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DISCUSSION

Physico-chemical effects on the behaviour of a coastal mudslide

R. MOORE and D. BRUNSDEN (1996). *Géotechnique* **46**, No. 2, 259–278.

R. W. W. Anson and A. B. Hawkins, *University of Bristol*

We read the paper by Moore & Brunsden with interest. It raises a new dimension to the study of landslides which, if further substantiated, has implications not only for coastal studies but also for the different chemical environment pertaining inland. However, we regret the paper does not give the reader sufficient information on which to make an independent assessment, particularly as it contains conflicting data.

The authors do not include a topographic map or discuss the nature of the inland surface catchment area. Although a topographic low can be seen in Fig. 8, they do not draw attention to the substantial valley feature from Tyneham which has a 10 m deep tributary stream approximately parallel to the coast, some 100 m inland of the cliff on which the mudslide occurs (see Fig. 16).

A detailed geological cross section indicating the thickness of the main source clay horizon and the relationship of the northern tributary source area shown in Fig. 10 would have been helpful. The fact that this tributary source area is not indicated in Fig. 4 undermines its importance.

The limited geotechnical/mineralogical data provided is confusing. For example, if it is assumed that the montmorillonite percentages given in Table 4 are proportions of the clay fraction and not the whole rock, at positions 6 and 5, 42 and 45% of the material is montmorillonitic. If the tributary source area does not contain a similar percentage of montmorillonite, it could explain the lower montmorillonite percentage (26%) below the confluence of the mudslides (position 2). Although the authors have suggested weathering as an explanation, it is surprising that the montmorillonite percentage rises from 23 to 42% within 10 m of the

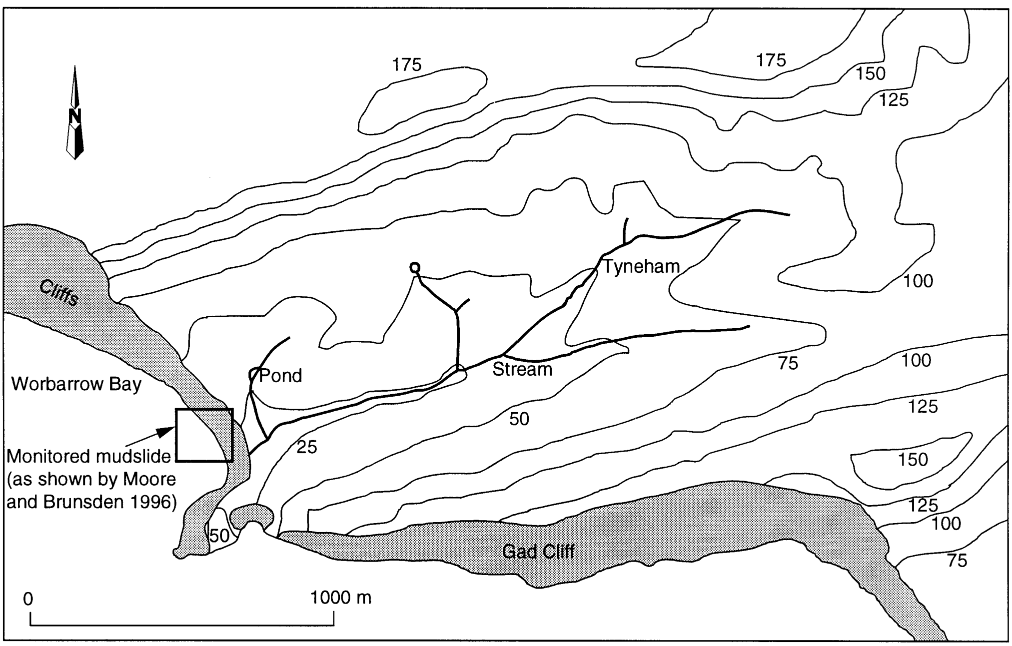

Fig. 16. Topography of the Worbarrow Bay area

rear scarp if the same source material is involved. The Atterberg limits at position 6 are also surprisingly low for a material with over 40% montmorillonite.

Readers are not given sufficient data to interpret the significance of the precipitation. It is surprising that, in a westerly facing bay, the total rainfall recorded on the mudslide in November 1986 is only one-fifth of that recorded at locations within the 100 m inland of the cliff top. The authors do not discuss where such water will manifest itself – in the tributary stream or passing through bedrock of permeabilities, with possibly a few days' delay.

No explanation is given for the different pore pressures indicated for the same time period in Figs 7 and 9. For example, in Fig. 7 the maximum pore pressures of 7 and 19 kPa recorded at the shear surface at positions 2 and 6 are approximately equal to the effective overburden pressure; in Fig. 9 the maximum pore pressures are almost double the effective overburden pressure.

Figure 13 implies that the pore water concentration is below 60 meq/l in the lobe of the mudslide where it would be anticipated that the maximum salt spray would occur. The values in this figure are not consistent with those given in Table 4.

In Moore (1991) the effects of sea water concentration on residual shear strength were measured at only one σ'_n (250 kPa) and the ϕ'_r determined assuming a c'_r of zero. In view of this it is difficult to understand how the values of c'_r given in Table 5 were established and their relevance for a shear surface at 0·45 m (position 6) to 1·2 m depth (position 2).

If the periods of movement shown in Fig. 7 are superimposed on Table 5, there is little correlation between the factor of safety shown in column C and the recorded movement. For February 1986, 5 m of movement is indicated in Fig. 7 and a factor of safety of 1·15 in Table 5; a similar situation applies for January 1987 when two surges are shown in Fig. 9.

In view of the inconsistencies in the paper and the authors' failure to adequately explain the role of precipitation and/or the passage of ground water through a bedrock of varying permeabilities, both elaboration and clarification are required before the value of the hypothesized model can be assessed.

A. Sridharan and K. Prakash. *Indian Institue of Science, Bangalore, India*

The authors have presented the results of a carefully-planned and carried out case study of a mudslide and have tried to explain the behaviour in terms of physico-chemical factors. It is well known that the soils with montmorillonite as the predominant clay mineral exhibit very low residual friction angles (Mitchell, 1976; Lambe & Whitman, 1983; Moore, 1991, to name a few). The values of ϕ_r and the montmorillonite content in the soil quoted by the authors make it very clear that the soil is of montmorillonitic type and perhaps predominantly with the monovalent ion. Careful observation of the other data presented in Table 14 and Figs 13 and 14 indicate that there is a mismatch between the liquid limit values mentioned and other properties like montmorillonite content, residual friction angle and CEC.

From the data given by the authors, the net montmorillonite content in the soil can be estimated (Table 6). For sodium montmorillonite clay, the liquid limit is more than 400% (Mesri & Olson, 1971; Lambe & Whitman, 1983; Mesri & Cepeda-Diaz, 1986; Sridharan *et al*., 1986; to name a few). Considering 400% as a lowerbound value, the liquid limit of the soil proportionate to its montmorillonite content can be calculated adopting the linear law of mixtures (Seed *et al*., 1964) (Table 6). Even if nonlinear variation is assumed (Sivapullaiah & Sridharan, 1985), the values predicted will not be very much different from those calculated as per the linear law. While the estimated values of liquid limit and ϕ_r values given by the authors are in line with the relationship between the liquid limit and ϕ_r mentioned by

Table 6. Soil properties

Parameter	In situ (core 7)	Source unit (core 6)	Feeder track (core 4)	Lobe (core 2)	Remarks
% Clay < 2 μm	45	55	39	33	Given by the authors
Montmorillonite: % (in clay fraction)	52	76	67	80	Given by the authors
Montmorillonite: % (in the overall soil)	23·4	41·8	26·1	26·4	Calculated by the discussors
Liquid limit: %	39	55	53	42	Given by the authors
Liquid limit: %	93·6	167·2	104·5	105·6	Estimated by the discussors
CEC: meq/100 g	49	44	54	52	Given by the authors
CEC for 100% clay: meq/100 g	108·9	80	138·5	157·6	Calculated by the discussors

Mitchell (1976) (p. 285), the value of ϕ_r back calculated from such relationships corresponding to the values of liquid limit and plasticity index mentioned by the authors are significantly high.

The CEC of the soil is primarily due to its clay content and clay type. With this assumption, the values of CEC for the soil, if it were to contain 100% clay, can be estimated (Table 6). It can be noted that the value of estimated CEC varies between 80 and 158 meq/100 g which is the range for sodium montmorillonite clay mineral. Hence, from the point of view of high CEC of the soil quoted by the authors, the lower liquid limit of the soils ranging from 39–55% cannot be justified.

There is fairly a good relationship between the clay content in the soil and the residual friction angle (Skempton, 1964, 1985). From the ϕ_r versus clay size fraction relationship, the clay size fractions in the soils corresponding to the values of ϕ_r obtained by the authors work out to be more than those reported by the authors.

There could be two reasons for the lower liquid limit and clay content values obtained by the authors depending upon the condition of the soil prior to testing for index properties.

(*a*) The properties of some of the marine soils are drastically affected by the drying process. Cochin marine clay and Mangalore marine clay belonging to the south-west coast of India are typical examples of that type. The data reported by Jose *et al.* (1988), Jose (1989), Rao *et al.*, (1989) and Abraham (1993) are used in plotting the Figs 17 and 18 which show the effect of air drying and oven drying the Cochin and Mangalore marine soils before testing them for liquid limit and clay content. While the air drying reduces the liquid limit by about 15–35%, the soils experience a reduction of about 30–70% in their liquid limits upon oven drying from their natural moist condition. The reduction in clay content of about 10–30% after air drying and of about 35–55% upon oven drying is also evident.

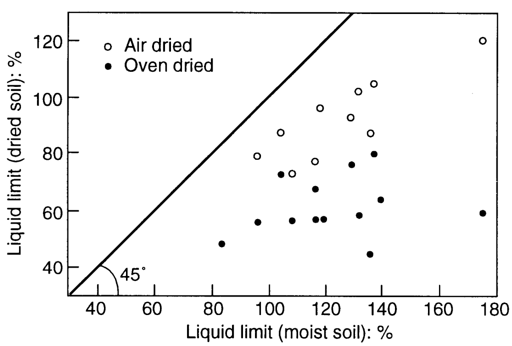

Fig. 17. Effect of drying the soil on liquid unit of Cochin and Mangalore marine soils

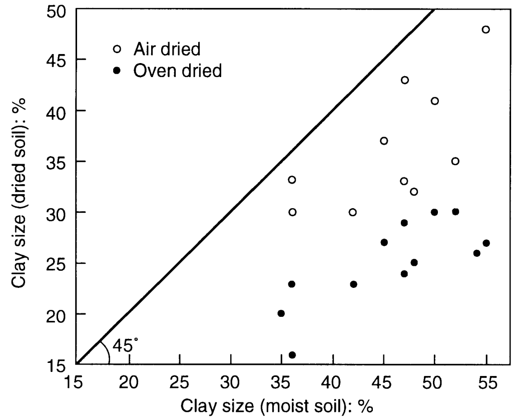

Fig. 18. Effect of drying the soil on percentage clay size fractions of Chochin and Mangalore marine soils

(*b*) The writers are not aware of the nature of the fabric of the soil investigated by the authors. If it has highly aggregated fabric, then disaggregation is expected to increase the liquid limit significantly with little further decrease in ϕ_r. Mesri & Cepeda-Diaz (1986) have quoted examples from the literature to support this view. In fact, the increase in the soil plasticity and montmorillonite content from the in situ samples to those from source area along the basal shear surface, as given in the paper under discussion, indicates the disaggregation during shear. In addition, Mesri & Cepeda-Diaz (1986) also quote examples to indicate how the grain size analysis can give misleading clay size fraction (5% instead of actual 42%) if proper precautions are not taken, especially for compositions that include montmorillonite.

The above could be the two possible reasons for getting the lower liquid limit and clay size fraction values, in case tests have been carried out (i) on oven or air-dried soils rather than on natural moist soil and (ii) without disaggregating the natural soil. The authors can throw some light on the above.

Apart from this, the writers wish to point out some discrepancies in the units/values of bulk unit weight and exchangeable cations presented in Fig. 14. While Table 4 gives bulk unit weight in the range 10·1–15·6 kN/m^3, Fig. 14 indicates a range of 1000–2000 kN/m^3. Similarly, Table 4 shows the exchangeable cations in the range 18·8–21·4 meq/100 g, but Fig. 14 furnishes altogether different values (i.e., 600–740 meq/100 g). Table 1 gives the sample depths (in metres?), possibly below the ground surface. The values of the sample depths under the category 'D' and 'U' do not match with their description given in the text. Either the symbols 'D' and 'U' or the numerical values appear to have interchanged their positions.

Authors' reply

The authors are grateful for the discussion contributions on the physico-chemical effects on the behaviour of a coastal mudslide. A number of points have been raised and we welcome the opportunity to provide further information and explanation. First some general comments.

Anson and Hawkins refer to the hinterland topography at Worbarrow Bay and we regret that a full topographic map and geological section were not provided. There is a small tributary valley behind the site, this was clearly shown in Fig. 8. However, the discussants must be careful not to confuse scales as the mudslide is much smaller than the main valley scale and has its source wholly within the sea cliff. Gradual retreat of the sea cliff is cutting back into the north facing valley-side slope. The tributary valley undoubtedly provides local surface and sub-surface drainage inland of the valley-side and cliff-top, towards the main stream to the south-east of the site. The tributary valley is, therefore, not considered to be a significant source of groundwater to the mudslide and coastal cliff at the present time. The main source of groundwater seepage observed in the rear scarp at the site is believed to originate from sub-surface drainage of the major chalk escarpment upslope to the north. We accept that we are unable to confirm the source and passage of groundwater through the bedrock because we have no data on this.

The distribution of rainfall was clearly shown in Figs 7 and 8. The automatic weather station was sited at a comparable elevation to the cliff-top (c. 28 m above local datum), around 100 m inland, and it is considered that the data recorded at this site is broadly representative of the climate at Worbarrow Bay, particularly since precautions were taken to assess the influence of micro-climate. Micro-climate is clearly influenced by topography. The tributary valley is sheltered from the prevailing south-westerly winds which plume up and over the cliffs. The observation of an increase in rainfall in the lee of the coastal cliffs is well known and we see nothing inconsistent with these results. At the site much of the rainfall drained away from the cliff, either down the tributary valley or down the mudslide complex developed on the cliffs. Salt deposition was found to occur mostly on the cliffs with little input from groundwater sources inland.

To provide further consideration of the discussants view that there is a mismatch between soil properties it is necessary to consider the lithology of the source rocks at the site in more detail. The mudslide is developed within the lower units of the Wealden Beds (consisting of 716 m of lacustrine and deltaic clays and sands), which dip to the north. Around 60% of the Wealden Beds are exposed at Worbarrow Bay and the site is located approximately 198 m from the base of the exposure. The Wealden Beds have been divided into two distinct units; the lower unit comprises the Wealden Marls or variegated clays and the upper unit the Wealden Shales (Melville & Freshney, 1982). The stratigraphy of the upper part of the Wealden Beds is reportedly similar to the Weald Clay (Anderson, 1967).

The clay mineralogy of the Wealden Beds has received little attention compared with London Clay and Weald Clay. A comprehensive review of the literature carried out by Moore (1988) showed that from 35 reported mineralogical analyses for Weald Clay, montmorillonites were found to dominate the clay fraction, as follows: 70% Montmorillonite; 20% Kaolinite; 10% Mica-Illite. Review of the literature also identified limited published data on the index and shear strength properties of the Wealden Beds and Weald Clay (Table 7).

Skempton (1953) used data for Weald Clay to compare the relationship between plasticity index and clay fraction which showed two groups of data, as follows: Group 1; clay fraction = 15–40%, plasticity index $\leqslant$ 20%; Group 2; clay fraction = 50–70%, plasticity index = 30–45%.

Taylor & Smith (1986) also show data that is consistent with this grouping. Although the discussants point out that the index properties are low, the range of values of clay fraction and plasticity fall between these sets of data. In comparing the data (Table 7), the plastic limit and clay fraction do appear to be on the low side, although we feel

Table 7. Reported properties for Wealden Beds and Weald Clay

Unit	LL %	PL %	Ip %	Clay %	Ip/Clay	ϕ'_r (°)	Source
Wealden (Paddock Wood)					0·68		Skempton, 1953
Weald clay (Sevenoaks)		26	39	60	0·65	15·5–16·5	Skempton & Hutchinson, 1969
Weald clay (Sevenoaks)	60 (40–80)	23	37	55	0·67	14–18	Skempton & Weeks, 1976
Wealden beds (Worbarrow Bay)	51 (39–62)	17 (16–22)	33 (17–43)	45 (33–59)	0·76 (0·38–0·97)	8 (6–9)	This study

this was due to the high silt fraction and some fine sand (see Table 8), particularly in the feeder track and lobe of the mudslide. Skempton (1985) showed the relationship between clay content and ϕ'_r for natural and artificial soils; for soils with an average clay content of 45%, ϕ'_r was estimated to be around 10°, which is slightly higher than found at the Worbarrow site. We do not feel that our data are inconsistent with the limited published data for the Wealden, rather they add to them.

With regard to some more specific points raised by the discussants, Table 8 provides additional data for all core samples obtained from the site. The semi-quantitative estimates of montmorillonite within the clay fraction and soil are shown, along with silt and fine sand content and calculation of activity ratio. The data shows there was higher montmorillonite content along the shear surface of the mudslide compared with in situ rear-scarp materials, which also had greater silt content. This was most likely due to lithological variability of source materials as suggested by Anson & Hawkins; the samples tested varied in elevation by at least 1–2 m, allowing for the northward dip in strata (Table 1).

It is also apparent that inputs of sediment occurred along the feeder track from adjacent cliffs and mud-runs (see Fig. 3), resulting in higher silt and fine sand content (Table 8). No sampling or testing was carried out in these secondary source areas although it is apparent that the clay fraction was less in cores 1–4 due to the mixing of materials, of different grading, caused by the degradation of the cliffs and mudslide. The montmorillonite content of the clay fraction within the mudslide was relatively constant averaging over 70%. Hence, the explanation for the lower montmorillonite content within the soil at position 2 is simply explained by the low clay fraction.

We accept that values of liquid limit appear on the low side for soils which may contain as much as 44% montmorillonite. Shridharan and Prakash suggest several reasons why clay content and liquid limit may be underestimated by inappropriate test methods. Determination of liquid limit was carried out using a cone penetrometer and standard procedures (BS 1377, 1975; Head, 1984); moist samples were used for this method. Although inevitably some air-drying may have taken place during transfer and preparation of samples, we do not feel that this will have significantly affected the properties of the clays.

Shridharan and Prakash are right to point out that disaggregation during weathering and shear is clearly a fundamental process in mudslide behaviour. The grain size analysis of all samples involved the use of a Malvern Laser Particle Sizer to determine the silt and clay-size fraction accurately. In this respect precautions were taken to ensure complete disaggregation of the samples. All samples were initially treated with 50 ml (25% solution) of Calgon dispersant and 25 ml of HCl; the samples were further treated with Calgon dispersant in the ultrasonic water bath of the laser particle sizer. Because of these precautions we feel that disaggregation of the clay fraction was achieved by this method and will not have resulted in inaccurate determination of the silt and clay fractions.

Reference is made to the relationship of cation exchange capacity and liquid limit. Whereas we accept the argument made by Shridharan and Prakash, that by assuming 100% clay content the cation exchange capacity would be similar to sodium montmorillonite with high liquid limit, it would seem unrealistic to ignore the influence of silt and other gradings on the liquid limit of natural soils. Clearly the values of cation exchange capacity at Worbarrow (Table 8) are much lower than those typical of sodium montmorillonite, and

Table 8. Laboratory test results

Soil properties	Lobe 1	2	Feeder 3	Track CORE 4	5	Source 6	*In situ* 7	MEAN
Fine sand: %	7	14	0	3	0	0	0	3
Silt fraction: %	55	53	55	58	41	45	55	52
Clay fraction (CF): %	38	33	45	39	59	55	45	45
Montmorillonite in clay: %	68	80	66	67	75	76	52	69
Montmorillonite in soil: %	26	26	30	26	44	42	23	31
LL: %	51	42	62	53	52	55	39	51
PL: %	17	16	19	15	15	18	22	17
Ip: %	34	26	43	38	37	37	17	33
Activity (Ip/CF)	0·89	0·79	0·96	0·97	0·63	0·67	0·38	0·76
ϕ'_r (°)	8	9	6	9	7	8	NA	8
Porewater: meq/l	66	74	82	76	92	76	49	74
Ex. cations: meq/100 g	17	19	30	21	25	20	19	22
CEC: meq/100 g	61	52	54	54	49	44	49	52

such theoretical comparisons mislead the reality provided by measured data.

Given that the site is located in the lower units of the Wealden Beds the physico-chemical properties at the site are highly variable and include a significant silt content which we believe may have resulted in the lower clay fraction and index properties than might have been expected, even though the montmorillonite content of the clay fraction averaged 69%. It should also be borne in mind that significant variation in soil properties was observed due to the effects of cliff instability; this was clearly demonstrated by our results for undisturbed materials from the rear-scarp and the highly disturbed materials from the source area of the mudslide (Table 8). The results obtained at Worbarrow do not show significant divergence from those reported by others for similar lithologies. We are grateful to both discussant groups for drawing attention to the variability in the data. However, we do not feel that the issues raised negates the conclusions or research questions raised by the paper.

Anson and Hawkins raise an interesting point with respect to mudslide movement and factor of safety. We pointed out that this is a very small and shallow mudslide and that it did not always move throughout its length or width at the same time. Thus, although an overall slope stability calculation will yield a generalized result it does not mean that this will sensibly correlate with a single point reading either simultaneously or in a lagged sequence. It is becoming clear with sophisticated real time recording that different parts of mudslides move episodically in both time and space and that there are many kinds of mechanism such as self-loading or kinematic, wave-like motion. It may be that some parts of a slide are below a factor of safety of unity but elsewhere the slide may be stable. The surge anomaly is a good example; a failure of a small part of the slide, a sudden supply from a feeder source, or a fall from the rear-scarp can cause a surge at the point of the monitor but not a significant change in the overall factor of safety calculated using average assumptions for the slope. Neither will it necessarily produce a recognizable change in the pore pressures and concentrations all over the slide at the same time.

It is also becoming obvious with real time continuous recording that many of our traditional beliefs about the relationships between controlling variables are as simple as they are made out to be. This explains the apparent difference between the plots given in Fig. 7 and others. Figure 7 gives monthly totals or averages to show broad seasonal variations in field data. Figure 9 uses daily totals or averages from the detailed continuous record. An understanding that this will suppress data variability is needed if the reader is to use the information with profit. This is not, however, a trivial point and it is worth emphasizing that many published accounts use irregular or regular, day-point readings of porewater pressure taken on the day of visit to the site, plotted against cumulative movement data for the period between visits. These are even more misleading data sets than the use of real-time continuous data and averages. It is necessary to carefully examine all published diagrams of such recordings to be sure of their message before reaching conclusions.

The piezometric distributions from the continuous record (Fig. 9) should be used for detailed assessment. From this data the maximum porewater pressure recorded in the lobe and source area was 34 kPa and 12 kPa, respectively. Porewater pressures in the lobe showed little influence from the sea. This was most likely due to impermeability of the clays and underdrainage promoted by the beach. The low salt concentration recorded at the shear surface in the lobe reflects the more important influence of groundwater drainage along the shear surface of the mudslide and the low rates of infiltration from the surface where the majority of salt from sea-spray is deposited.

Anson and Hawkins question the relevance of residual strength testing at normal effective stress of 250 kPa. As explained by Moore (1991) it was necessary to test at this level to prevent excessive soil extrusion and disturbance to the flow of solutions through the sample during the single stage tests which took up to 20 days to complete. We accept that this normal effective stress is much greater than appropriate for the site, although we consider the effects of porewater chemistry on residual strength may be more significant at low normal effective stress. Improved ring-shear apparatus is required to enable residual strength determination at low normal loads with porewater chemistry controls.

With respect to Table 5, and as explained in the text, changes in residual shear stress established from control tests with a range of porewater salt concentrations was directly calibrated against seasonal fluctuations in porewater concentration monitored in the field. The resultant theoretical fluctuation in residual shear strength (kPa) was applied to the cohesion term of the stability equation as chemical properties were not considered likely to influence the frictional term. We do not feel that this was unreasonable given that porewater chemistry is known to have a significant influence on residual shear strength. The purpose of the stability analysis was merely to show how seasonal variations in porewater chemistry may influence shear strength and consequently mudslide stability, albeit through simplified factor of safety calculations. The stability model took account of the detailed subsurface distribution of soil properties established from the core samples throughout the mudslide.

In response to some final points raised by the discussants, first, the bulk unit weight shown in Fig. 14 should read in the range of 10–20 kN/m^3. The units for exchangeable cations shown in Fig. 14 are incorrect and should read 20, 24 and 28 meq/100 g in place of 600, 670 and 740, respectively. These cartographic errors were unfortunately overlooked from an earlier draft. Second, the porewater salt concentrations shown in Fig. 13 and Table 4 are from different dates. Table 4 shows porewater salt concentrations established from the core samples taken in April 1986 while Fig. 13 shows the porewater salt concentrations from field data in August 1986. Finally, the sample depths shown in Table 1 are given as elevations in metres above local datum.

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