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On modeling the deposition of drill cuttings and mud on the sea floor

by

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Summary:

Experience has shown that discharges of drill cuttings and mud from a platform have sinking velocities considerably above what is expected from the sinking velocities of the individual cuttings and barite (weighting material) particles. The reason for this is partly due to formation of larger particles when the discharge mud has "sticky" properties (for SBM and OBM), and partly because a near-field plume is formed with a density larger than the ambient water.

When WBM is used, the downward motion of the particles may still be enhanced due to the downward motion of the near-field plume. However, the formation of larger particles may not be evident in this case because the "sticky" properties of the mud are absent. It is sometimes argued that "flocculation processes" may still form larger particles which will enhance the sinking velocities of the particles also for the WBM case.

The presence or absence of these "flocculation processes" are important for the calculation of the deposition, because larger sinking velocities will tend to concentrate the debris closer to the drilling site, compared to calculations that does not include the effects from flocculation processes.

The paper explains the efforts undertaken to examine the presence of "flocculation processes" for discharges of WBM. These efforts include a comparisons between measured and model simulated depositions of barite on the sea floor when WBM is used, an extrapolation of results from laboratory experiments to examine the expected importance of the flocculation processes, a re-examination of field data collected on the US coast (the *CAMP* study) and finally observations of the particle properties from an ROV present in the discharge area during actual drilling with WBM.

1. Introduction

During the drilling of an offshore well, debris from the well (cuttings) and chemicals used (mud) are in some cases discharged to the sea. These discharges may have an impact on the marine environment, both on the biota in the water column and on the sea floor.

In order to predict (or minimize) the environmental impact, numerical models are developed to describe quantitatively the expected concentrations of chemicals in the water column as well as the expected deposition on the sea floor. These models are then applied prior to the execution of the drilling operation.

The user's confidence in such models will be dependent on how well they are able to reproduce or simulate the actual processes going on during a discharge. Experience has shown that the deposition on the sea floor is important to calculate in particular because the restitution time of the bottom fauna can be rather large, in particular when oil based mud (OBM) or synthetic based bud (SBM) is used.

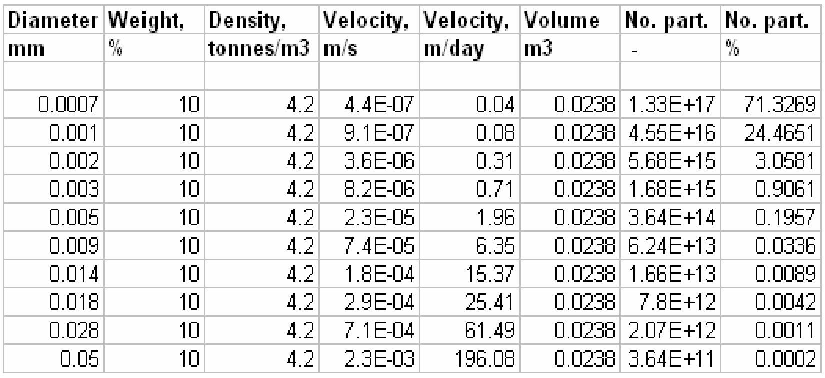
Therefore, a realistic assessment of the amounts deposited on the sea floor and the spreading on the sea floor becomes important. One important factor here will be the sinking velocities of the debris discharged from the drilling rig. A smaller sinking velocity will cause larger horizontal transport distances in the water column of the debris (due to the presence of time-varying ocean currents) before it hits the sea floor. This will in turn cause a larger spread on the sea floor.

This paper deals with how the sinking velocities for drilling debris should be treated in numerical models in order to have a realistic assessment of the amounts deposited as well as the distribution on the sea floor. In particular, it will be focused on the role of possible "flocculation" processes on the estimated sinking velocities.

2. The particle size of cuttings and barite

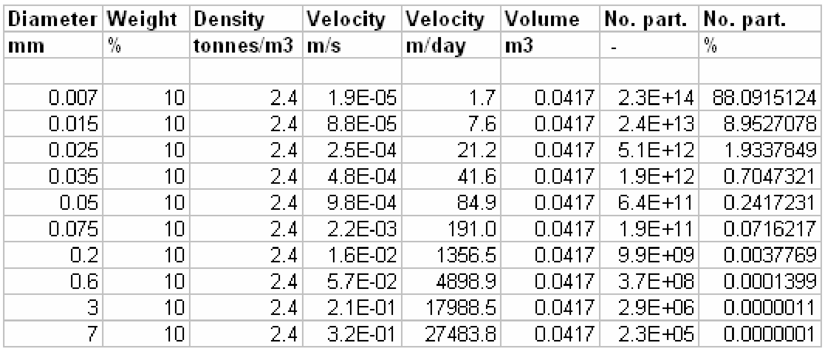
The cuttings and the weight material in the mud (usually barite is used) have both a particle structure. Their behavior in the water column will therefore be strongly dependent on the sizes of the particles. Small-sized particles have a small ability to fall through the water column, and will thus be carried away with the currents. Saga (1994) has investigated the particle size distribution (by weight) of drilling mud and cuttings during an exploration drilling in the Barents Sea. A typical particle size distribution found by Saga (1994) is shown in the Tables 2.1 and 2.2.

Table 2.1. Barite in drilling mud. Particle distribution, their density, sinking velocities and numbers. Particle size distributions are according to Saga (1994). Amounts considered are 1 000 kg barite.



Diameter	Weight,	Density,	Velocity,	Velocity,	Volume	No. part.	No. part.
mm	%	tonnes/m3	m/s	m/day	m3	-	%
0.0007	10	4.2	4.4E-07	0.04	0.0238	1.33E+17	71.3269
0.001	10	4.2	9.1E-07	0.08	0.0238	4.55E+16	24.4651
0.002	10	4.2	3.6E-06	0.31	0.0238	5.68E+15	3.0581
0.003	10	4.2	8.2E-06	0.71	0.0238	1.68E+15	0.9061
0.005	10	4.2	2.3E-05	1.96	0.0238	3.64E+14	0.1957
0.009	10	4.2	7.4E-05	6.35	0.0238	6.24E+13	0.0336
0.014	10	4.2	1.8E-04	15.37	0.0238	1.66E+13	0.0089
0.018	10	4.2	2.9E-04	25.41	0.0238	7.8E+12	0.0042
0.028	10	4.2	7.1E-04	61.49	0.0238	2.07E+12	0.0011
0.05	10	4.2	2.3E-03	196.08	0.0238	3.64E+11	0.0002

Table 2.2. Drill cuttings. Particle distribution, their density, sinking velocities and numbers. Particle size distributions are according to Saga (1994). Amounts considered are 1 000 kg cuttings.



Diameter	Weight	Density	Velocity	Velocity	Volume	No. part.	No. part.
mm	%	tonnes/m3	m/s	m/day	m3	-	%
0.007	10	2.4	1.9E-05	1.7	0.0417	2.3E+14	88.0915124
0.015	10	2.4	8.8E-05	7.6	0.0417	2.4E+13	8.9527078
0.025	10	2.4	2.5E-04	21.2	0.0417	5.1E+12	1.9337849
0.035	10	2.4	4.8E-04	41.6	0.0417	1.9E+12	0.7047321
0.05	10	2.4	9.8E-04	84.9	0.0417	6.4E+11	0.2417231
0.075	10	2.4	2.2E-03	191.0	0.0417	1.9E+11	0.0716217
0.2	10	2.4	1.6E-02	1356.5	0.0417	9.9E+09	0.0037769
0.6	10	2.4	5.7E-02	4898.9	0.0417	3.7E+08	0.0001399
3	10	2.4	2.1E-01	17988.5	0.0417	2.9E+06	0.0000011
7	10	2.4	3.2E-01	27483.8	0.0417	2.3E+05	0.0000001

The sinking velocities are estimated by means of Stokes law for the smallest particles (that is, velocity of the particle proportional to the diameter squared). The largest particles are dominated by friction forces (that is, velocity of the particle proportional to the square root of the diameter). Between these two categories, there is a transition zone. Formulas are given in CERC, 1984.

Note that the drill cuttings and barite distributions may be separated into a coarser and a finer part. For both cases, the coarse parts consist of the 5 classes with the coarsest (largest sized) particles. For the cuttings, these are the particles with sinking velocities larger than order 100 – 200 m per day. For the barite, these are the particles with sinking velocities larger than order 2 - 5 m per day. It is also evident that the sinking velocities for the different particle classes vary a lot, ranging over several orders of magnitude. If the barite particles were assumed to sink to the sea floor according to their individual sizes, only a small part would deposit close to the drilling site due to presence of horizontal currents.

3. The problem formulation

The issue is to what extent the sinking velocities given in the Tables 2.1 and 2.2 for the individual particles can be applied directly into numerical models or not.

Some discharge cases can however be excluded immediately.

- Discharges of drill cuttings and mud when oil based mud (OBM) or synthetic based mud (SBM) is used. For these cases, the mud has "sticky" properties and will therefore tend to form aggregates or lumps with sizes of some mm. These will sink with velocities generally larger than the sinking velocities of the individual particles within the lumps.

- Discharges that are redirected to the sea floor once they return from the drilling well. A common practice for drilling a well is to discharge the upper sections (mainly the 36" and the 26" drilling sections) directly on the sea floor. (For production drilling, a provisional pipe is usually laid on the sea floor to divert the drilling discharge away from the template which is to be installed.) These discharges are therefore not subjected to any phase of a free-fall through the water column. Therefore, the deposition of these will not depend on the particle size, but will deposit on the sea floor rather immediately.

It is therefore the discharges from the platform that will be of interest here in the case that water based mud (WBM) are used. This is however the most usual case today. The chemicals used in the WBM have not the same "sticky" properties as for OBM and SBM. Larger aggregates are therefore not formed, unless attraction forces between the different particles in the mud (and the cuttings particles as well) are present.

Another mechanism that will cause an enhanced downward motion of the platform discharge is the effect from the near-field plume formed immediately after the discharge has left the outlet opening. A numerical model for simulating the discharges of cuttings and mud from a platform typically consists of two sequential steps:

1. Convective descent in the near-field zone
2. Passive particle transport and spreading in the far-field zone

The near field zone lasts for a few minutes or so; they involve the creation of the "mud plume". The density difference between effluent and ambient leads to the initial convective descent of the plume. As the plume moves vertically, it entrains ambient water. This often enables the plume to attain a density equal to that of the ambient before the plume hits the ocean bottom. This neutral buoyancy signals the end of convective movement (for the most part) and the beginning of the spreading in the far field zone.

The descent of the plume will cause the particles in the discharge to move downwards with the plume, more or less independent on the size of the particles in the plume/discharge. At the end of the near-field plume, the descent ceases to occur. This will be the entrance to the second step, the far-field zone. The particles are then subjected to motion caused by oceanic turbulence, ocean currents and sinking velocities in accordance with their sizes and densities. It will be during this last (far-field) stage that the flocculation of the particles may play a role for enhancing the sinking velocities down to the sea floor.

Flocculation is the process of forming aggregates of particles suspended in the water column due to attraction forces between the particles. New particles are then formed, which are the aggregates (or “flocks”). The particles will then not appear as moving according to their individual size, shape and density, but will adapt the characteristics of the flock that it belongs. Because the flocks generally have an over-all larger diameter than the particles forming it, the sinking velocity may increase, compared to the sinking velocity of the individual particles.

4. Comparison between model results and measurements

In case that the vertical descent of the near field plume is small compared to the total water depth, the distribution of the particles on the sea floor will be influenced by the extent of flocculation processes present. If the water depth is smaller than, say 100 m, the near field plume may contribute substantially to the vertical descent. For depths larger than 200 – 300 m, the vertical descent caused by the near-field plume will generally be small compared to the total distance between the discharge point and the sea floor. This is the case that will be important for the flocculation processes, and will be considered in the following.

It is the barite particles that will primarily be subjected to attraction forces due to their large numbers. The Table 2.1 indicates the number of particles for the different particle classes. Note that for one ton of barite, number of particles surpasses 10^{17}. This number is quite high. As an illustration, note that dividing one m^3 of barite into particles all sized by 1 μm diameter would form about

(10^6 x 10^6 x 10^6 =) 10^{18} particles.

The Table 2.1 also shows that the sinking velocities of the barite particles are generally slow. For depths larger than order 100 m, it will only be the largest one or two classes of particles (with sinking velocities larger than order 50 – 100 m per day) that will have the ability to deposit relatively close (within some km) from the discharge site. The rest is expected to be carried away with the ocean currents for deposition at larger distances.

The presence of flocculation processes will however be able to alter this picture by forming flocks with larger diameters and thus larger sinking velocities. One way of finding out would therefore be to investigate to what extent the barite discharged is found on the sea floor close to the discharge point or not. Fortunately, barium is one of the parameters usually incorporated into the surveillance programs carried out in drilling areas. Models for simulating the spreading and the deposition of the barite on the sea floor can then be compared to observations of the barium in the vicinity of the discharge site. The relation between the barite (mainly $BaSO_4$) deposited on the sea floor (expressed through mg/m^2 $BaSO_4$ deposited) and the barium observed in the sediment (Ba in mg/kg dry sediment) can be written approximately as

$$1 \text{ g Ba/kg dry sediment} \iff 27.2 \text{ g } BaSO_4/m^2$$

where the atomic weights of Ba, S and O are used. Sampling of the sediment for the determination of the barium content is assumed to be within the upper 10 mm of the sediments on the sea floor. The amount of dry sediment within the upper 10 mm of the sea floor is assumed to be 16 kg (about 35 % porosity) per m^2. Background concentrations of Ba in the sediment are neglected.

Model simulations of the deposition of the barite can then be compared with results from measurements of barium in the sediment. One such comparison is reported in Rye et. al. (2004). The model used is the *ParTrack* model described in Rye et. al.

(1998). Discharges were simulated for the Norne field in the Norwegian Sea, comprising one area with three templates installed and one area with two templates installed. The depth in the area is about 380 m. Water based mud was used. The total discharge of barite and cuttings from the platform was of order 10 000 tons of each. Figures 4.1 and 4.2 show the results from the comparison between the barite deposited (calculated) and barite (converted from barium) in the sediment. The correspondence between the measured and the calculated deposition of the barite is good. The maximum levels of barite (exceeding 100 g/m^2 towards the NW of the discharge points) are well reproduced in both cases, and also the lower concentration levels at larger distances from the discharge points (interval 10 – 30 g/m^2 and also interval 30 – 100 g/m^2) appear to be well reproduced in both cases. Further details are given in Rye et. al. (2004).

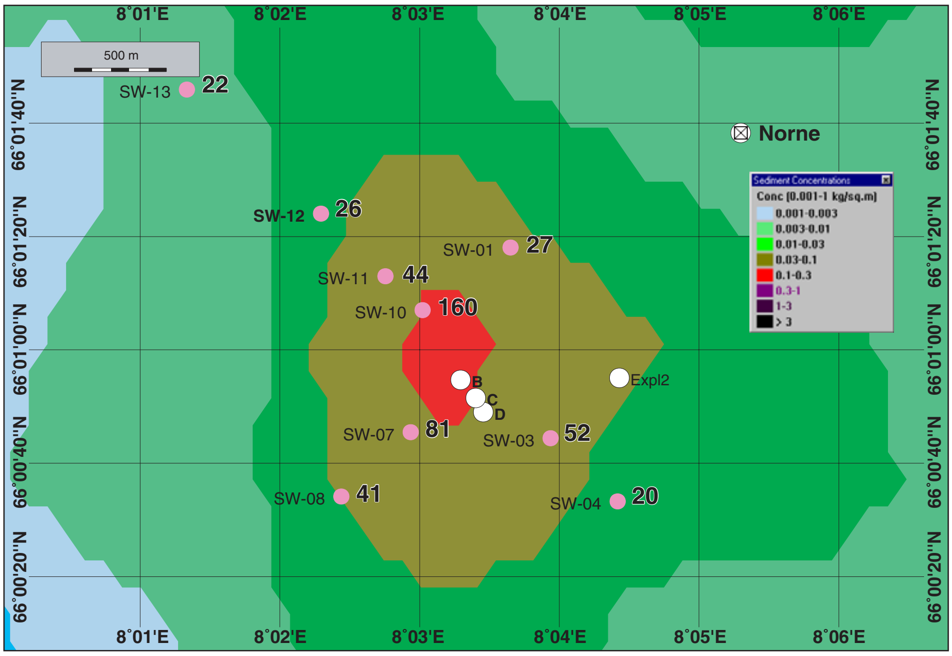


Figure 4.1 Calculation of the total deposition of the barite, shown jointly with the measured deposition of the barite on the sea floor. B, C and D indicate the location of the templates. Discharge point and measuring stations are shown as well. Units of barite deposited are g/m^2 from field measurements and kg/m^2 from the ParTrack calculations. SW part of the field.

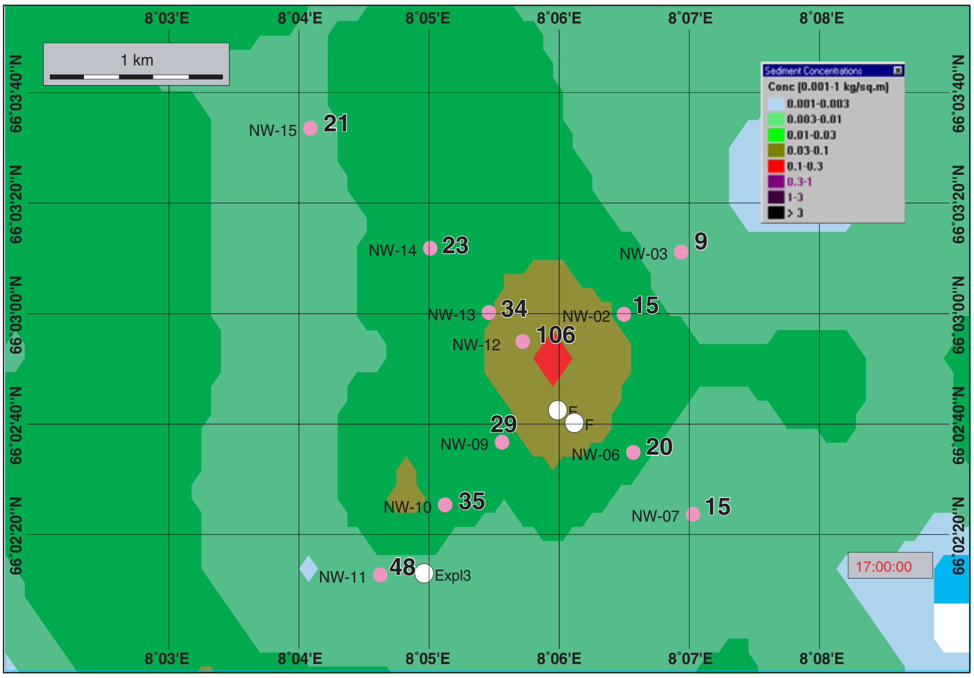


Figure 4.2. Calculation of the total deposition of the barite, shown jointly with the measured deposition of the barite on the sea floor. E and F indicate the location of the templates. Discharge point and measuring stations are shown as well. Units of barite deposited is g/m^2 from field measurements and kg/m^2 from the ParTrack calculations. NW part of the field.

The amounts of the barite is on a much lower level (order 100 g/m^2 close to discharge location), compared to the amounts of the cuttings deposited (calculated to be of order 1 kg/m^2 close to discharge location). While the amounts discharged of both the cuttings and the barite summarize to about 10 000 tons each, it is evident that the cuttings tend to concentrate much closer to the discharge points than the barite. One reason for this is the differences in the particle size distributions, where the barite comprises much smaller particles than the cuttings, as shown in the Tables 2.1 and 2.2.

The barite particles are thus expected to deposit on a much larger geographical scale than the cuttings. Figure 4.3 shows the deposition of the barite on the sea floor on a larger scale (up to order 25 km from the discharge area). The barite deposits at larger distances, but the layer build-up is small, of order within 10 g/m^2 (which will represent a barite layer thickness of maximum 5 – 6 μm). Also note the amount of barite still present in the water column at the end of the simulation period (see the bars inserted in Figure 4.3). More than 50 % of the barite has not reached the sea floor at all during the simulation period. This is basically the fine parts of the barite particles, which have small sinking velocities. Recall Table 2.1, which shows that the fine parts of the barite particles have sinking velocities smaller than 2 – 5 m per day. This means that the sinking velocities for these particles are too small to reach the sea floor during a simulation period of 40 days if the depth (below the depth of trapping of the underwater plume) is larger than order 100 m (which is actually the case for the *Norne* field).

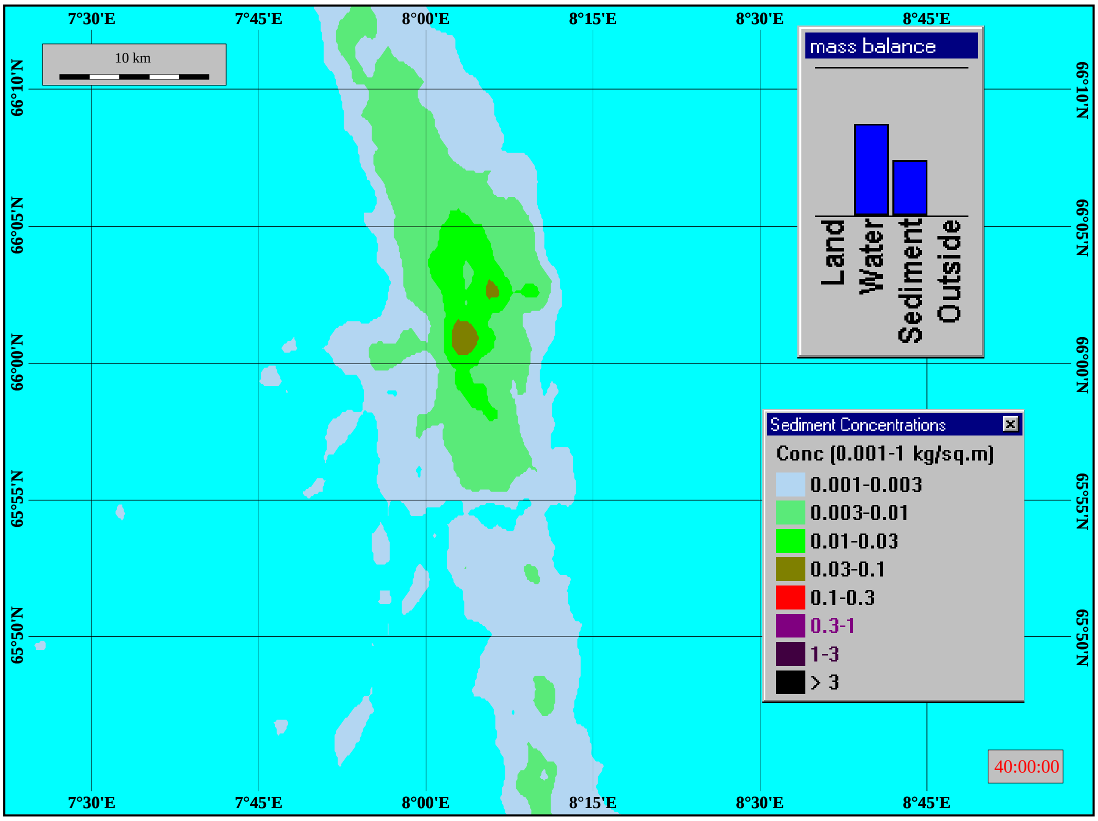


Figure 4.3. Deposition of the total barite on the sea floor. Regional scale. Calculation results from the ParTrack model. From Rye et. al. (2004).

No flocculation (or re-suspension processes) is included in these simulations. The amounts of the barite found on the sea floor close to the template areas represent only order 10 % of the total discharges of barite, which will be of order 1000 tons. The observed (and also simulated) order 100g/m^2 (or 100 tons/km^2) of the barite close to the drilling sites represents an area or order 10 km^2 in the vicinity of the drilling sites.

Other indications of the lack of influences from any flocculation processes of the barite are described in the CAMP (*California Outer Continental Shelf Phase II Monitoring Program*) results. This study was also carried out at depths larger than 100 m. Discharges from three drilling sites located on 131, 183 and 204 m depth were measured extensively during a time periods of about two years (Coats, 1994). Barium concentrations were used as a “tracer”, similar to what was done in the *Norne* study. Reasonably agreements with observations were found in the CAMP study, assuming that the barite were descending with an over-all velocity of 0.06 cm/s (or about 50 m/day) from the depth of entrapment of the underwater plume (at about 100 - 150 m above the bottom). This means that the particulate matter (barite) used order 2 - 3 days to descend the last 100 - 150 m of the water column before it reached the sea floor. One of the consequences of this was that about 80 % of the barite settled at larger distances than 500 m from the discharge points. This conclusion is rather consistent with the far-field spreading of the barite found in the studies on the *Norne* field (Rye et. al., 2004).

The assumption used in the CAMP study that all barite descended (as an average value) with a velocity close to 0.06 cm/s is a rather crude one. The reason for this is that particle diameters in the barite are highly variable, which will cause the barite to descend through the water column with different velocities. It could be worth while to point out that the particle distribution found by Saga (1994) indeed indicates that about 20 % of the barite particles descends with velocities larger than 50 m/day (or 0.06 cm/s). The other 80 % of the particles descended with lower sinking velocities (down to below 1 m/day for the smallest particles). See the Table 2.1 for the sinking velocities of the barite particles based on Saga’s results. These velocities are estimated on the basis that no flocculation takes place. Since the smallest particles (sinking velocities pr. day smaller than 2 – 5 m) are not expected to reach the sea floor within a reasonable distance from the source, it will only be the coarse part of the barite that is expected to be determined on the sea floor. For the coarse part, an average sinking velocity will be within the interval 15 – 61 m/day, see Table 2.1. Thus, the observational results from the CAMP project could therefore be explained by the sinking velocities of the size varying barite particles alone, without involving any influence from flocculation processes.

5. Results from laboratory experiments

Laboratory investigations on the flocculation processes have been carried out. One attempt to approach the flocculation issue in a systematic manner has been made by Huang (1992). In the following, the results from Huang's flume experiments will be used to look into the importance of the flocculation processes for the descent of the barite down on the sea floor.

Two opposing processes act upon the flock formation process:

- First, increased concentration of the particulate matter tends to stimulate the flocculation process.

- Second, the presence of shear currents in the ambient water (like the presence of turbulence, boundary layer flow or an underwater plume) will tend to break up the bonds between the particles in the flock.

It is difficult to decide which of the processes that will dominate the flock formation (or disintegration) process without making attempts to quantify these processes. The flock formation could both hamper and accelerate the descent of the barite. If the flocks formed have a large surface area compared to its weight, the sinking of the barite could be slowed down due to friction (drag) forces. If the flocks formed have a more dense structure, the descent of the barite can be accelerated.

Hening Huang (1992) made laboratory experiments on the settling speeds, resuspension and flocculation properties of drilling muds and river sediments. He was able to simulate in the laboratory both the driving force of the flocculation process (the concentration of the solids) and the disintegration of the flocks by means of the fluid shear (by using what Huang denotes a “Couette flocculator”). He was also able to formulate a non-dimensional number (the “flocculation number” F_l) which expresses the relative importance of these two forces. All of Huang’s results were then expressed in terms of this non-dimensional parameter F_l.

The non-dimensional flocculation number F_l was defined as

$$F_l = \frac{G\,C_m\,{d_{m0}}^2}{\mu} \qquad (5.1)$$

where d_{m0} and C_m are the median diameter and the concentration of the primary (undisturbed) solid particles, respectively. μ is the dynamic viscosity of the fluid and G is the effective turbulent shear defined as

$$G = \sqrt{\frac{\nu}{\varepsilon}} \qquad (5.2)$$

where ν is the kinematic viscosity of the fluid and ε is the turbulent energy dissipation rate. The fluid shear properties are then expressed through the turbulent energy dissipation rate ε. It is possible to relate the turbulent energy dissipation rate to the characteristics of a stationary near-field plume by the relation

$$\varepsilon = C\frac{u^3}{b} \qquad (5.3)$$

where C is an empirical non-dimensional constant, u is the average velocity within a near-field plume and b is the corresponding width of the plume. All these properties are easily determined from a near-field plume calculation. The constant C has been estimated by Johansen (1997) to be 0.012.

Likewise, the concentration of the particulate matter C_m within a plume can also be determined from the output of a near-field plume model.

The final parameter to be determined is then the median size of the particulate matter before the flocculation process starts, d_{m0}. Huang used drilling mud from a platform in the Santa Barbara Channel, USA. Excluding water, approximately 65 % of the mud was barite and 30 % was bentonite, while the rest consisted of small amounts of additives. The particle size distribution (for both the barite and the bentonite) compared well to a log-normal distribution with a median diameter of 6 μm and a standard geometric deviation of 2.4. All of Huang's results are related to this particle distribution. Note that the median diameter of 6 μm seems to compare well with the observed distribution of barite particle sizes shown in Table 2.1.

Restricting to the flocculation processes studied by Huang for the drilling mud, he obtained the following relations based on the lab experiments:

$$d_{ms} = d_{m0} 1.788\ F_l^{-0.146} \qquad (5.4a)$$

$$T_s = 0.00134\ F_l^{-0.564} \qquad (5.5)$$

$$w_s = 6.75 G^{0.20}\ d_f^{0.56} \qquad (5.6)$$

where d_{ms} is the medium diameter of the flocks formed, T_s is the time to reach the steady state of flocculation (minutes) and w_s is the measured settling speeds of the flocks (in 10^{-6} m/s). The flock size d_f is in equation (5.6) given in 10^{-6} m. G is taken from equation (5.2) and has the dimension s^{-1}. d_f in equation (5.6) is put equal to d_{ms}.

These formulas are restricted to be used for a state where the flocks are formed from a balance between the flock forming processes (concentration) and the ocean current shears. One such state would be within a near field plume. It should therefore be applied for the shears and the concentrations expected within a near-field plume resulting from a discharges of drilling debris into the sea.

Application of Huang's results to a typical drilling operation.

OLF (1966) made some estimates of typical discharge rates of chemicals, cuttings and barite expected during drilling. Typical amounts of barite discharged during drilling is of order 1000 tons (water based mud), depending on the depth of the hole. Along with it, cuttings and chemicals are discharged as well. As order of magnitudes, 1000 tons are assumed for the cuttings as well and for the chemicals (including water) for one single well.

Typical duration of the release is of order 8 days (4000 m well depth, penetration rate of order 20 m/hour). We then assume that discharges only take place during drilling operation. These numbers result into a discharge rate of order 4 – 5 kg/s for the mixture of barite, cuttings and other chemicals.

During later years, the amounts of barite used have tended to be reduced. The reason for this is economy and also possible environmental impacts from the barite. Two discharge rates of barite are therefore considered, one rate based on 100 tons of barite discharged in total and one rate with 1000 tons of barite discharged in total.

These amounts are then used as a basis for calculations of expected plume width (*b*), velocity (*u*) within the plume and barite concentration (C_m) within the plume. Along with numbers for ν (10^{-6} m^2/s) and μ (= $\rho\,\nu$, where ρ is the density of the ambient water, of order 10^3 kg/m^3), numbers for the parameters in the formulas (5.1 – 5.6) can be estimated. d_{m0} is chosen equal to 6 μm.

The plume calculations are based on the near-field plume model *DeepBlow* (Johansen, 2000). This model calculates the plume path, width and velocity, given the ambient stratification and vertical current profile. For the case with a weak ambient stratification (typical for offshore conditions) and with weak ambient currents (which will allow the plume to sink to considerable depths), the plume concentration of barite, the plume velocity and the plume width have been calculated as shown in the Figures 5.1 – 5.4. Further assumptions for the calculations are release depth at 10 m, density of barite 4200 kg/m^3, density of cuttings 2400 kg/m^3 and over-all density of other ingredients in the discharge (chemicals, water) 1000 kg/m^3.

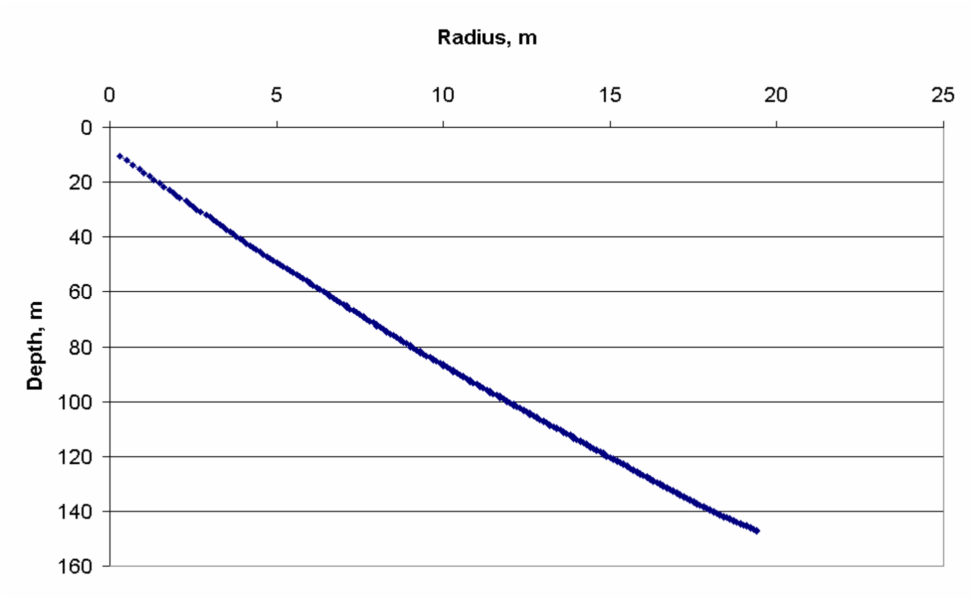


Figure 5.1. Typical near-field plume radius calculated with the DeepBlow model.

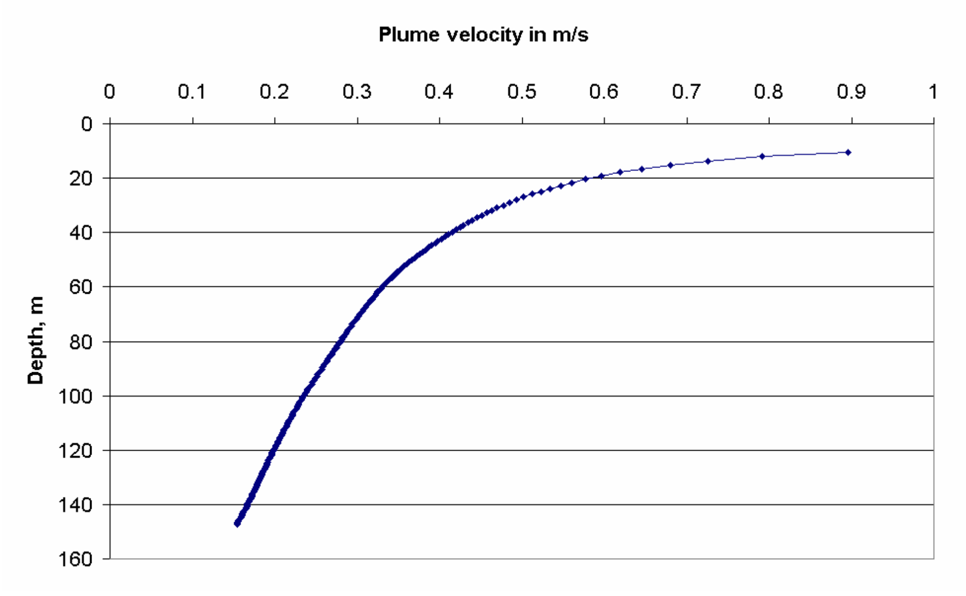


Figure 5.2.Typical plume velocity of the near-field underwater plume calculated with the DeepBlow Model.

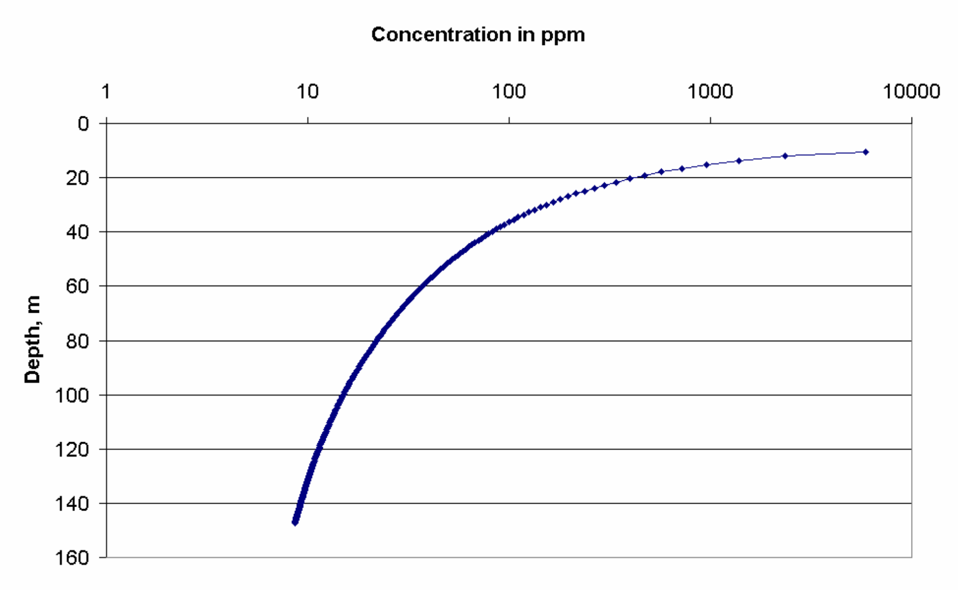


Figure 5.3. Concentration of barite in a near-field plume calculated by the DeepBlow model, 1000 tons of barite discharged in total.

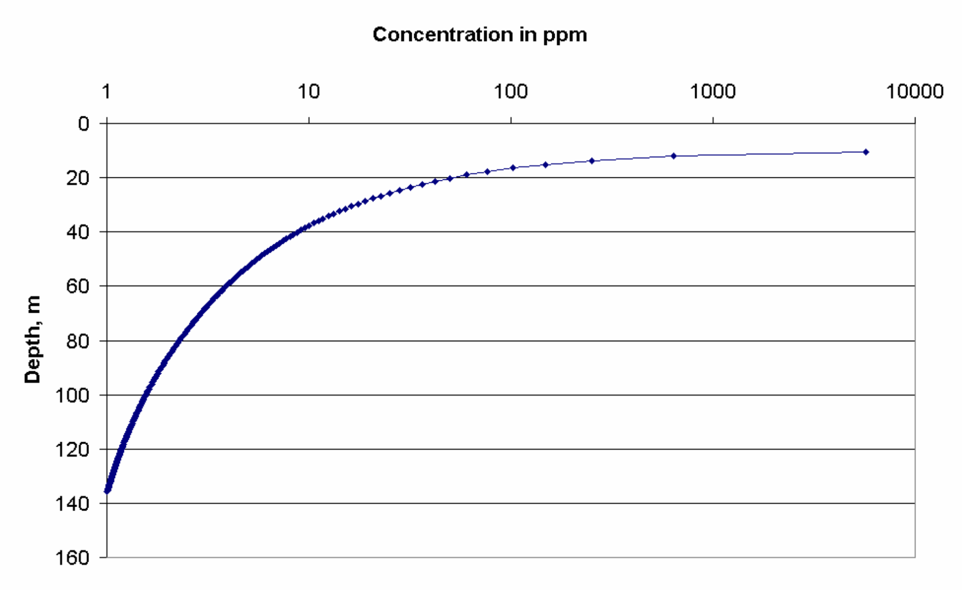


Figure 5.4. Concentration of barite in a near-field plume calculated by the DeepBlow model, 100 tons of barite discharged in total.

These calculations form the basis for evaluation of the parameters in the formulas 5.4 – 5.6, namely the size of the flocks, their sinking velocity and the time spent to an equilibrium state (that is, a balance between the flock forming and the flock reduction processes) is reached.

When numbers for the flock formation processes expected in the plume calculated are substituted into the formulas, it turns out that the flocculation number range studied in the lab (F_l of order 10^{-6} – 10^{-8}) is different from the flocculation number range calculated for the underwater plume (F_l of order 2 - 6 x 10^{-10} for the high barite content in the plume case, F_l of order 2 - 7 x 10^{-11} for the low barite content in the plume case). It is therefore uncertain to what extent the parameter range applied in the lab experiments by Huang can be extrapolated into the parameter range that is typical for underwater plumes generated from discharges of drill cuttings and mud. A lower flocculation number in the field means that the flock formation processes are much weaker in the field than what has been simulated in the lab, compared to the flock disintegration processes.

Actual number ranges for the flocculation processes calculated for the near field plume are as given in Table 5.1:

Table 5.1. Results from the calculation of the flocculation processes for a near-field plume.

Flocculation parameter	**Low amounts of barite**	**Large amounts of barite**
Flocculation number	2 – 7 x 10^{-11}	2 – 6 x 10^{-10}
Flock diameter, μ m	325 - 385	235 - 278
Flock sinking velocity, m/day	7 – 15	6 - 13
Time to equilibrium state, min.	713 - 1360	70 - 150

The table shows that the flocks are increasing to considerable diameters (increasing by a factor of 50 or so), but the sinking velocity is still low (generally lower than 15 m/day). This means that the increase in sinking velocity only represents an increase in diameter from 6 to maximum 14 μm for not flocculated particles, which represents a very moderate increase in the sinking velocity, see Table 2.1. These results indicate that the flocks may be formed, but the increase in sinking velocity is almost negligible.

Also, the time to reach an equilibrium state is large, of order 1 – 20 hours. This is far longer durations than the transition time of the particles through a near-field plume. As an example, a 0.2 m/s velocity (see Figure 5.2) of a plume over a range of 150 m will cause the particles to pass through a plume after about 12 minutes, which means that the equilibrium state within an underwater plume will not be reached.

To sum up, the parameter range studied by Huang (1992) seems to be out of range, compared to what would be expected within an underwater plume generated from an actual discharge of drill cuttings and mud. If the results from Huang's study are still assumed to be valid for an underwater plume, they indicate that formation of flocks probably does take place, but the increase in the sinking velocity will only be slight. The practical implication of these results will therefore be that the benefit from including flocculation processes in the simulations is questionable. The sinking velocity of the flocks will be more or less similar to the sinking velocities of the particles, assuming that no flocculation processes are taking place.

6. Observational evidence

Flocks of particles originating from debris from drilling activity have been observed in the field. Photographic equipment has been brought down on the sea floor at a drilling site off the coast of Nova Scotia (Copan oil fields on Sable Island Bank, at about 35 m depth). Extensive coverance of flocks on the sea floor (90 %) was observed within 500 m from the drilling site. Flocks were observed up to 15 km from the drilling site (Muschenheim et. al., 1995).

As explained in chapter 3, the debris from the drilling might in the Sable Island Bank case have been deployed directly on the sea floor from the drilling of the upper 36" and 26" sections. Also, the depth is so small (35 m) that the near-field plume might have hit the sea floor directly. In any of these cases, flocculation would not have had any influence on the deposition of the barite.

In the particular case on the Sable Island Bank, the flocks observed were formed largely by bentonite and not barite. Bentonite is commonly used in the upper 36" and 26" sections. Bentonite is also known to have better flocculation properties that barite. It is therefore likely that the flocks observed in this case stem from debris from the upper drilling sections discharged directly on the sea floor.

During drilling operations in the North Sea, ROV's are often used to survey the operations on the sea floor. A lot of recordings are made from these ROV surveys. Looking at such materials might give some impressions on the properties of the materials deposited on the sea floor. By inspecting such ROV recordings for a case where the upper drilling sections are finished, but before the drilling of the deeper sections starts (that is, before the discharge is taking place from the platform), reveals that the debris on the sea floor from the upper drilling sections has a very "muddy" character, an apparent presence of flocks formed, and is also very easy to bring into re-suspension (by touching the sea floor with the ROV). This might explain the observation of the flocks at 15 km from the drilling site in the Sable Island Bank base (Muschenheim et. al., 1995). These flocks might have been brought into re-suspension and then been carried away a long distance before it re-settles again. In the Sable Island Bank case, it was also observed to be easy to bring to matter into re-suspension. They were also difficult to sample due to a high ability of the flocks to follow the water motions (which indicate that the sinking velocity of the flocks is low).

It has also been attempted to observe with an ROV the presence of flocks in the water column during drilling. By moving the ROV into the cloud of debris suspended in the water column in a case where WBM is used and discharged from a platform, it is possible to have an impression of the character of the debris that separates out of the cloud above. By using a close-up camera of the ROV, while moving inside the debris separating out of the "cloud area" above, the impression is that these are cuttings material separating out of the cloudy area, and not flocculated material.

However, it is difficult to be conclusive based on such visual impressions. Flocks formed may be so small that they do not show clearly on an ROV picture, compared to the size of cuttings material separating out of the cloudy area (diameters typically of some mm). But it may be an indication that these flocks appears to be difficult to observe in the water column in the field. Their observational evidence seems to be limited to the sea floor (or just above the sea floor) only.

7. Conclusions and recommendations

Discharges of drill cuttings and mud contain a lot of particulate matter (like barite, cuttings and sometimes bentonite) that might form flocks when discharged into the sea. This flocculation process might give rise to enhanced speeds of sinking velocities of the particles when these are moving down to the sea floor. If this is the case, flocculation processes should be included in the modeling of the discharges of drill cuttings and mud. This should be done in order to have a proper model representation of the most important processes that are taking place.

This paper has been aimed at comparing field data and numerical model data on the deposition of barite on the sea floor. As a part of this, the study has also considered possible importance of flocculation processes on the deposition rates, based on results from laboratory experiments.

Model results from the calculation of the deposition of barite with the *ParTrack* numerical simulation model (not including flocculation processes) have been compared with field data on the deposition of barium in the vicinity of the *Norne* field, where water based drilling fluid (mud) were used, basically. Laboratory results on the flocculation of drilling fluid (including barite) were applied on the typical conditions expected within a near-field plume for the discharge of drill cuttings and mud, using the *DeepBlow* near-field model. Both these studies tend to point to the same conclusion that flocculation processes are probably not sufficiently important or significant to be included in the modeling process. A reasonably good correspondence between field data and numerical simulation results were obtained for the *Norne* field without including any flocculation processes in the simulations. Also, the application of the laboratory results to a typical near-field plume tend to indicate that although flocks may form, the sinking velocities of the flocks will not change to a considerable extent (compared to the sinking velocities estimated from no flock formation conditions).

This conclusion seems also to be supported by observational evidence based on ROV recordings, observations on the sea floor at the Sable Island Bank and also supported by results from the CAMP study.

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