Sediment Formation in Nearshore Environments: Strength, Rheology, Microstructure, and Stability

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LONG-TERM GOALS

Our goals are to understand how geotechnical and physical properties develop in marine sedimentary deposits on continental margins and how these properties influence sediment transport processes and the development of geomorphology. Our studies include predicting stability of sediment on the continental shelf and slope, providing input parameters for models of sediment transport and deformation, and distinguishing morphologic features caused by slope failure from those caused by other gravity-driven processes. Our studies also include improving our understanding of the transition between initial slope failure and the development of debris flows and turbidity currents and predicting the rheological properties that determine the dynamics of such flows. We plan to apply our studies to the EuroSTRATAFORM project, within which we collaborate with scientists seeking to model the formation and alteration of nearshore sedimentary bodies.

OBJECTIVES

Our main objectives for FY05 focused on:

(1) understanding the ways in which sediment bodies develop shear strength, rheological properties and structure;

(2) test shear strength development models in controlled environments,

(3) further the development of the concept of seismic and biologic strengthening;

(4) relate regionally distributed geotechnical properties to index properties that can be determined easily or, potentially, mapped remotely;

(5) assess the signatures of catastrophic events to determine whether they are produced by deformational (landsliding) or depositional (turbidity current sediment waves) processes, with a particular attention to the Cap de Creus Canyon;

(6) provide the scientific community the rheological properties of fully deformed sediment masses to be used by turbidity current and debris flow modelers.

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14. ABSTRACT
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15. SUBJECT TERMS

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APPROACH

Our research focuses on the geotechnical changes that occur to sediment as it is buried under the seafloor. These changes include the direct influence of burial, the impact of repeated seismic shaking (seismic strengthening), and the effects of biological activity (biological strengthening). Part of this analysis also relies on obtaining information on non-bioturbated, normally consolidated sediments via SEDCON (SEDimentation-CONsolidation) tests which can be integrated into geotechnical profiles as a reference curve enabling us to extract the relative influence of bioturbation and/or seismic strengthening. We use samples taken in connection with the EuroSTRATAFORM project in the Adriatic Sea and Gulf of Lions as well as synthetic sediment produced in the laboratory (SEDCON). We also determine the sediment microstructure using SEM techniques and mercury microporosimetry. We compare field geotechnical and microstructure profiles with those developed in the laboratory following the application of compressive loads. This will help ascertain the significance of seismic and biological strengthening in altering geotechnical profiles. Some of the observed behavior, when evaluated on cores, may have been influenced by the effect of gas dissolution leading to sample disturbance. This is being evaluated by coupling CATSCAN imaging and geotechnical properties of the cores obtained as part of EuroSTRATAFORM and PROMESS projects with *in situ* penetration test results available as part of the PROMESS project.

Key individuals, at Laval: Jacques Locat, Marie-Claude Lévesque, Serge Leroueil, Geneviève Cauchon-Voyer, Mylène Sansoucy and Pierre Therrien: strength and compressibility measurements, SEM studies, rheology measurements, and simulation of sediment accumulation; at the USGS: Homa Lee, Dianne Minasian, Pete Dartnell, and Kevin Orzech: physical property logs of sediment cores and relations between geotechnical and classification properties, algorithms relating sediment properties, environmental factors, and slope stability within the framework of a GIS, and strength development from seismic shaking. Partners in Europe are N. Sultan (France), M. Canals and R. Urgeles (Spain), and F. Trincardi (Italy). D. Orange, partner in EuroSTRATAFORM has also been participating in our work.

WORK COMPLETED

During FY 05, we completed the work related to the effect of bioturbation on strength development (Lévesque *et al.* 2005). Work completion also included detailed CATSCAN analysis of cores provided as part of the PROMESS project and cores taken in the Cap de Creus Canyon (CCC, Southwestern end of Gulf of Lions) as part of the October 2004 EuroSTRATAFORM cruise (leg 2). All the CCC cores were logged onboard the Oceanus using the USGS Multi Sensor Core Logger, and deck work also included fall cone testing and water content measurements. Once at Laval, all the CCC cores were run through the CATSCAN. All these results have been put in a report available on the internet for everyone (Sancoucy *et al.* 2005). Seven, approximately 25 cm long subsections from the deep PROMESS borings in the Adriatic Sea and Gulf of Lions were provided to the USGS and Laval by our European collaborators. These subnsections were analyzed in detail with the CATSCAN system in order to determine the effect of gas disturbance on the sampling quality and strength. Work on these PROMESS cores also included detailed physico-chemical, mineralogical, microstructural, porosimetry, and geotechnical analyses. Geotechnical testing on CCC cores has been initiated both at Laval and at the USGS, and includes Atterberg limits, water content, strength tests (intact and remoulded) using the Swedish fall cone testing, and cyclic and static direct simple shear tests (at USGS). Rheological tests were also carried out on a selected mixture of CCC samples. Work completion in FY05 also included papers prepared for various conferences and journals (Cauchon-

Voyer *et al.* 2005; Sancousy *et al.* 2005; Lee *et al.* 2004; Lee, 2005; Tappin and Lee, 2005; Locat 2005, Locat *et al.* 2005) and to a special book on debris flows (Locat and Lee 2005). FY_05 also included the completion of a major contribution to the Master Volume of STRATAFORM (Lee, Locat, et al., 2005, ch. 5).

RESULTS

CATSCAN analyses of PROMESS cores, taken in both the Adriatic Sea and the Gulf of Lions (GOL) have revealed the presence of significant artifacts likely due to gas expansion after coring (Fig. 1). For the GOL cores, in situ tests, carried out as part of PROMESS, show that a depth of 20 m corresponds more or less to the depth below which strength results from in situ testing and laboratory testing start to diverge. Below 20 m, the laboratory tests indicate a much lower strength compared with *in situ* values. This is also well illustrated by the numerous gas expansion structures seen in Figure 1 for samples below 20m. (i.e. 60 and 126 m). Cores from the Adriatic Sea and Gulf of Lions (GOL) have very different compositions. The Adriatic sediments have a significant amount of smectite compared to the GOL samples, and this impacts their plasticity index, specific surface area, and cation exchange capacity.

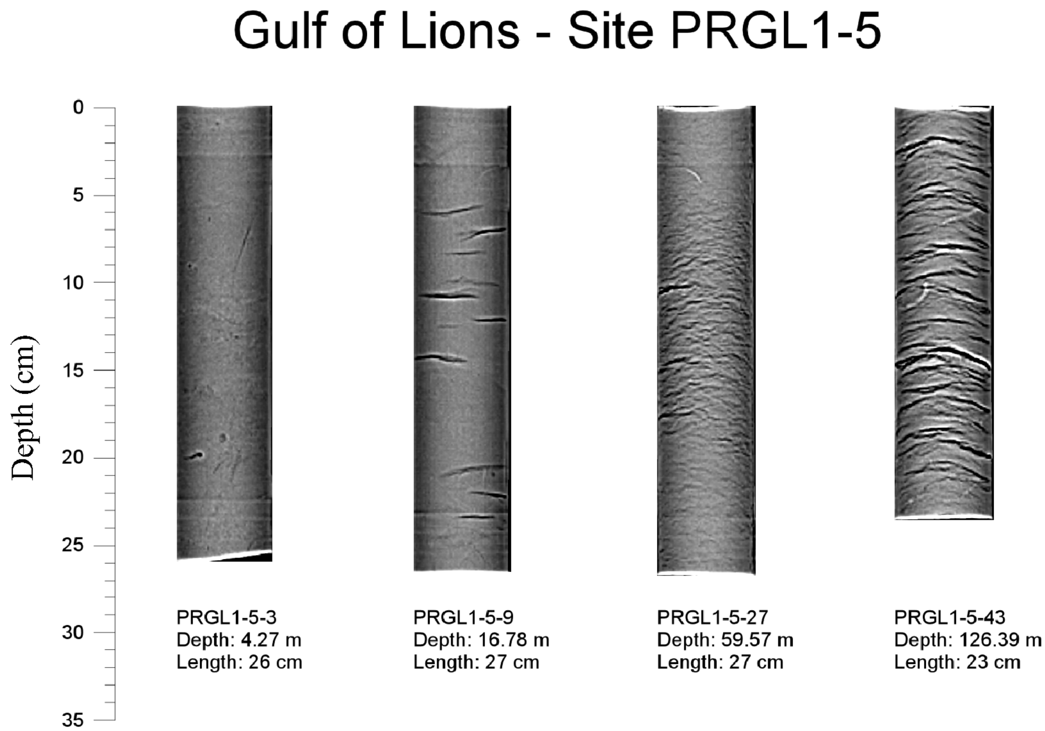

Figure 1. CATSCAN images illustrating sampling disturbance of Gulf of Lions samples as a result of gas expansion following core recovery.

As part of **EuroSTRATAFORM** a portion of the Cap de Creus Canyon has been selected for a detailed analysis of slope instability. The selected area is located on the north side of the Canyon in water depths ranging between 280m and 750m. This sector presents evidence of landsliding which has led to the accumulation of debris at the toe of the slope. The headwall escarpment is about 30m high at a slope of 27° whereas the failure plane is inclined at about 20° and is about 450m wide. The slope of the debris where sample PCFL-665 was taken is at about 5° reducing to about 1° near the thalweg. Sample PCFL-665 has been analyzed in order to determine the nature of the sediments along with the geotechnical and rheological properties. The profile is composed of two facies: a homogenous (hemipelagic ?) brownish grey clay with a plasticity index of about 47% and a bluish grey clay of lower plasticity (24%) and of variable water content which is present in the form of clasts reaching about 5cm in diameter with a water content around 40%. This unit is interpreted as corresponding to a debris flow event. A minimum of three events has been identified in the core. The water content, liquidity index and strength profiles are also quite different between the two units. The hemipelagic clay exhibits a typical decrease in water content and liquidity index and an equivalent increase in strength with depth. In the debris flow units, the water content, liquidity index and strength in the fine portion just above the clast layer are nearly constant. Reasons for these differences are being investigated.

The rheological behavior of the Cap de Creus clay is quite similar to what has been measured in sediments with similar physico-chemical properties (Fig. 2). Various relationships have been defined for the Cap de Creus clay:

$$\eta = 0.52\tau_c^{1.12} \qquad \eta_p = \left(\frac{6.89}{I_L}\right)^{4.28} \qquad \tau_c = \left(\frac{8.51}{I_L}\right)^{3.77}$$

Where η is the plastic viscosity, in mPa.s, τ_c is the yield strength in Pa, and I_L is the liquidity index $[(w-w_P)/w_L-w_P)]$ where w is the water content (in percent by weight), w_P the water content at the plastic limit (in %) and w_L the water content at the liquid limit (in %). It is also interesting to note that for this clay, there is a direct (1:1) relationship between the yield strength (τ_c) measured with the rheometer and the undrained remoulded shear strength measured with the fall cone (Cu_r)..

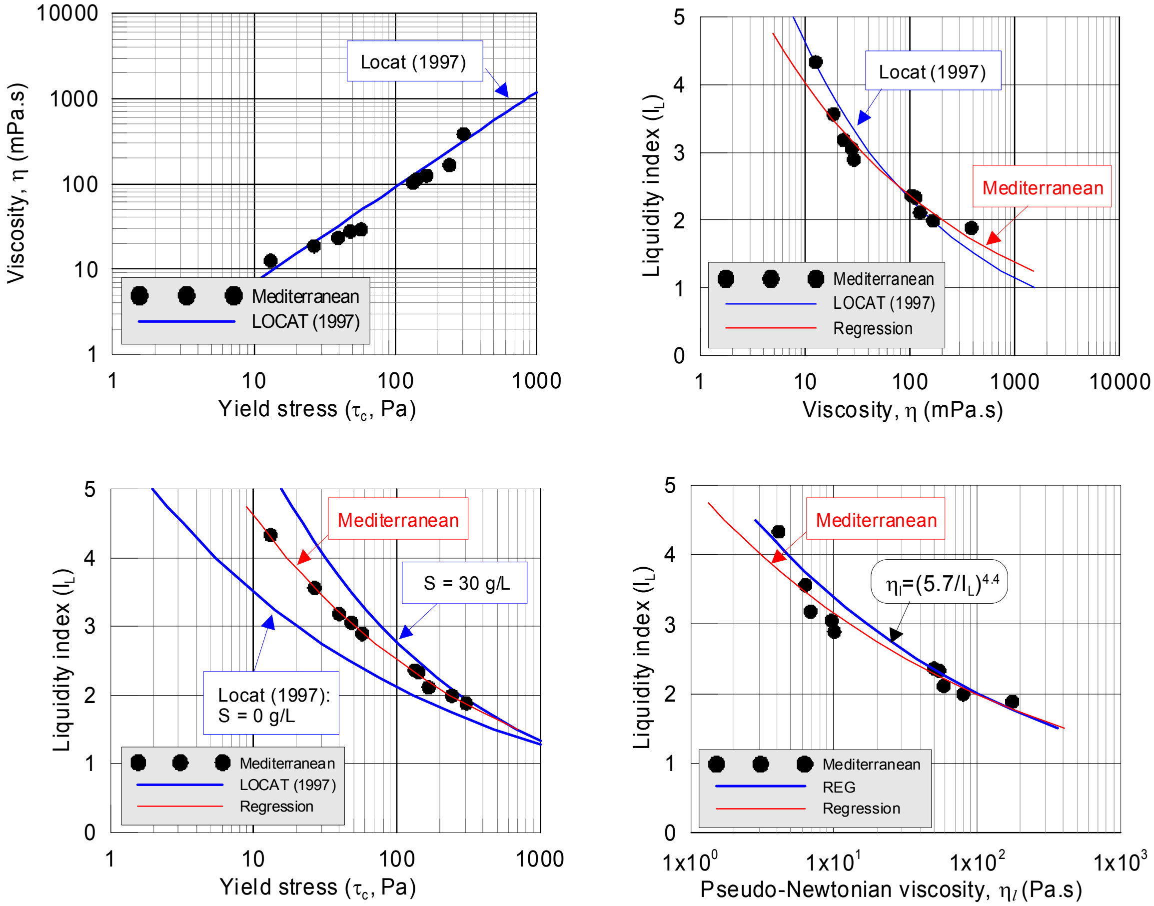

Figure 2. Rheological properties of Cap du Creus sediments as a function of the liquidity index.

IMPACT/APPLICATION

Results obtained in FY05 provide a unique opportunity to clearly demonstrate the potential of CATSCAN analysis in understanding the geotechnical properties of sediments along with the sediment sedimentary structures. Rheological testing of Cap de Creus sediments has strengthened the usefulness of the liquidity index as a way of estimating basic rheological properties of muds. Our results can also be used to improve strength development models used for analyzing sediment accumulation and stability.

TRANSITIONS

Our CATSCAN analyses and multi-sensor track profiling of various cores illustrate the value in using these non-destructive methods to study sediment architecture and properties. Rheological properties are being used by modelers to represent debris flows (Imran *et al.* 2001). Offshore research groups interested in margins and in oil and energy development were used as a platform to present our knowledge on submarine slope stability and hazard acquired as part of STRATAFORM and EuroSTRATAFORM. We have also contributed to a major effort in assembling our knowledge on submarine debris flows and their consequences by publishing a chapter on this topic (Locat and Lee

2005). We also transfered our knowledge developed as part of STRATAFORM to those interested in mass movements analysis (Locat 2005).

RELATED PROJECTS

Lee has developed a USGS project to investigate sediment and pollutant transport on the Los Angeles margin that uses techniques produced by STRATAFORM. The development of this project benefited from approaches developed within STRATAFORM. A group of Canadians led by J. Locat, and H. Lee developed a new project in collaboration with project COSTA (COntinental Slope STAbility) in Europe that will last until the end of October 2005. We have been very active in establishing IGCP-511: a UNESCO International Geological Cooperation Program on submarine mass movements and their consequences (2005-2009).

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