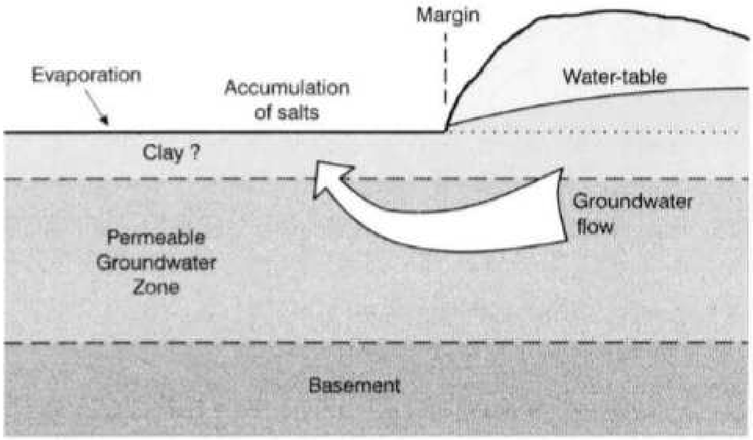

Figure 2.1.: Cross section of a saline lake [1]

2.3.1. Saline boundary layer

The thickness of the saline boundary layer described in section ?? depends on the evaporation rate and the diffusivity of the salt in water and is therefore given by [1]

$$\delta = \frac{D}{\epsilon} \ . \tag{2.3}$$

Higher diffusivity means, that the salt diffuses faster downwards, which leads to a thicker layer with a steep salt concentration rate. With a higher evaporation rate the boundary layer gets thinner, since the salt concentration near the surface increases faster.

2.3.2. Groundwater flow

To quantify the dynamics of the saline groundwater equations for the motion of the salt and the water are required.

In general the continuity of mass gives with the flow velocity $\vec{v}$ and the density ρ:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{2.4}$$

According to [2] the continuity of mass of the saline fluid can be described with

$$\Phi \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{q}) = 0 \tag{2.5}$$

where Φ is the porosity of the subsurface areas and is assumed to be constant and where q is the volume flow rate per unit area, which is also used in Darcy's law.

The conservation of mass for the dissolved salt is

$$\Phi \frac{\partial \rho f_s}{\partial t} + \nabla \cdot (\rho f_s \vec{q} - D \rho \nabla f_s) = 0 \tag{2.6}$$

in which f_s is the fraction of mass that is salt in the solute [2]. D is the diffusion coefficient. This equation shows the competing nature of advection and diffusion.

Adding a gravity term to Darcy's law gives

$$\frac{\mu}{\kappa} + \nabla p - \rho g = 0 \tag{2.7}$$

Lastly it should be noted that the density is a function of the salt mass fraction f_s. In [2] the function is given with ρ_w as the density of fresh, saltless water and a constant $\gamma = 0.6923$ by

$$\rho = \rho_w e^{\gamma f_s} \tag{2.8}$$

With equations (3), (4), (5) and (6) the dynamics of the saline water are fully described. Boundary conditions for the surface and the edges of the saline lake are needed. Because of the strong coupling of the equations through the great impact of the density ρ in all of them solutions are not trivial. Assumptions and simplifications are needed to make to find solutions.

3. Experimental approach

3.1. Permeability measurements of sand

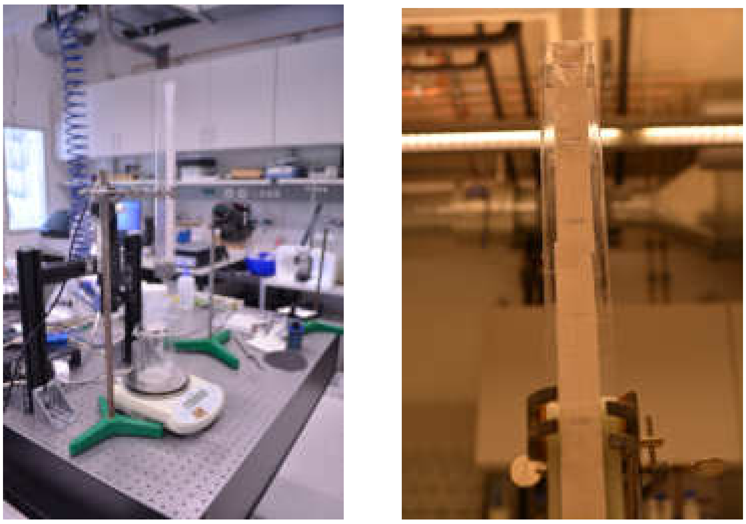

Figure 3.1.: Setup of the experiment to measure permeabilities

A tube with a square base ($A = 2.9\text{cm} \times 2.9\text{cm}$) was filled with the sand whose permeability should be measured. The height of the sand in the tube was 20cm. Then water was filled into the tube until the sand was saturated and there was a water column of additional 20cm height. On the bottom end the tube was sealed with a piece a fabric, which held back the sand, but the water could easily flow through it. Therefore its impact on the flow rate is negligible.

The tube was fixed, so that it hung above a beaker which stood on a balance. With the balance connected to a computer the mass of the permeated water was measured every 0.4s.

3.2. Setup 3D models

Each experiment set up consists of two same sized boxes with a footprint of 32cm × 38cm. One of them is used as a water reservoir, the other one is the model. Via tubes the reservoir is connected to the second box, the water can flow in from holes on the bottom of the box. For some experiments four inlets were used, for some eight were used. The position of the inlets is shown in fig. 3.2.

The first layer of sand is quartz sand, which consists of beads with diameters of 0.4mm to 0.8mm. The idea is, that the water can flow free in this layer and an even distribution of water is therefore given. On top of that there is the actual sand sample, which has much smaller bead diameters (Table 3.1).

The surface of the water in the reservoir should be at a height of just a few centimeter below the sand surface, so that fresh water is pumped into the sand up to that height due to pressure difference. The zone up to that height should represents the permeable groundwater zone shown in fig. 1. The water gets sucked up to the surface due to capillary forces.

All in all six different experiments were performed. The setup was slightly changed for every experiment. A fan and lamp were put up to change the evaporation rates in some experiments. The fan was put up so that it blew a few centimeters above the surface of the model. The lamp used was hung in the middle of the experiment about 40 cm above the surface, it has a power of 500W.

	exp.1	exp.2	exp.3	exp. 4	exp.5
inlets	4	4	4	8	8
grain size [μm]	70-110	150-250	200-300	100-200	100-200
salt conc. [ppt]		130	130	130	130
height qsand [cm]	4	4	4	6	6
height sand [cm]		10	10	9	9
height box [cm]	30	18.5	18.5	18.5	18.5
fan	-	yes	after 7 days	after 5 days	yes
heat lamp	-	-	-	-	yes
dying (after... days)	-	49 and 51	43	8 and 13	2 and 7
layers (after... days)	-	52	-	14	8

Table 3.1.: Characteristics of different setups of 3D models

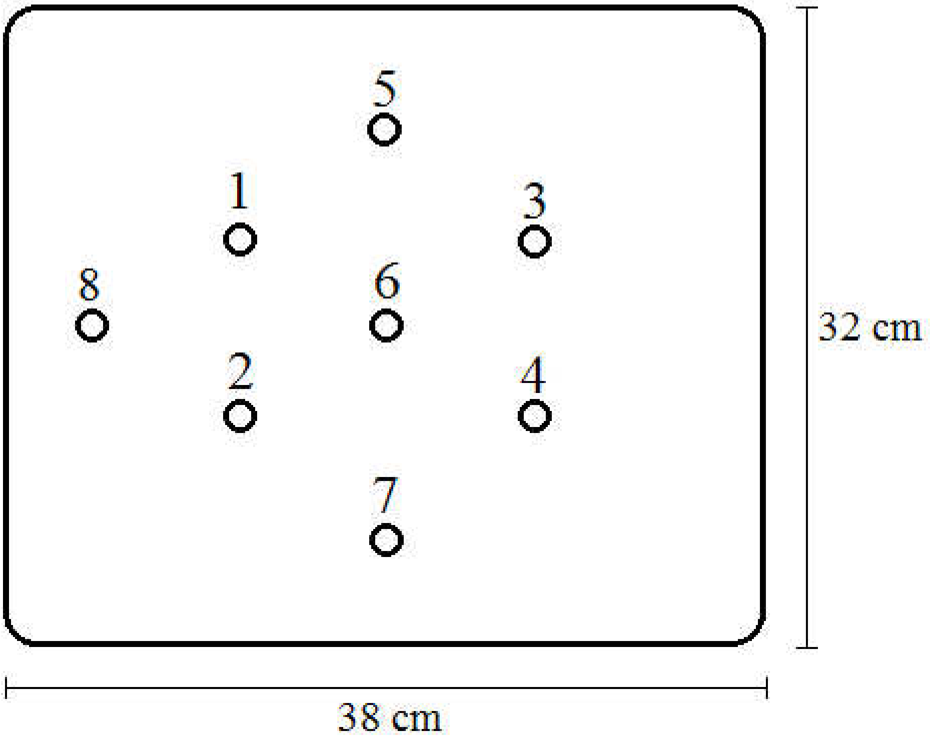

Figure 3.2.: Inlet positions (for exp. 1-3 only inlets 1-4)

3.3. Evaporation rate

A scale was fixed on the water reservoir. Every day at about the same time the water level was read and if it was to low, new water with the respective salt concentration was added.

This measurement technique is not really accurate, since the error margin is $0.5\frac{\text{mm}}{\text{day}}$. Using a water reservoir with a smaller footprint would result in a smaller error, but the water level in the actual experiment (sand box) would change much faster and it would be necessary to add new water more often, which might counteract the smaller error.

3.4. Coloring

To understand better what is going on in the model, color was used (Rhodamin and Fluorescein). It was injected through a plug in the tube right below the inlets, so it can be assumed that no more uncolored water flows into the experiment after injecting the color.

The biggest problem is, that only the dynamics at the surface can be observed. To see what is happening inside the experiment was dissected in layers of a thickness of 1 cm. A picture was taken of every layer and in every second layers samples of about 1cm^3 the wet sand were taken to analyse the salt concentration of the contained water.

3.4.1. Sample analysing

To calculate the salt concentration of the water in the samples several steps were needed. At first the mass of the sample including the container (m_0) was measured. After that the samples were completely dried and weighed again with their containers (m_d). The difference of those two masses is the mass of the fresh water that was in the sample $m_0 - m_d = m_w$.

Then about 20 ml distilled water is added to the dry sample and that is weighed again, so that the actual mass of the added water $m_a w$ can be calculated. Since the masses that are dealt with are very small, it is not accurate enough to measure the volume as accurate as possible and then convert it into mass, since the temperature has an effect on the volume. The last step is to measure the salinity of the new solution with a salinity meter, which measures the connectivity and calculates that into the salinity S. With that the amount of salt (m_S) in the solution can be calculated via $m_S = S_{meas} \cdot m_{aw}$. The last step is to calculate the original salinity of the water in the sample with

$$S_{orig} = \frac{m_s}{m_w} = \frac{S_{meas} \cdot m_{aw}}{m_w} \tag{3.1}$$

The results for measuring the salinity are only relative and therefore the results for the mass of the salt and the salinity of the original sample are relative, too. To have absolute values, they need to be calibrated.

4. Results

4.1. Permeability measurements

The volume of the permeated water can be calculated with the measured mass and the given density of water, which is about $\rho_w = 1\frac{\mathrm{g}}{\mathrm{cm}^3}$. Therefore the position of the water head is

$$h_{wh} = h_0 - \frac{m}{A \cdot \rho_w} \tag{4.1}$$

The water head position results verify the measurements, if it does not decrease further after reaching a height of about 20cm. This worked out for all measurements. Moreover pictures of the water column were taken over the course of the experiment and the calculated water head position could be verified with them.
With the water head position the volume flow rate per unit area can be calculated.

$$q = \frac{1}{A}\left(-\frac{dV}{dt}\right) = \frac{1}{A}A\left(-\frac{dh_{wh}}{dt}\right) = -\frac{dh_{wh}}{dt} \tag{4.2}$$

The differentiation was performed over ten time steps, each 4s long, since especially with the smaller bead sizes the flow rate became so small that the water dripped into the beaker.

Finally the volume flow rate per unit area is used with Darcy's law to calculate the permeability. L is the length of the distance the fluid flows through the porous medium and over which the pressure drop occurs, so it is the height of the sand. The viscosity of water is $\mu = 1\mathrm{mPa\,s}$

$$\kappa = \frac{-q\mu L}{\Delta p} = \frac{\frac{dh_{wh}}{dt}\mu L}{\Delta p} = \frac{\frac{dh_{wh}}{dt}\mu L h_0}{h_{wh}\rho g} \tag{4.3}$$

It can be seen, that the data of the three experiment runs overlap very well for all used sands and all calculated quantities (e.g for bead diameter 100-200 μm: fig. A.1.). The first run seems to always have a slight smaller flow rate than the second and third one. A possible explanation for this is could be that there was still some air trapped between the sand grains when the first measurement was performed.

bead size R [µm]	permeability $\kappa \cdot 10^{-11}$ [m^2]
$200 - 300$	8.27 ± 0.3
$150 - 250$	4.7 ± 0.2
$100 - 200$	1.67 ± 0.12
$90 - 150$	1.44 ± 0.1
$70 - 110$	0.77 ± 0.13

Table 4.1.: Permeability results for different bead sizes

4.2. Evaporation rates

4.2.1. General observations

In Figure 4.1 the height of the water in the reservoir of all experiments can be seen. It makes sense to look at this general plot of all experiments first to check why changes in the evaporation rate occur.
The first thing that can be seen is that the evaporation rate does not depend on the height of the water in the reservoir.

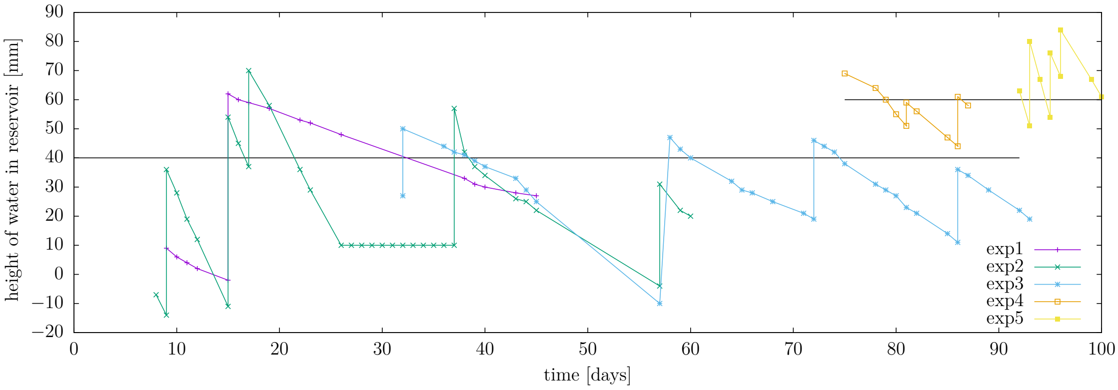

Figure 4.1.: Evaporation rates of all experiments

Evaporation is sensitive to temperature and pressure of the environment and since the lab is not temperature controlled it is not given that the environment does not have effects on the evaporation which could be falsely associated with changes on the experiment setups. Since most of the time two experiments were set up at the same time in the same lab correlation of changes of the evaporation rate could indicate, that they occurred due to the lab condition. But this seems to not be the case. Even on the overview it can be seen that a fan and a lamp increase the evaporation and a crust seems to decrease it. This is going to be described more precisely in the following sections.

4.2.2. Observation each experiment

Experiment 1

Since experiment 1 was the only experiment set up in another lab and the box had higher walls, it can not be compared to the other experiments. The mean evaporation was $(1.6 \pm 0.1)\frac{\mathrm{mm}}{\mathrm{day}}$

Experiment 2

The second experiment was set up with a fan from the first day on. Over 18 days the evaporation rate could be measured and resulted in $(7.3 \pm 0.2)\frac{\mathrm{mm}}{\mathrm{day}}$. The water reservoir was shut off for 10 days to see if a crust would form. When turned on again, the crust went away in about 6 days. In those days the evaporation was about $(3 \pm 0.2)\frac{\mathrm{mm}}{\mathrm{day}}$, but even with the crust disappeared, the evaporation rate stayed that small (only observed over two more days).

Experiment 3

Experiment 3 ran 11 days without a fan or lamp. The mean evaporation rate was $(1.6 \pm 0.1)\frac{\mathrm{mm}}{\mathrm{day}}$. After those days the fan was turned on and the evaporation rate was only measured over 3 days, which gave an evaporation rate of $(4 \pm 0.2)\frac{\mathrm{mm}}{\mathrm{day}}$. The experiment was then left unobserved for 12 days. After that the tube connecting the experiment with the water reservoir was not fully filled with water anymore. So it can be assumed, that the experiment dried for some days.

After that time a crust, which can be seen in fig. D1, had formed. Even with filling up the water reservoir the crust stayed and only changed slightly (further discussed in section 4.5.1.). Giving that and that the evaporation rate did not change except the usual variations due to inaccuracy, it made sense to calculate the mean evaporation rate with that salt crust. It is $(2.1 \pm 0.1)\frac{\text{mm}}{\text{day}}$.

Experiment 4

Experiment 4 ran 4 days without a fan, the mean evaporation for that time is $(1.7 \pm 0.3)\frac{\text{mm}}{\text{day}}$. The rate for the experiment with the fan was measured over 9 days and is $(3.4 \pm 0.2)\frac{\text{mm}}{\text{day}}$.

Experiment 5

Since experiment 5 had a growing crust while measuring the evaporation rate it does not make sense to calculate a mean evaporation rate, when assuming the crust influences the evaporation. Therefore the total evaporated water with time is shown in fig. 4.2.

It can be seen, that the rate decreases after the third day, that is when about half of the surface was covered with crust. As the crust grew further (fig. D.2) and nearly covered the whole surface the evaporation rate drops to about half of the initial rate. The evaporation rate from day 2 to day 3 is slightly higher than the first two measured rates, although about a quarter of the surface was already covered with salt crust. But since it is only one measurement it can easily just be an error in reading the scale.

In the first two days, when nearly no salt had accumulated on the surface yet, the evaporation rate was about $(13 \pm 0.3)\frac{\text{mm}}{\text{day}}$, which gives an idea of how the lamp influences the evaporation. These values need to be treated carefully, since the time over which they are measured is again really short, therefore it probably is not an exact result.

In the last day, when the crust was spread over nearly the whole surface, (6 ± 0.5)mm evaporated.

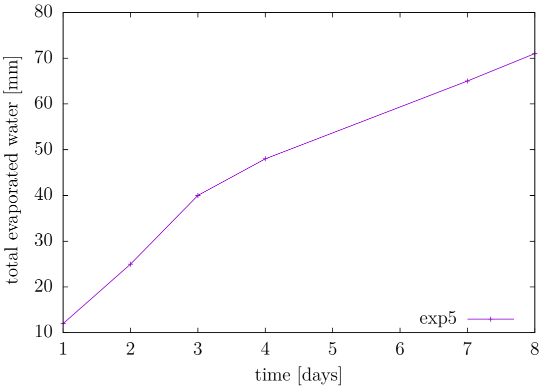

Figure 4.2.: Evaporation exp. 5 when crust started to form

4.3. Dying

The first thing that can be noticed in all experiments (in the pictures of the surface as well as in the pictures of the layers) is, that the incoming water from the tubes directly flows upwards. Therefore the position of upflowing water is given by the positions of the tube inlets. Not all inlets are active at the same time, most of the time water flows upward out of only one inlet.

4.3.1. Experiment 2

Surface

No pictures were taken of the surface, after the water in the tubes was dyed pink with Rhodamin. A salt crust was still on the surface, so not much could have been seen. The surface two days after dying the water can be seen in fig. B.1. It seems like no water came out of inlet 1, but the other three inlets were used during those two days, since circles formed above them.

After dying the water orange, a spot of dyed water occurred first above inlet 4 (after 1 hour), then above inlet 3 (four hours) and then above inlet 2 (5 hours). All of them spread out in a circle around the initial spots. The circle above inlet 4 stopped growing around the time when color appeared first over inlet 2. This indicates, that water probably stopped coming in from inlet 1, when it started coming in from inlet 2.

Both circles over inlet 2 and 3 spread further. Initially the one over inlet 3 was bigger, since it appeared earlier, but then the growth rate of the circle above inlet 3 either slowed down much or it stopped growing completely and the one above inlet 2 grew bigger. What the surface looked like in the end, when the experiment was dissected, can be seen in fig. B.1

Layers

One day after the orange color was applied the experiment was stopped with cutting off the water reservoir. The sand was dissected into 9 layers. The first layer shown in fig. C.1. is 1cm below the surface, and then pictures were taken every 1cm of depth.
In the bottommost layer just three colored spots just above inlets 2,3 and 4 can be seen. Therefore every other colored parts in the other layers that are not right above those spots are water that went downwards from the surface.
In the first (uppermost) layer roughly the same structure can be seen above inlet 2 and inlet 3. Around both of them there are two rings and in between those two rings, perpendicular to them, are stripes. Although the circles on the surface do not have the same size, the inner rings in the first layer do.
The radius of these inner rings increase with higher layers.
The second rings can not be seen in the second layer and below.
The spaces between the stripes in the pattern above inlet 3 seem to be narrower in the first two layers, but below that it becomes clear, that there are around the same number of stripes around each inlet, even though it is hard to count them, especially where both overlap.

The pink parts can not be seen very well. But it seems like a lot of the orange dots/stripes overlap with pink ones, which would mean, that partly the motion of the pink dyed water was the same as the motion of the orange dyed water.

4.3.2. Experiment 3

Experiment 3 was dyed once and the surface was observed after that. The experiment was not dissected. Since it makes only sense to describe the behavior of the dyed water in correlation to the crust, the observations are discussed in section 4.5.1.

4.3.3. Experiment 4

Surface 1

After eight days of running, experiment 4 was dyed with Rhodamin (pink). The surface was observed for five days. It seems like fresh water is only flowing upwards from inlet 8.

At first the dyed fresh water spread evenly in a circle (at least in the directions where there is no wall) on the surface above inlet 8.

After one day some kind of patchiness can be seen at the edge of the colored area (fig. B.2 top left).

After 1.5 days as shown in fig. B.2. a certain pattern can be identified. It looks like a circle with three extra rings around the spot where the water reaches the surface at first. The rings themselves have a structure with colored spots periodically appearing in a certain distance from each other on the ring.

The number of rings as well as the number of single colored spots on the ring do not change, but the whole structure stretches further across the whole surface.

After a total of four days the single rings can not be identified anymore. The pattern formed into stripes, which show outwards from the colored circle over inlet 8 (fig. B.2. bottom right). It looks like the stripes developed with the single spots on the rings connecting.

The dyed water has spread across the whole surface after five days.

Surface 2

Then after those 5 days the water in the tubes was dyed a second time, this time with Fluorecein (orange/yellow).

This time dyed water first appeared on the surface right above inlet 7. But three separate spots appeared (fig. B.3. top left). But they seem to grow together and build a circle, which stretches out (fig. B.3. top right).

At the same time colored water appears above inlet 8 again and stretches out into a small circle, but stops growing after about 14 hours.

In this time the circle of colored water on the surface, that appeared first, grew further. Moreover the edge on the right and the lower left side is thicker than the rest of it. This probably occurred due to the initial three spots that merged into one circle.

After the colored area over inlet 8 stopped growing new orange water appears in

the light middle of the first circle, which indicates that inlet 8 was inactive for some time and water started flowing through it again.
This indicates that it is probable that water only flowed through one inlet at a time. On the outer parts of the circle a stripe pattern can be seen again, similar to that of the pink colored water.

Layers

Even though in the bottommost layer, there are some colored spots, which are not directly over inlets, it can be safely assumed, that those flowed downwards from the surface, since there was no colored water in the quartz sand below them. So the position of upflowing water is again directly above the inlets.

The pink dye was used 6 days before dissecting.
In the first two layers, so the first two centimeters below the surface, the pattern looks nearly like the pattern on the surface.
Below the area, which was nearly all pink on the surface around inlet 8, small circles can be seen. Starting from the right side, where inlet 8 is, these small circles disappear with depth. This means, that the pink water, traveled from inlet 8 up to the surface, spread there and then flowed down in fingers. The fingers near to the inlet are not as deep as those further away. It can not be seen if they just developed slower or stopped going deeper.
The stripes on the right side of the box, are visible up to the bottommost layer. But the parts on the right go deeper as well. Along the top and bottom wall of the box there is pink water. That indicates, that the box is to small and a similar pattern like the one on the right side would have formed, if there was enough space.

The water in the tubes was colored orange one day before dissecting. Over inlet 8 an orange circle can be seen, which is biggest in the lowest layer, a little smaller in the seventh and sixth layer and even smaller in all layers above. This is probably the upflowing water coming from inlet 8. In the first layer another 5 small circles can be seen around the upflow, in the second layer two of them (the ones nearer to inlet 7) are not there anymore. These are again downflowing parts, with different depths.
Over inlet 7 a pattern similar to those in experiment 2 occurred (except the extra circle in the middle, but that is already discussed).

Again an inner ring with decreasing radius with depth can be observed.
Also the outer rings and the stripes in between the rings can be seen in the first layer again. Below that the structure becomes more unclear and regularities are not as strong as in the other observed patterns. But a lot of orange stripes/circles overlap with pink ones, which is interesting, because as opposed to experiment 2, in this case the pink and the orange water flowed upward out of different inlets.

4.3.4. Experiment 5

In experiment 2 and experiment 4 it became clear, that it is very useful for understanding the dynamics of the water to have both pictures of the surface and of the dissected layers to combine the observations. In experiment 5 this was not possible, since a heat lamp was used. To take pictures of the surface, while the experiment was running, the camera would be to close to the heat. But since a crust formed, it would have not been possible to see much at the surface anyway.

The experiment was dissected six days after the pink color was applied and again one day after the orange one. At first it can be seen that the whole time water only flowed in through inlet 8.
The pink pattern looks like the one in experiment 4, the only difference is, that it has not reached the left wall.
This time there can not be seen an orange inner or outer ring in the first layer, it is rather a circle with stripes in it pointing outwards. But in the second layer the inner ring is visible with perpendicular stripes to it. Again, the inner ring becomes smaller with increasing depth and some of the stripes disappear, which shows how deep the dyed water could already flow down. Again an overlap of pink and orange color can be observed, which means the downflowing fingers occur in the same places.

4.4. Salt concentration of samples

The initial idea was to calibrate the salt concentration with assuming the salt concentration right over the inlet was equal to the concentration in the reservoir. At some measurement points the concentration was lower than right over the inlet, so this assumption does not make any sense, the concentration would not get lower than the reservoir concentration. That would contradict the second law of thermodynamics ($\Delta S > 0$ with entropy S) since the accumulated salt on the surface in the experiments is negligible compared to the salt coming in with the new water.
Therefore the concentrations shown in fig. C.1. to fig.C.4. are given relative to the lowest measured in each experiment ($S_{min} \hat{=} 1$).

This measurements need to be treated really carefully due to many possible error sources (which are further discussed in section 5.5.1.). Therefore the following statements just describe tendencies of the concentrations and intendedly do not go into many details.

4.4.1. Experiment 2

In general the salt concentration of the sample taken in experiment 2 increase with depth. The highest concentration is about twice as big as the lowest. Due to the poorly chosen positions of the taken samples it is hard to make more observations in combination with the dyed water in this case.

4.4.2. Experiment 4

In experiment 4 the salt concentration again increases generally with depth and the factor between the smallest and biggest measured concentration is about 3.
In all layers the concentration is bigger on the right side of the box were the pink water, which came in from inlet 8 went and flowed down.
Moreover the concentrations above inlet 7, which was the active one right before the samples were taken, are the smallest in every layer.
Another observation is that the sample on the bottom left and the one above inlet 8 rather small salt concentrations.

4.4.3. Experiment 5

In experiment 5 no clear tendency of increasing concentrations with depth or a side can be seen.

The difference between the highest and lowest concentration is with a factor of 5.7 much higher than in the other experiments.

Additionally the differences in the uppermost layer are also much bigger. And in this layer it is clear that the concentration is higher on the right side, where the water flows down.

Above inlet 8, the active inlet, the concentrations are the smallest in every layer, except the lowest one.

4.5. Crusts

4.5.1. Due to low water table

Experiment 2

The crust in experiment 2 grew after the water reservoir was shut off. Four days after that nearly the whole surface was covered with crust, which grew evenly. After the reservoir was turned on again the surface disappeared again. This took about six days for the crust to disappear at the whole surface. No particular pattern in the disappearing could be observed.

Experiment 3

As described in section 4.2.2. the experiment probably dried for some days and a crust formed. The crust was thinner in a circular area above inlet 4 ($r = 13$ cm). In the salt crust a stripe pattern can be recognized, those stripes are perpendicular to the circle of thinner crust (fig. D.1. top right).

When the water reservoir was filled up again the crust stayed nearly the same the whole time. It only disappeared in small circles (ca. radius of 7 cm) above alternating inlets (fig. D.1. top right, bottom left).

When the incoming water was dyed pink, the color appeared at the surface right in the middle of the hole in the crust and therefore right above an inlet (fig. D.1. bottom right).

This proves the assumption, that the holes appear above the active inlet and the fresh water which flowed from the reservoir to the surface takes up the salt at those parts.
When and where the holes in the crust appeared is shown in Table4.2.
x means there is a hole in the crust above the inlet and (x) is for days, where no photographs were taken, but a hole is still assumed, since it was there the day before and the day after.
It needs to be noted, that it takes about two days for a hole to have its final size. Also it does not become overgrown with crust immediately, but a thin layer of salt grows and then becomes thicker again (also about two days to not being visible anymore). In this case, as soon as some crust disappears (it is assumed this means water started flowing through the inlet underneath) , the hole counts and then stops to count, when it starts to become overgrown (means no more water comes through the inlet underneath).

4.5.2. Due to high evaporation rate

As explained in section 4.3.4 it was not possible to observe the surface with a camera the whole time due to the heat of the lamp. Still, with the pictures taken it can be seen that the crust started growing on the right side, with the water coming in through inlet 8 on the left side (which becomes clear with the dyed water). After about two days the whole left half of the box is covered with a crust, while on the right only a little bit of salt has accumulated in the bottom edge.
After four days nearly the whole surface is covered and the crust shows similarities to those observed in experiment 2, after it was turned on again. The only part where there is no crust is right above the active inlet and a structure in the crust with stripes pointing outwards from that point is visible.

inlet	1	2	3	4
day 1	x			x
day 2	(x)			(x)
day 3	(x)			(x)
day 4	(x)			(x)
day 5	(x)			(x)
day 6				x
day 7			x	x
day 8			x	x
day 9			(x)	(x)
day 10			x	x
day 11			x	x
day 12			x	x
day 13			x	
day 14			x	
day 15		x	x	
day 16		x		
day 17		x		
day 18		x		
day 19		x		
day 20		x		
day 21		x		
day 22				
day 23				
day 24				
day 25				
day 26				x
day 27				x
day 28				x
day 29				x
day 30				x
day 31				x
day 32				x
day 33				x
day 34				x
day 35				(x)
day 36				(x)
day 37				x
day 38				x

Table 4.2.: Holes in crust above inlets of exp. 3 after filling up the reservoir

5. Discussion

5.1. Permeability

A good approximation to calculate the permeability is the Kozeny Carman equation, which describes a laminar flow through a packed bed with beads with a diameter D and a sphericity s [[4]].

$$\frac{\Delta p}{L} = \frac{180\mu}{s^2 D^2} \frac{(1-\epsilon)^2}{\epsilon^3} q \tag{5.1}$$

ϵ is the porosity of the porous medium.
Assuming perfectly spherical beads ($s = 1$) and the definition of the permeability gives

$$\kappa = \frac{D^2}{180} \frac{\epsilon^3}{(1-\epsilon)^2} \tag{5.2}$$

The porosity of the medium can be calculated with the bulk density and the density of the beads. They are given by the producer. The porosity actually depends on bead size, but for the used diameters the differences are negligible and the average is calculated.

$$\epsilon = 1 - \frac{\rho_{bulk}}{\rho} \tag{5.3}$$

Fig. 5.1. shows the calculated permeabilities of the sands in the experiment, the distribution given by Kozeny Carman with the calculated porosity and Kozeny Carman fitted via the porosity.

$$\epsilon_{calc} = 0.44 \quad \epsilon_{fitted} = 0.4 \pm 0.01$$

The small difference between the calculated and the fitted porosity shows the measurements give values for the permeabilities really close to theoretical predictions.

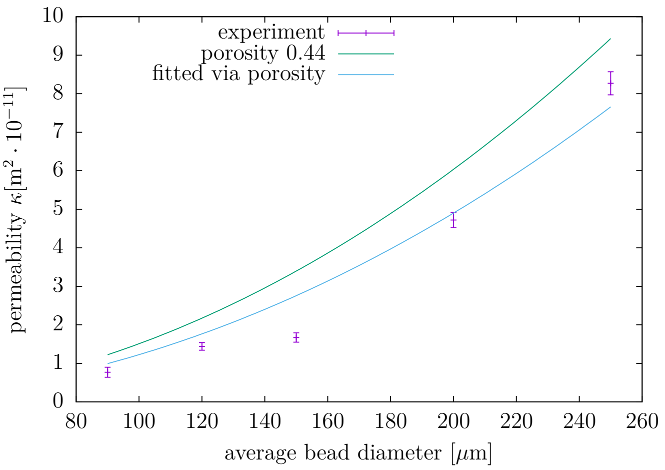

Figure 5.1.: permeability of sand depending on bead size

5.2. Evaporation rates

In table 5.1 the measured evaporating rates are shown for experiment 2 to experiment 5.

The rates of the first experiment are not shown here, since no changes were made in the setup of this experiment.

It can be seen that adding a fan to the setup of the experiments increases the evaporation rate by a factor of (2.3 ± 0.3).

It is harder to state what the increasing factor for adding a lamp was, since the lamp was used from start in experiment 5. But assuming the bead size does not influence the evaporation and therefore being able to compare the evaporation rates of the different experiments give a factor of (2.7 ± 0.5) for adding a lamp to a setup with a fan.

More interesting to see what differences the setup changes make in the evaporation rates is how a crust influences them.

For a setup with fan as well as for one with a fan and a lamp the crust the evaporation rate decreases by a factor of (2.2 ± 0.3). That means the crust blocks the water from evaporating.

It would be interesting to see if that factor still holds for an experiment without a fan.

setup	evaporation rate $[\frac{\text{mm}}{\text{day}}]$
exp. 2 with fan	7.3 ± 0.2
exp. 2 with fan and crust	3 ± 0.2
exp. 3	1.6 ± 0.1
exp. 3 with fan	4 ± 0.2
exp. 3 with fan and crust	2.1 ± 0.1
exp. 4	1.7 ± 0.3
exp. 4 with fan	3.4 ± 0.2
exp. 5 with fan and lamp	13 ± 0.3
exp.5 with fan, lamp and crust	6 ± 0.5

Table 5.1.: Overview evaporation rates

5.3. Reconstructing dynamics

The coloring of the water and then dissecting the experiment give the strongest hint how the dynamics of the salt water in the models look.
The first thing that could be observed is, that the position of the upflow is always right above an inlet. The water flows up from there in a ring, which gets bigger with height.
The water then spreads out into a bigger circle at the surface, from it flows downwards in stripes perpendicular to the upflow ring. These stripes can already been seen at the surface (in some cases better than in others). The stripes themselves do not flow downwards evenly, but some sort of fingers occur with the tendency, that the ones further away from the upflowing water flowed down deeper, which also could just mean faster, since this method only gives static pictures.

The described inner ring (upflow) seems to have a correlation with the evaporation rate, it is bigger and grows faster with higher evaporation (fig. 5.2.).
Another interesting observations is that in many pictures of the layers the orange color overlaps with the pink one. That it happens when the pink and orange water comes out of the same inlet shows that the sizing of the convection is steady.
But it could also be observed in experiment 4, where different inlets were active, so the convection is influenced by prior dynamics.

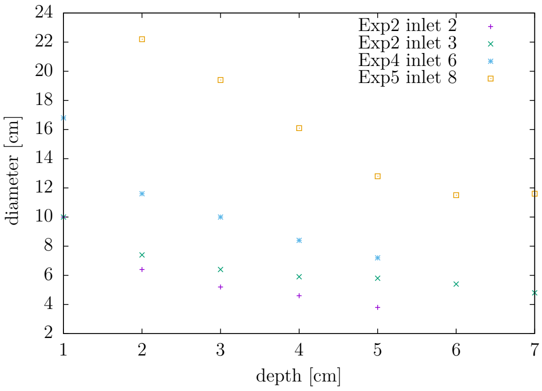

Figure 5.2.: inner ring (upflow) diameters

The salt concentration measurements verify these results in some parts. The fact that the parts were the water probably flows upwards above the inlets have the lowest salt concentrations makes sense. Moreover the tendency of higher concentrations on the right side of the box in experiment 4 matches with the fact that water coming from inlet 8 over the surface flows down there.
In general the higher salt concentrations in the lower layers also confirm convection, since diffusion would not be fast enough to even up the instable density gradient induced by evaporation to a stable one (turning it around).

5.4. Crust formation

Two crusts were observed, which developed due to drying of the experiment. Interestingly one of them was stable, while the other one disappeared again with turning on the water reservoir again.
The reason for that is unclear. The evaporation rates of these two experiments were similar, as well as the setups, especially the salt concentration.
Since experiment 5 was the only one were a crust grew without turning off the water reservoir it becomes clear, that a high evaporation rate is needed for a crust to grow. That makes sense, since a crust only grows when the salt concentration is higher than saturation. In the other experiments, the denser water which developed at the surface due to evaporation had enough time to flow downwards before saturation was reached. This can be also seen in the salt concentration measurements, since in all experiments except experiment 5 the salt concentrations measured at the top are lower than the ones measured in deeper layers.

It is clear that the other crucial factor for crust formation is the initial salt concentration. The reservoir concentration was the same in all experiments done, but it would be interesting to see how it affected crust formation.
In both experiments in which a stable crust had formed small circles without crust can be seen (7 cm for exp. 3, 10 cm for exp. 5). With the colored water could be shown that those circles always appeared above the active inlet. This can be explained, since the water coming from the inlet flows directly upward, so the concentration at the surface is about the same as the reservoir concentration and can even solve salt if there was a crust before. The salt concentration measurements confirm that, since the samples taken above inlets always had the lowest salt concentrations.
In both crusts a pattern with stripes pointing outwards can be seen, which correlates with the stripe pattern of the downflowing water (section 5.3).

5.5. Review 3D models

In general the models made it possible to get an idea of convection of salt water and its relation to crust formation.
The biggest flaw of this experimental approach is that it is not possible to observe much, while it is still running. The best method to make the path of the water visible is to dissect the experiment and therefore end it. Still this gives only a picture of one moment in time.
To verify assumptions about the motion of the water based on the colored water it is good to compare it to the crust and the salt concentrations.
The idea that the layer of quartz sand with bigger beads at the bottom of the model to guarantee an even distribution of incoming water clearly did not work and therefore the position of the convection depended on the inlet positions. It would be interesting to see, how the convection cells would look like if this was not the case. An idea for that is to use a similar model, but with some kind of narrower grid of holes in the bottom of the box with the box standing directly in the water reservoir.

All in all it needs to be noted, that the models only give good qualitative results. The few quantitative measurements (e.g. size of upflowing ring) need to be treated really carefully and just give an idea of probable dependencies.

5.5.1. Salt concentration measurements

The salt measurements have undoubtedly many error sources. For the calculations a lot of single measurements are needed and they need to be really accurate, for example mass differences of the order of 0.1 g.

But the biggest error source was probably measuring the salinity via the connectivity with a salinity meter. Even without calibrating the results and with just looking at relative values something seems to have gone wrong. The saturation of salt in water is reached, when 357 g salt are dissolved in 1 l water. For the reservoir concentration 150 g salt was dissolved in each liter water. This means, that concentration in the experiment can be higher than $2.4 S_{min}$. There are too many values were this is violated, so there probably went something wrong.

To avoid this it would have been better to measure the concentrations differently, instead of measuring the salinity of the new solution directly via the connectivity, the new solution could be seperated from the sand and then dried. Then the salinity of the original sample could be calculated back the same way as before.

It is also questionable if it makes sense to take the samples in a grid as it was done here. It would be easier to match the concentrations with the colored water and therefore the dynamics of the water, if the samples were just taken at interesting parts in every layer, for example of downflowing and upflowing parts.

6. Summary

In summary it can be said, that the 3D models gave a good idea of how the dynamics of salt water look like and how it affects salt crusts at the surface.
It was shown the water flows upwards in a growing ring, spreads at the surface and develops a certain structure with stripes, which flow downwards again. This could be observed in several experiments.
The convection of the salt water had a direct influence on the crusts that were observed, with the pattern with stripes reoccurring in the crust and holes in the crust, where the fresh water flew upwards.
Moreover all observations could be matched to the measured salt concentrations of the taken samples.
All in all the convection can be described qualitatively really well, the next step would be to investigate it further and get quantitative results, as well as a comparison to measurements in the field.

A. Permeability measurements

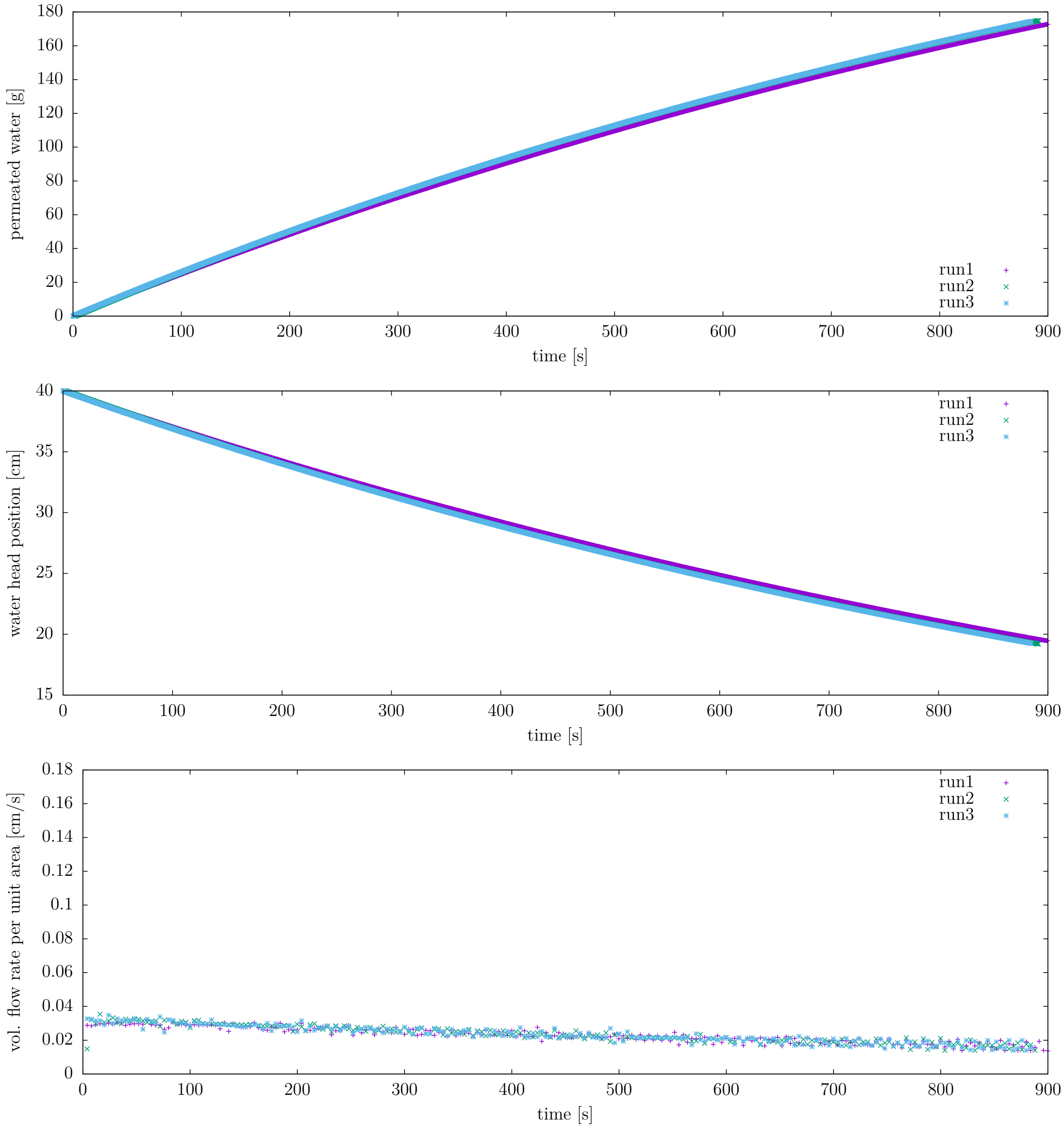

Figure A.1.: Permeated water, water head position and volume flow rate depending on time for bead diameter of 100-200 μm

B. Dyed experiments: surface

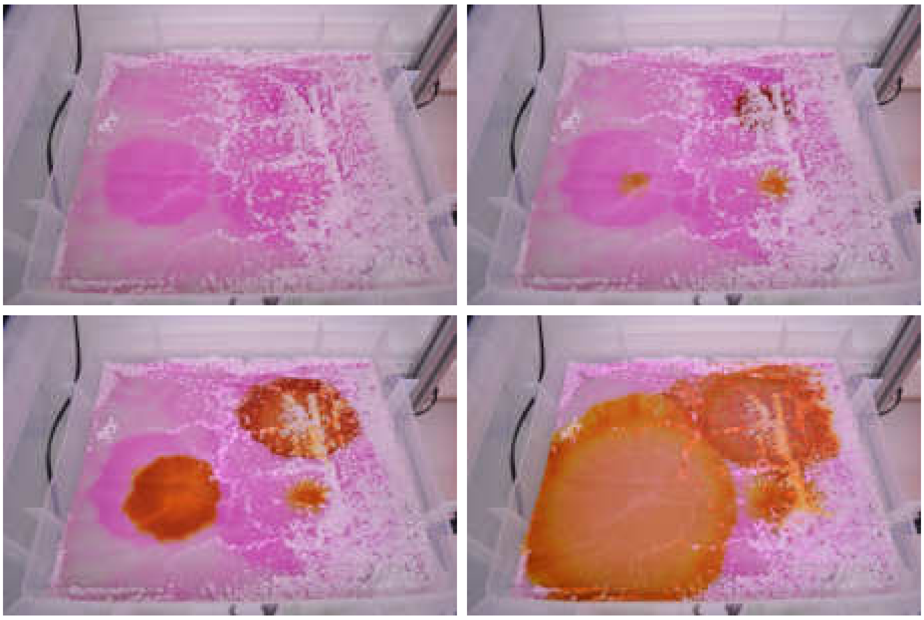

Figure B.1.: Surface experiment 2 (top left: before coloring orange; top right: after 5 hours, bottom left: after 10 hours ;bottom right: after 1 day, before dissecting)

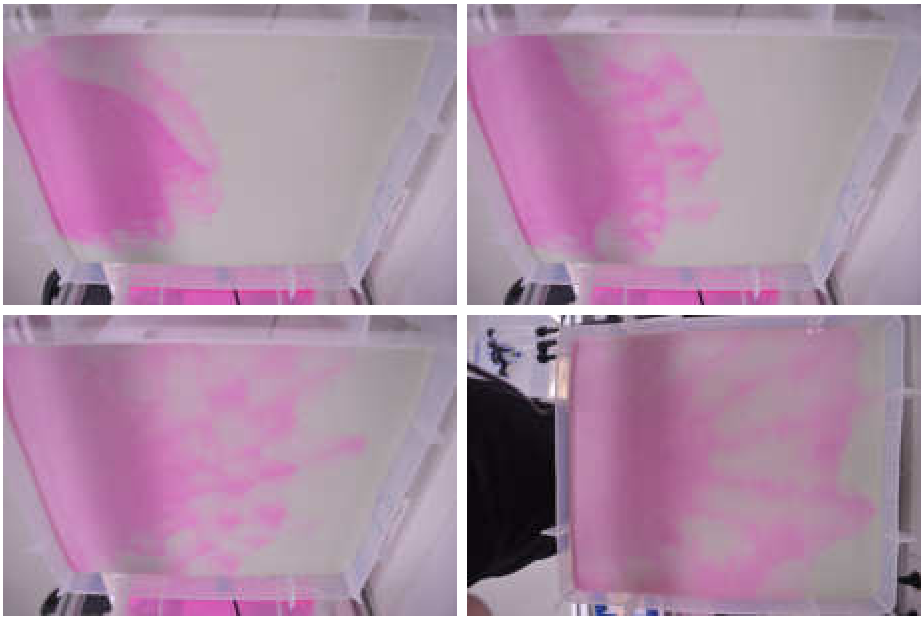

Figure B.2.: Surface experiment 4 after coloring water pink (top left: 1 day ;top right: 1.5 days ;bottom left: 2.5 days ;bottom right: 4 days)

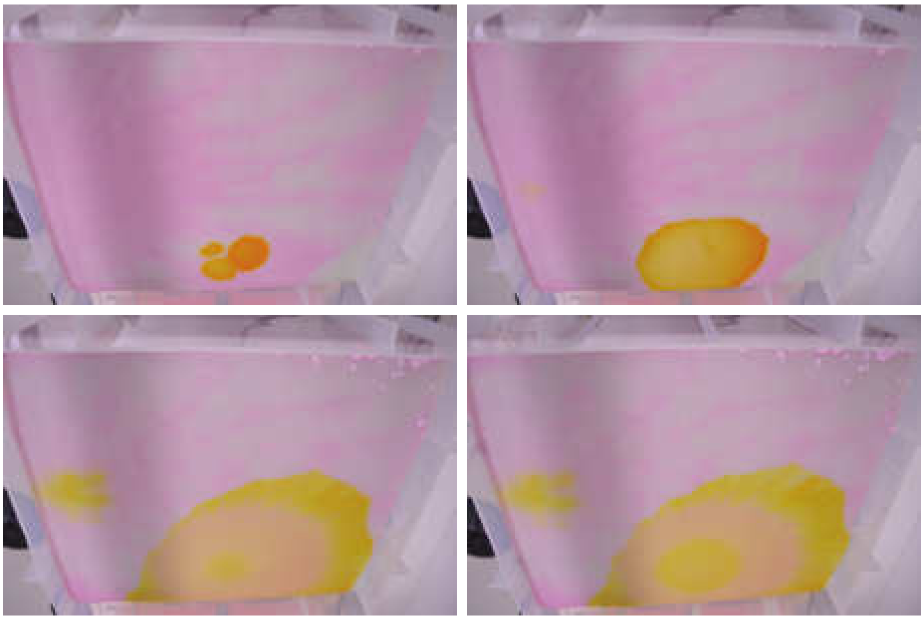

Figure B.3.: Surface experiment 4 after coloring water orange (top left: 5 hours ;top right: 8 hours ;bottom left: 22 hours ;bottom right: 1 day)

C. Dyed experiments: layers with salt concentration of samples

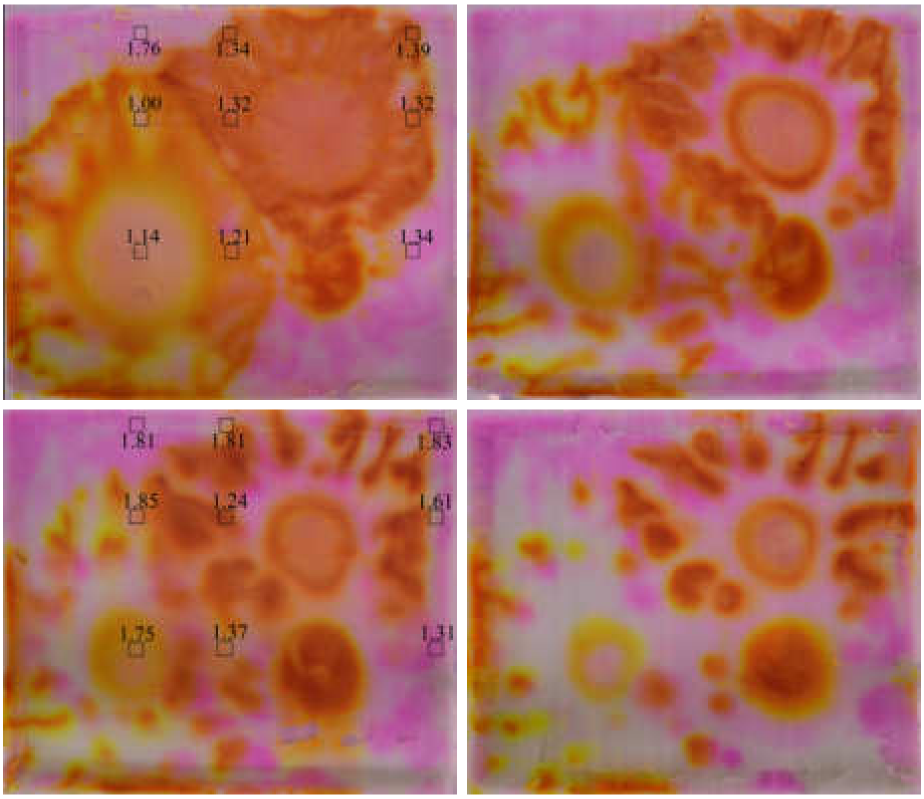

Figure C.1.: From top left to bottom right: Layers 1-4 experiment 2

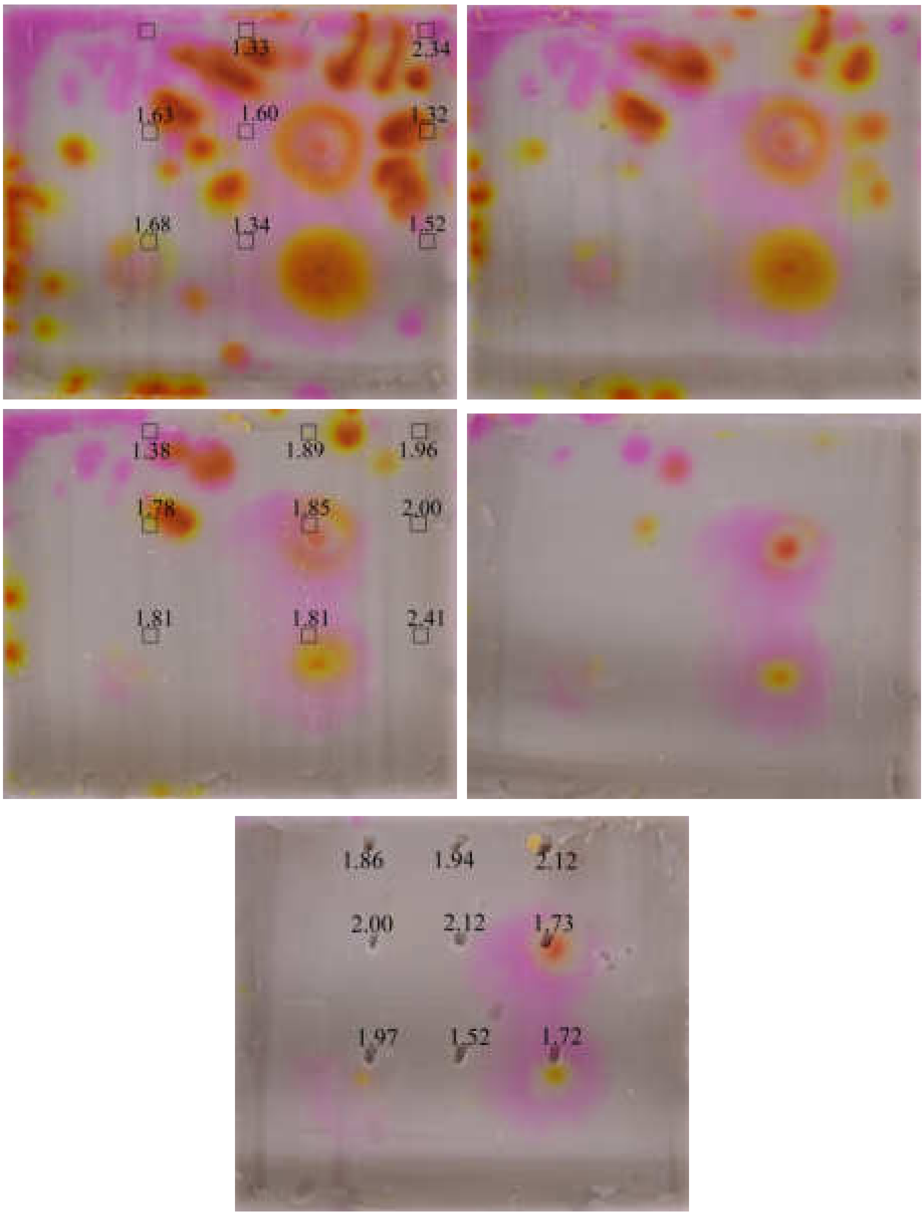

Figure C.2.: From top left to bottom right: Layers 5-9 experiment 2

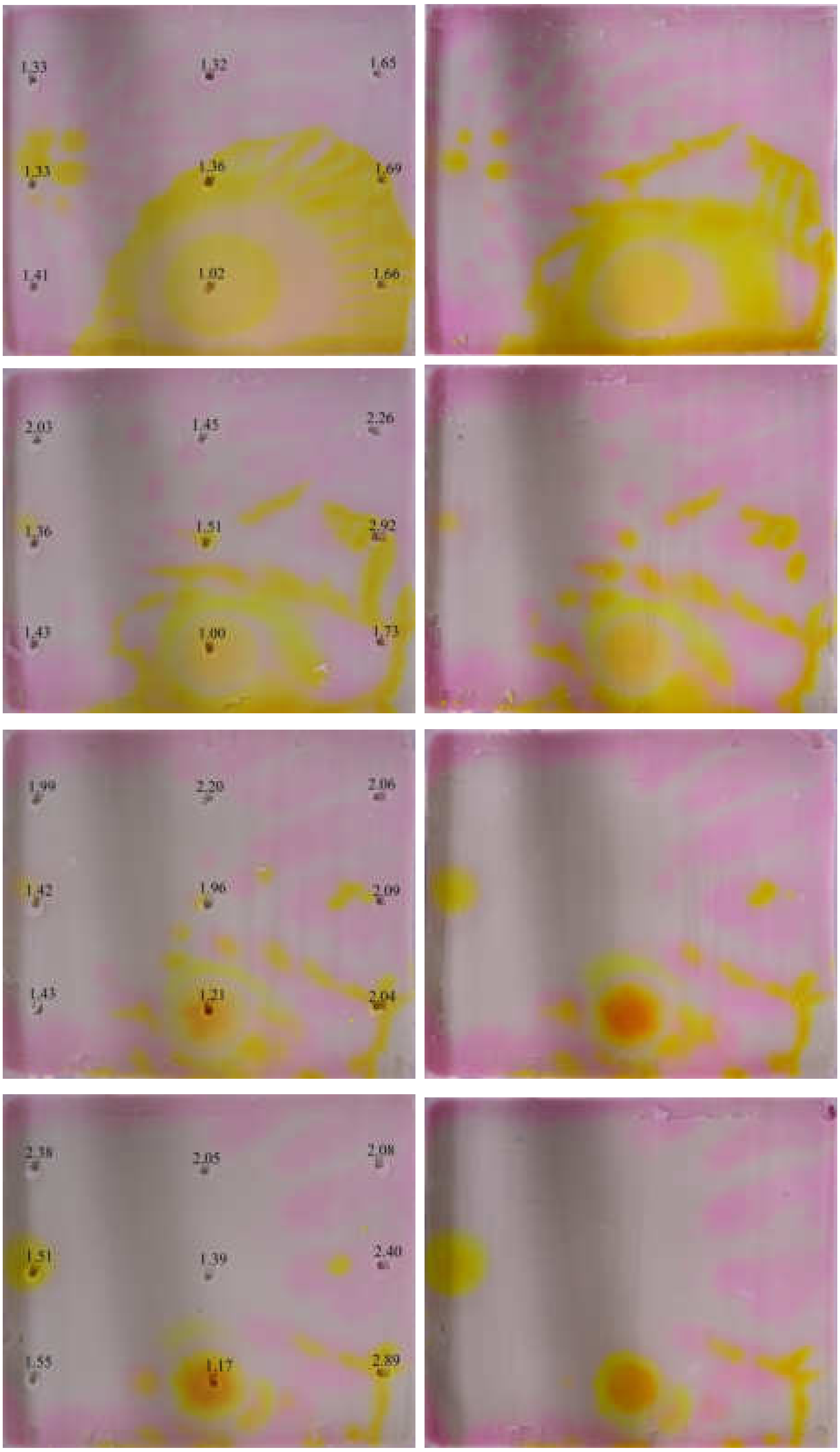

Figure C.3.: From top left to bottom right: Layers 1-8 experiment 4

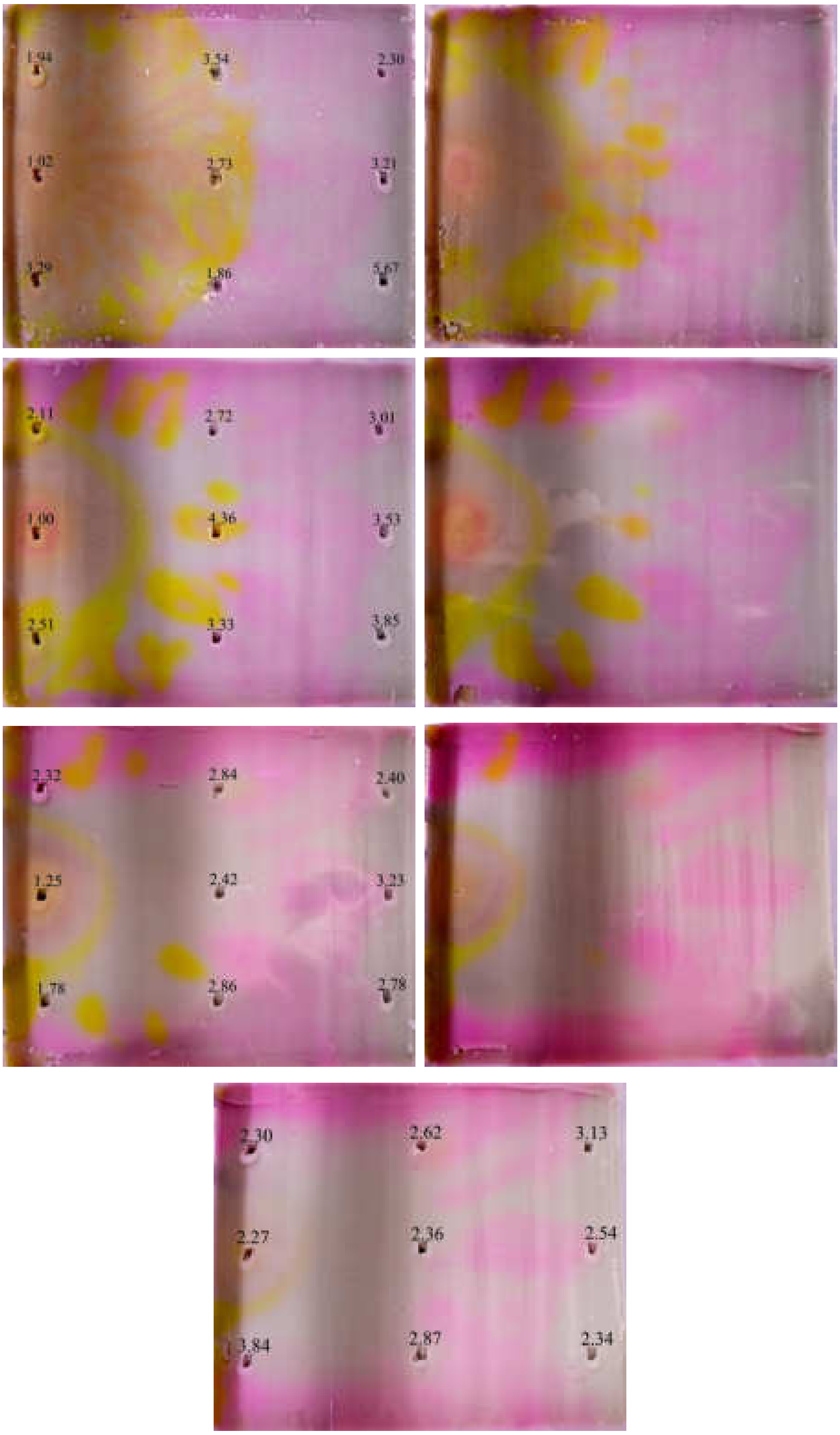

Figure C.4.: From top left to bottom right: Layers 1-7 experiment 5

D. Crusts

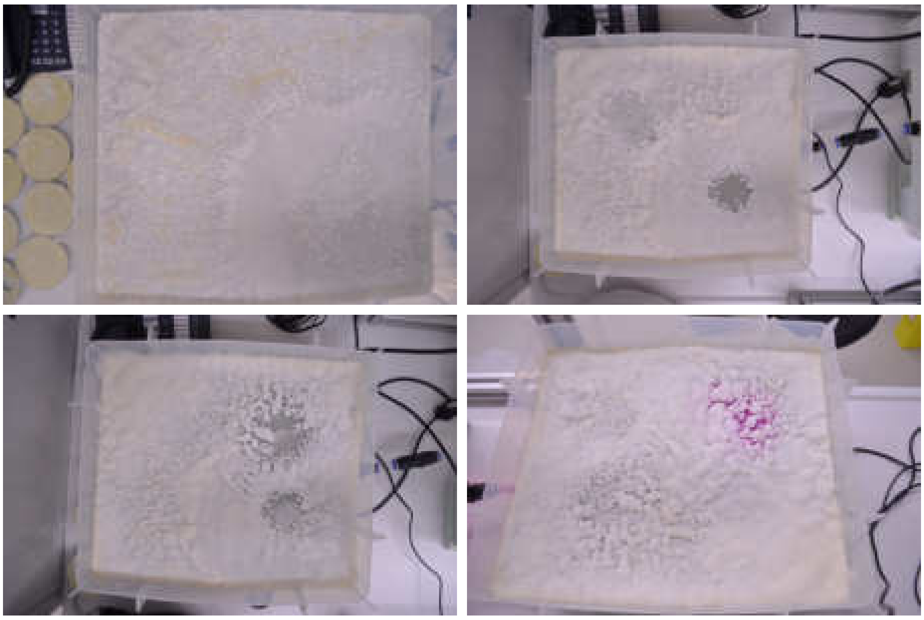

Figure D.1.: Crust experiment 3 (top left: after drying; top right: 6 days after turned on again; bottom left: 14 days after turned on again; bottom right: 16 days after turned on again, 1 hour after coloring)

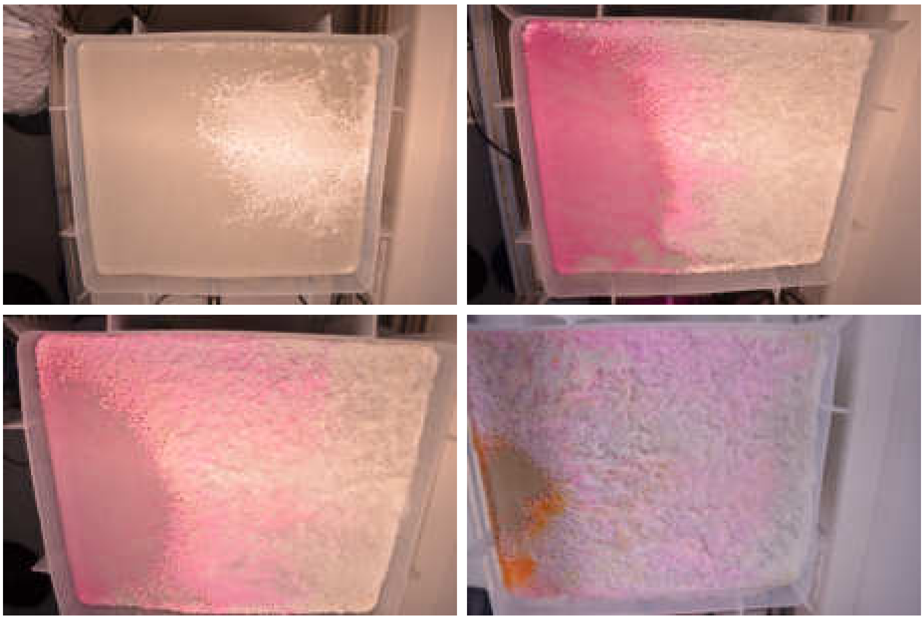

Figure D.2.: Crust experiment 5 (from top left to bottom right day 1-4)

Bibliography

[1] Wooding, R.A., Tyler S.W., White, I., 1997, Convection in groundwater below an evaporating salt lake: 1. Onset of instability, *Water Resources Research, Vol 33, No. 6,* 1199-1217

[2] van Duijn, C.J., Peletier, L.A., Schotting R.J., 1993, On the analysis of brine transport in porous media, *Eur. J. Appl: Math., 4,* 271-302

[3] Nield, J.M., Bryant, R.G., Wiggs, G.F.S., King, J., Thomas, D.S.G., Eckardt, F.D., Washington, R., 2014, The dynamism of salt crust patterns on playas, *GEOLOGY, January 2015; v.43; no.1* 31-34

[4] McCabe, Warren L., Smith, Julian C., Harriot, Peter., 2005, Unit Operations of Chemical Engineering

Erklärung nach §13(8) der Prüfungsordnung für den Bachelor-Studiengang Physik und den Master-Studiengang Physik an der Universität Göttingen:

Hiermit erkläre ich, dass ich diese Abschlussarbeit selbständig verfasst habe, keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe und alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten Schriften entnommen wurden, als solche kenntlich gemacht habe.
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Göttingen, den December 23, 2016

(Birte Thiede)