Stratigraphic development of large-scale turbidite slope systems: rules for reservoir modeling and prediction

Preliminary consortium proposal

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Introduction

It is well known from modern and ancient studies of deep-water slope depositional systems that they consist of a combination of channel, levee, hemipelagic drape, and mass-transport deposits. The primary objective of the research proposed here is to examine a number of slope systems to develop 'rules' that can be used to predict reservoir properties. These rules will be generated through observation, parameter correlation and verification using a family of deterministic outcrop and seismic datasets, and cross-tested against the various datasets. The intention is that they take the form of generic rules that can be exported to different systems with appropriate input changes.

This proposal arises out of three existing projects conducted at UC Santa Barbara on (1) three-dimensional architecture of channel-levee systems, (2) the impact of mass transport systems on hydrocarbon reservoirs (both ending late 2004) and (3) prediction of turbidite reservoir architecture and facies distribution through numerical modeling of turbidity currents (ongoing). The proposed work draws directly on the experience gained from those projects, from the extensive experience of Gardner in the Brushy Canyon Fm., and from the techniques developed by Gardner and Kneller in the field. Meiburg is one of the foremost exponents of direct numerical simulation, with extensive experience in the field of gravity currents. Dykstra has worked extensively on both channel-levee complexes (Rosario Fm), and mass-transport deposits in outcrop and seismic. Gardner will take an advisory role until his move to Montana State University in fall 2005, with full involvement in the field beginning late spring 2006.

Objectives and deliverables

The project will utilize a combination of outcrop data, seismic data and advanced numerical modeling techniques, to develop general rules for the prediction and modeling of stratigraphic architectures in deep marine clastic systems across a range of scales, focusing on large-scale slope systems. Outcrop data are unsurpassed at providing a detailed understanding of not only the small-scale (sub-seismic) elements of a system, but also how those elements are interrelated, and of course provides information that seismic data simply cannot resolve, such as facies and grain-size information. The outcrops are limited, on the other hand, in the degree of three-dimensionality they can provide and, therefore, the degree to which the true geometries of large-scale architectural and stratigraphic elements can be discerned from 2D or quasi-3D outcrops. Shallow, high-resolution seismic data, on the other hand is unrivalled for providing a detailed 3D context and for investigating the variability of architectures and geometries in slope systems. The numerical modeling will be crucial in testing not only the process interpretations of the outcrop data, but also will be important in examining the processes by which various grain-size populations are distributed across different parts of the system.

The output will consist of a set of such rules, presented in a context of:

- fully documented three-dimensional architectures of examples of the elements of these systems that we think are crucial to their development,
- sequence stratigraphic frameworks for the various datasets, and
- a detailed understanding of transport and depositional processes, aiding the generalization and export of the conclusions based on individual systems
- a set of tested input parameters that we believe are key to the architectural development of slope systems.

These will be derived predominantly from slope systems, but the process rules will likely be applicable elsewhere. Gardner comes with a set of fully developed rules from the Brushy Canyon Fm that will be immediately testable in the new context (Fig. 1). Additionally we have developed classification frameworks from the Rosario Formation that will contribute to these rule sets (Fig. 2).

Digital output will be delivered in 3D graphical and quantitative forms, in searchable format suitable for integration into sponsors' intranets. The outcrops also offer unrivalled training opportunities.

Work program

Fieldwork will concentrate on the Rosario Formation (Mexico; Figs 3 to 5), and the Carboniferous Paganzo basin (Guandacól and Jejenes Fms, La Rioja and San Juan provinces, Argentina; Figs 6 and 7). The Late Cretaceous Rosario Formation of Baja California, Mexico has been the subject of a 2001-4 study. Experience gained here and in the Brushy Canyon Formation has provided an outstanding framework from which to develop a more holistic treatment of slope systems. These areas provide excellent exposures of relevant systems, with considerable along-strike and dip continuity. The Rosario and Guandacól Formations together include mass transport deposits, canyon and channel systems, with varying degrees of structural control. The logistics are established, and the background geology is well understood.

Fieldwork will concentrate on

- acquisition of detailed architectural data on representative examples of each of the elements of the slope system, building on the existing database

- placement of the major components of the these systems within a sequence stratigraphic framework
- comparative studies with other outcrops, including large-scale mass transport deposits and channel systems.

All the outcrop data will be acquired in a fully three-dimensional context, geo-referenced using GPS, and maintained in a GIS (geographical information system) environment. Mapping of significant geologic surfaces will be undertaken using hand-held laser rangefinders, and traditional mapping techniques allied to GPS. Fieldwork will be undertaken by the PI's, senior research staff from the host institutions, and graduate students.

Seismic interpretation will involve a comparative study of the shallow sections of data sets that we already hold, from three slope systems: the Gulf of Mexico (Green Canyon; Figs 8 to 11); Brunei; and the western Nile Delta. The seismic will be used as a complement to the field data, to elucidate three dimensional architectures of individual elements, and to place them in a sequence stratigraphic context. Seismic interpretation will be undertaken by Kneller and graduate students at Aberdeen, and by Dykstra at UCSB. The students will also participate in the fieldwork.

The numerical modeling component will consist of a development from the single-sponsor (BHP Billiton) program for the direct numerical simulation of turbidity currents. This work has extended and refined a model that was originally derived to describe simple laboratory flows (Fig. 12), but which is now applicable in geological situations (Fig. 13). The consortium will support a PhD studentship to focus initially on the development of levees, and flow within channels. The numerical modeling will be closely tied to both the outcrop work, and to data from modern systems, and will be critical in understanding grain-size distributions within the systems, and linking the field data to process interpretations.

Timetable

Year 1

- Fieldwork will focus on:
    - reconnaissance of the Rosario Formation for additional elements to be targeted for detailed architectural studies;
    - development of digital mapping workflows based on handheld laser range-finders;
    - refinement of models for levee formation developed during the phase 1 program;
    - assessment of sequence stratigraphic development of the El Rosario channel system based on mapping in the phase 1 program.
    - Reconnaissance fieldwork will also begin on a large-scale mass transport complex of the Guandacól Formation in the Paganzo Basin in Argentina, one of very few well-exposed examples of truly seismic-scale MTCs.
- Seismic interpretation will focus on

    - the internal structure of mass transport complexes, and the distribution of structures and structural facies within them
    - stratigraphic architecture of channel systems, drawing on the results of recent studies of shallow seismic by Kneller and his post-docs and PhD students
    - mapping of stratigraphically significant surfaces

Year 2

- Fieldwork will include
    - detailed architectural analysis of the elements of the Rosario Formation, based on digital field mapping and incorporation of the results into a three-dimensional description of the outcrop
    - regional and detailed field analysis of the Jejenes Fm and Guandacól Fm MTCs to determine the sequence stratigraphic significance of the mass-transport events,
    - a focused analysis of the distribution of structural facies and strain within the Guandacól and Jejenes Formation MTCs, and how this relates to local accommodation space and the distribution of sediment pathways
    - comparative studies and testing of rules on other slope systems.
- Seismic analysis will include
    - continuing analysis of the stratigraphic patterns within the seismic data, especially the sequence stratigraphic context of channel evolution, and mass transport events.

Year 3

- Completion of detailed analysis of Rosario Formation architectures
- Continued comparative studies
- Integration of learnings from the outcrop and seismic data, synthesized as a set of stratigraphic principles, and tested against the various systems.

Facilities

All required facilities are in place to accomplish the work, including field equipment, seismic interpretation platforms, GoCad, GIS software, etc.

Synergies & leveraging

The project will benefit from

- considerable industrial experience from both PIs
- an unparalleled level of field experience from both PIs
- established techniques developed by the PIs
- blending of complementary skills and data types
- University salaries for both the PIs
- a no-cost PhD studentship at Aberdeen
- the results of a single-sponsor numerical modeling study

Collaborations

The project will benefit from the academic quality of the environments in which it will be conducted, high levels of industrial collaboration at Aberdeen, and from additional collaborations (e.g. Ifremer, the French oceanographic institute, on modern oceanographic studies; Leeds University Turbidites Research Group Phase 5 program).

Costs and duration

Costs for Phase I of this three-year program will be $50k per year, beginning January 2005 based on a ten-company membership (see page 6). If the program is under-subscribed, but a minimum of eight companies support this research, the study will be restructured to the mutual agreement of participating companies. Consortium members are requested to state their intention to continue participation by yearend.

Although the proposed study duration is three years, the yearly distribution of study results through annual field conferences, CD-ROMS, and continual on-line updates of the consortium web-site provides short-term deliverables for immediate application to company needs. As with previous proposals, companies that join after the initial startup date will be asked to fund the study at the level of participating companies.

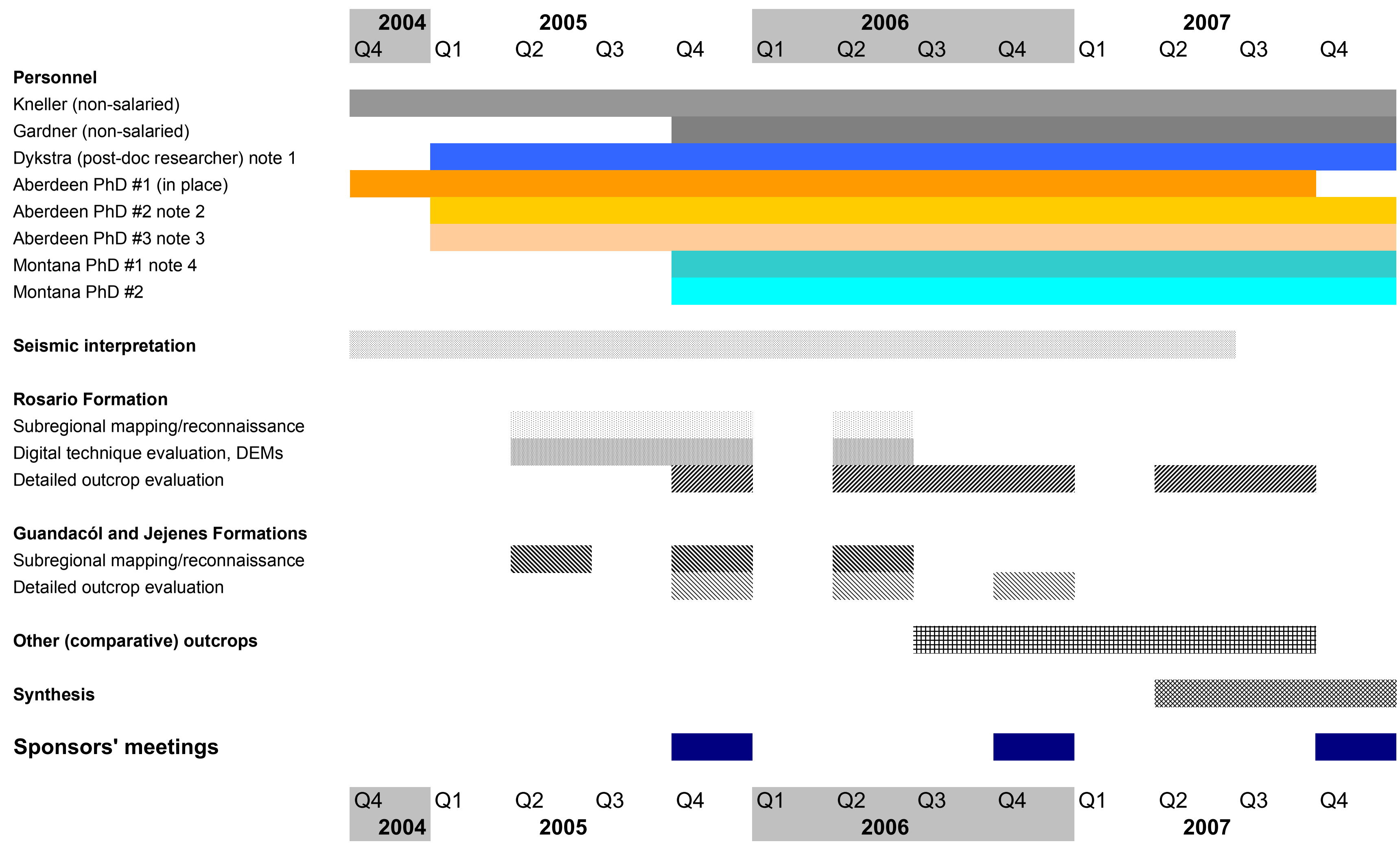
Outline budget

Costs in thousands of USD

	2005	**2006**	**2007**	
Dykstra[1]	90	114	120	
Abdn student 2[2]	57	60	63	
Abdn student 3[3]	44	46	48	
Mont student 1[4]	10	42	44	
Mont student 2[4]	10	42	44	
UCSB student[5]	64	43	45	
Meiburg summer		20	20	
Gardner summer		20	20	
Aerial recon.	20	20		
2 vehicle lease	12	12	12	
Equipment#	20	10	10	
Fieldwork costs	30	50	50	
Travel	30	60	60	
Incidentals#	10	10	10	
TOTAL	397	549	546	
GRAND TOTAL				**1492**

Equipment includes handheld laser rangefinder and computers; incidentals include conferences, material costs, and additional travel

1. Total salary, benefits and overhead $90k year 1, $109k per annum plus increments, years 2 and 3.
2. Non-European Union student at $57k per annum
3. European Union student at $44k per annum
4. Out-of-state student approximately $40k per annum
5. 1st year out-of-state; in-state thereafter


2004
Q4
2005
Q1
Q2
Q3
Q4
2006
Q1
Q2
Q3
Q4
2007
Q1
Q2
Q3
Q4
Personnel
Kneller (non-salaried)
Gardner (non-salaried)
Dykstra (post-doc researcher) note 1
Aberdeen PhD #1 (in place)
Aberdeen PhD #2 note 2
Aberdeen PhD #3 note 3
Montana PhD #1 note 4
Montana PhD #2
Seismic interpretation
Rosario Formation
Subregional mapping/reconnaissance
Digital technique evaluation, DEMs
Detailed outcrop evaluation
Guandacól and Jejenes Formations
Subregional mapping/reconnaissance
Detailed outcrop evaluation
Other (comparative) outcrops
Synthesis
Sponsors' meetings

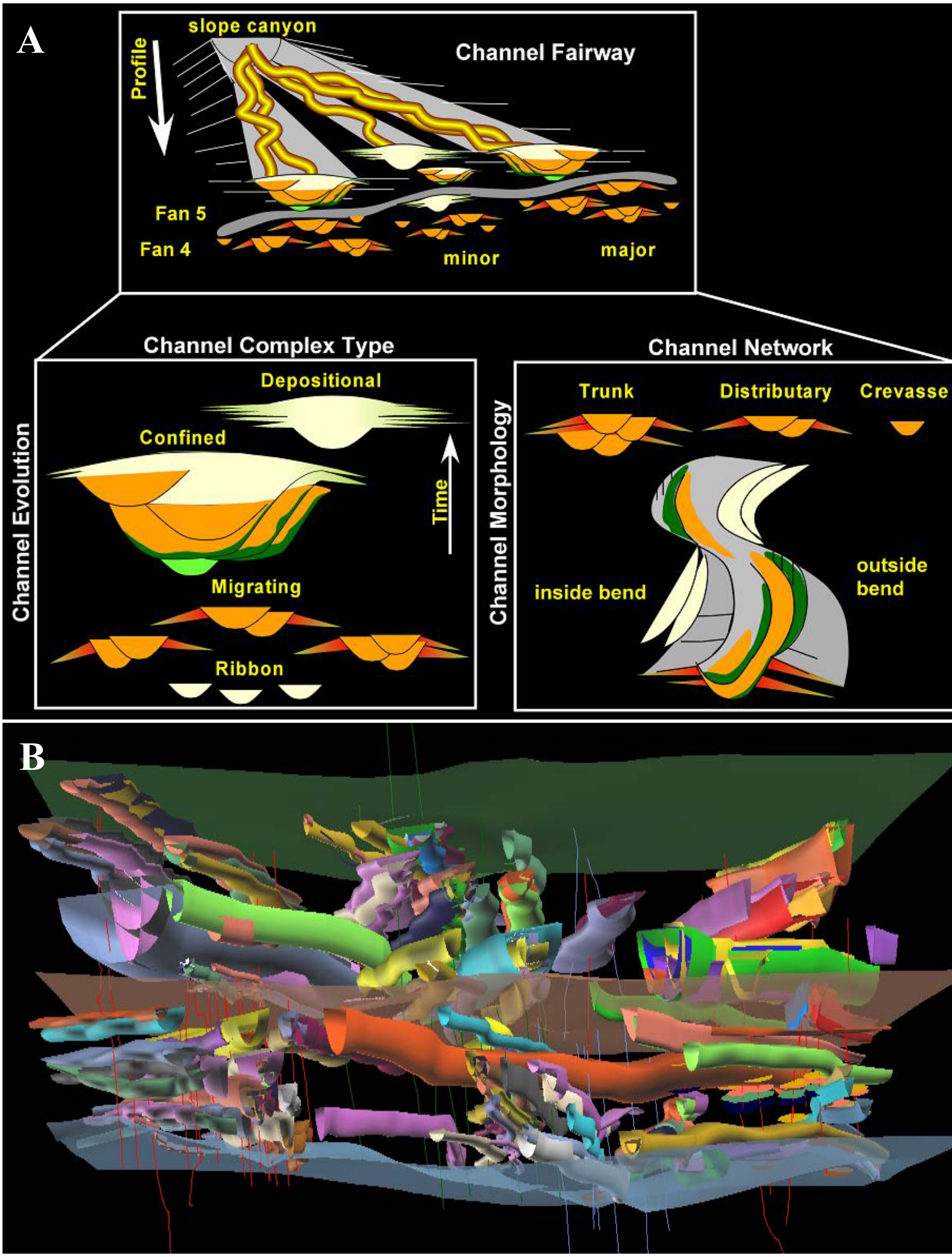


Figure 1. Slope channel attributes (A) and a 3D model (B) derived from the Brushy Canyon Formation, illustrating the importance of the following geologic inputs: channel type, channel placement, major and minor fairway regions, interfairway regions, channel-interchannel connectivity, and down-dip variability. From the Slope and Basin Consortium, 2004.

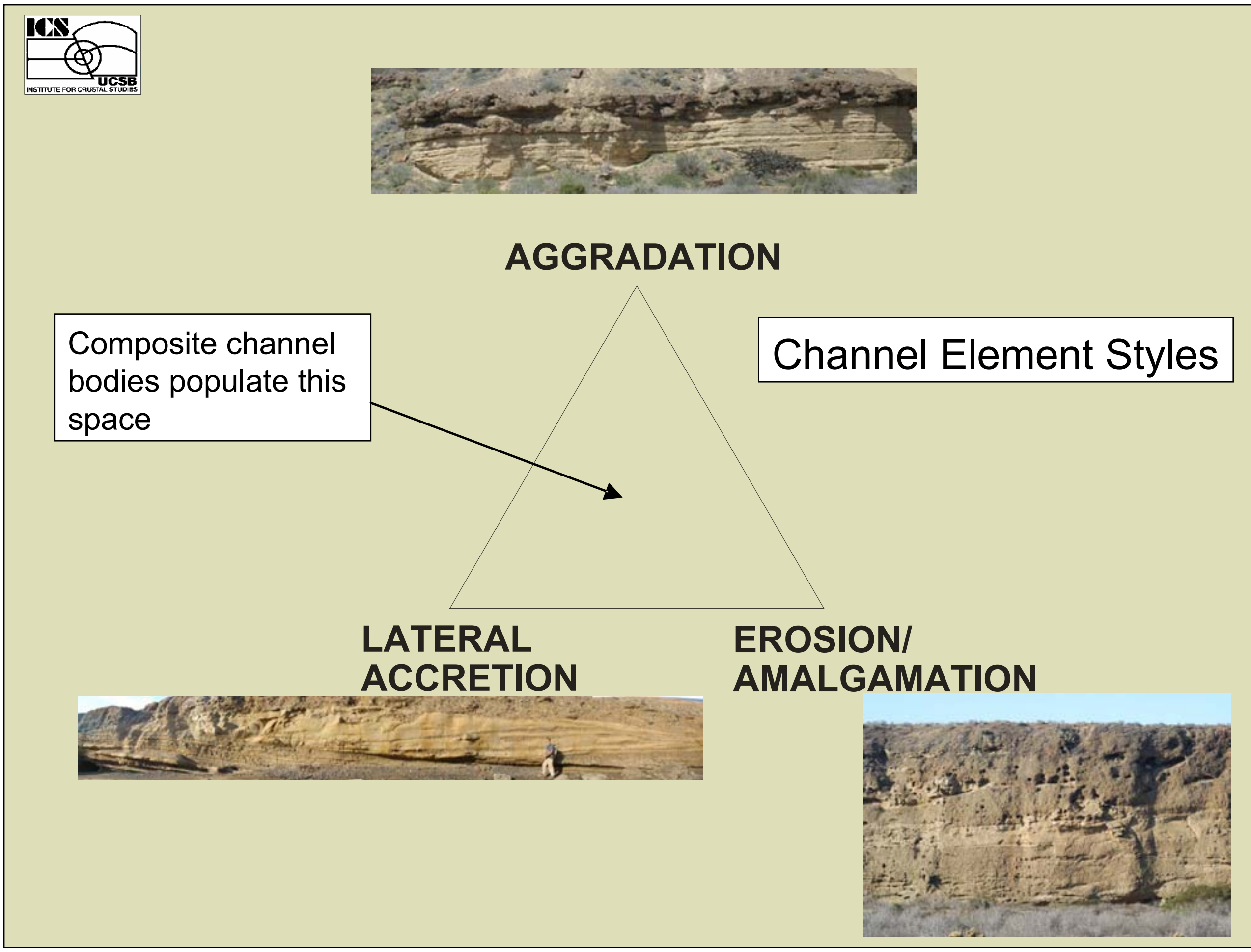


Figure 2. Simple classification of single-storey channel elements, based on assessment of outcrop data at Arroyo San Fernando, Baja California, consisting of three end-member styles that together build composite channel bodies. This classification scheme will be tested on different scales and in different types of slope systems to examine how truly representative (and hence exportable) it is of the building blocks to slope-channel systems.

Figure 3. Exposures of the Rosario Formation slope system (Campanian-Maastrichtian) at Arroyo San Fernando, Baja California Norte, Mexico, illustrating the degree of exposure and dissection of one of the channel-levee complexes. Width of view about 3 km.

Figure 4. Detail of the Rosario Formation at Arroyo San Fernando, showing composite sheets of coarse-grained, laterally-accreting channel fill within the channel-levee system shown above – one of three end-member channel element styles identified at outcrop.

Figure 5. Composite canyon fill at Punta San Carlos, with erosional/amalgamational coarse-grained elements (left), and mass transport deposits (right).

Figure 6. Outcrop of the Guandacól Formation (Carboniferous, Paganzo Basin) at Cerro Bola, La Rioja Province, Western Argentina, illustrating the exceptional quality and extent of outcrop.

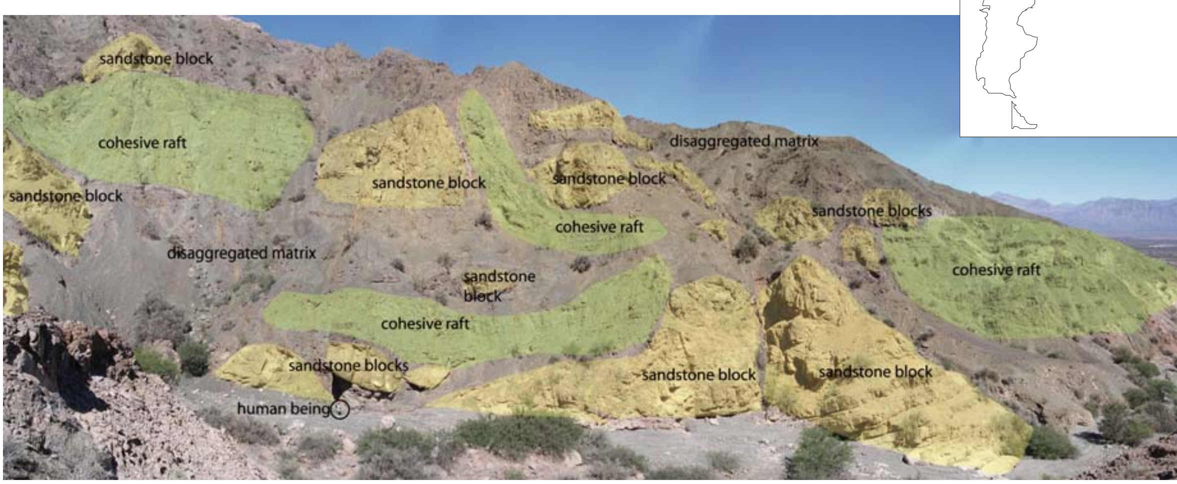


Figure 7. Representative seismic-scale exposures of part of a c. 100 meter thick mass transport deposit within the Guandacól Formation; human at base for scale. This MTD can be traced continuously in outcrop of this quality for tens of kilometers.

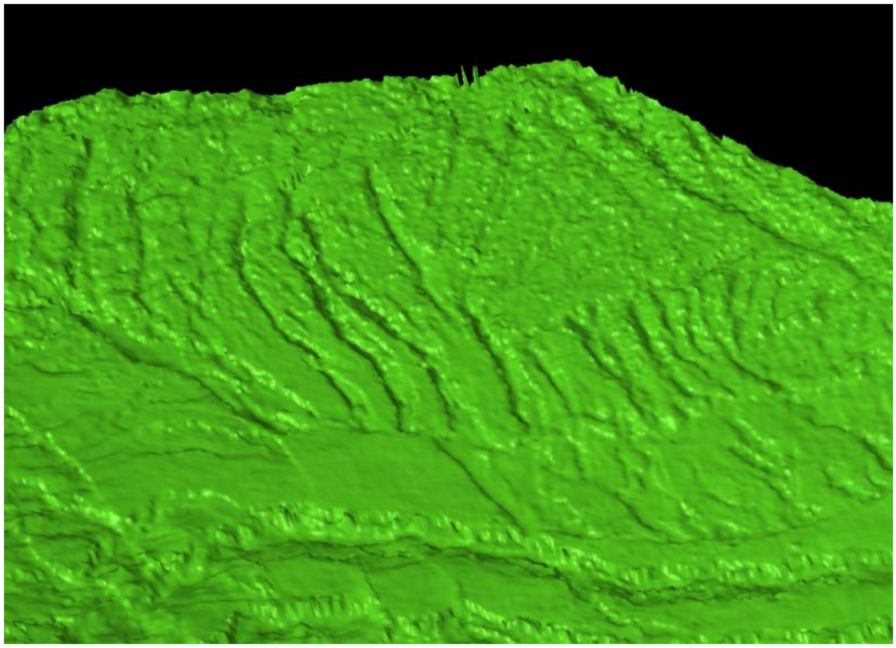


Figure 8. 3D rendering, from shallow conventional seismic data, of a deformed surface within a mass transport complex, illustrating multiple directions and styles of faulting within the same body. Field of view about 5 miles. Green Canyon protraction area, Gulf of Mexico. Seismic data courtesy of BHP Billiton.

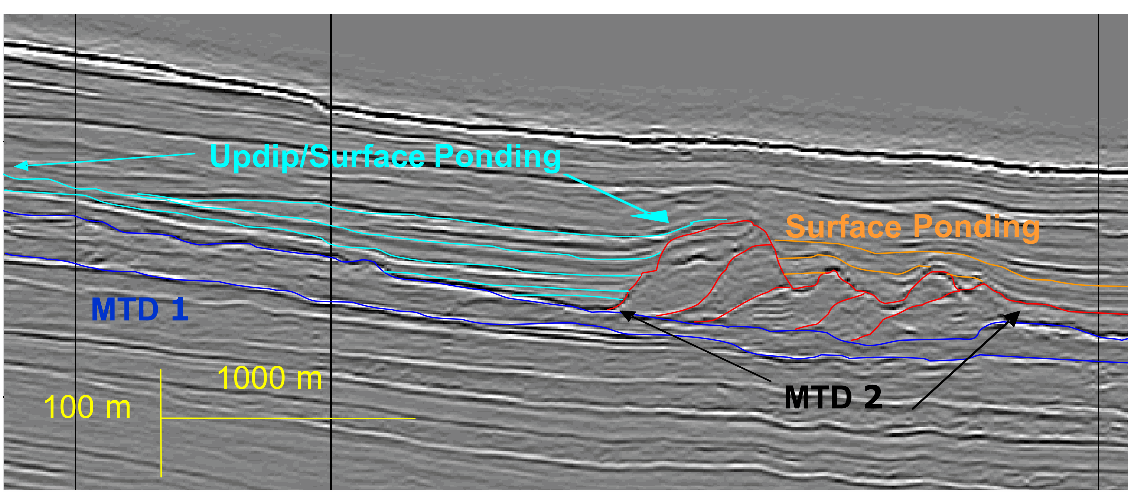


Figure 9. Illustration of the value of shallow seismic data in demonstrating the link between internal structural facies, external morphology, and the generation of accommodation for turbidite systems associated with a mass transport complex; Green Canyon area, Gulf of Mexico. Seismic data courtesy of BHP Billiton.

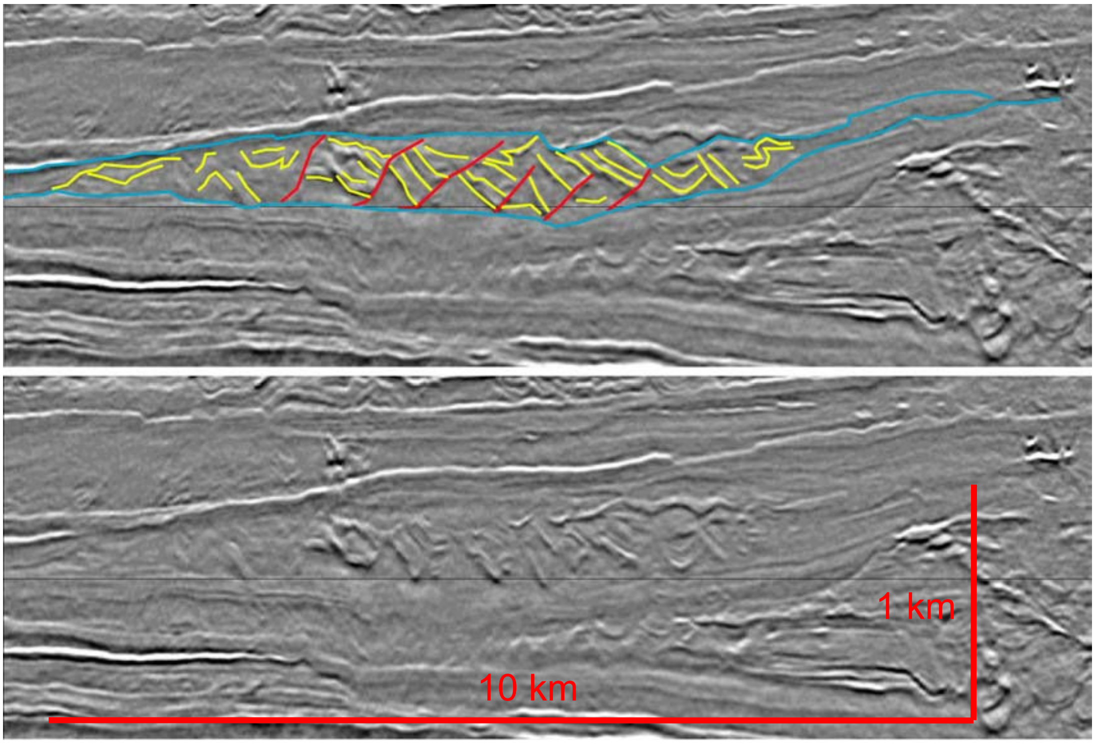


Figure 10. Large-scale gravitational collapse features on a submarine channel levee, illustrating the process continuum between channel development and mass transport; Green Canyon area, Gulf of Mexico. Seismic data courtesy of BHP Billiton.

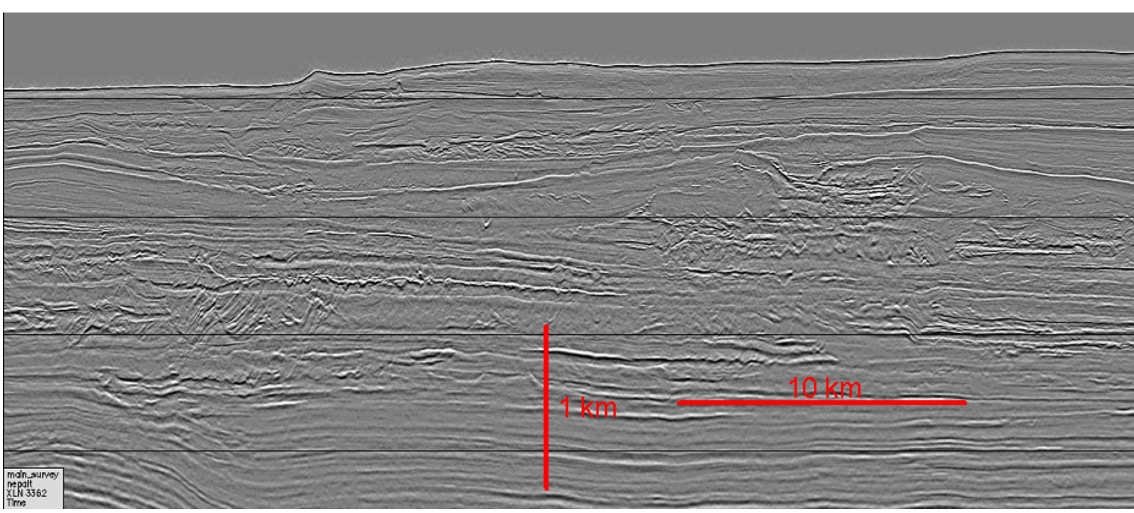


Figure 11. High-resolution seismic section of coherent leveed channel, Green Canyon area, Gulf of Mexico. Seismic data courtesy of BHP Billiton.

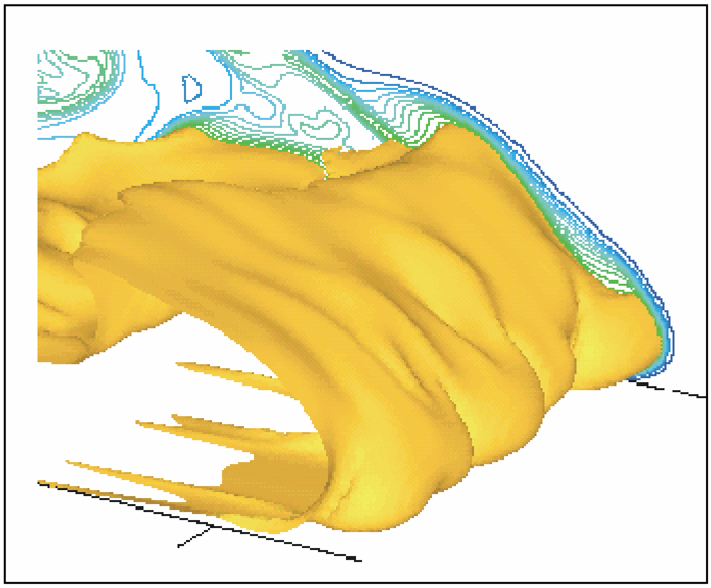


Figure 12. Close-up of the nose region of a particle-driven gravity current from a 3D numerical simulation, visualized by isosurfaces of concentration, and isolines of concentration in the back plane.

(From F. Necker, C. Haertel, L. Kleiser and Meiburg, 2002, *High-Resolution Simulations of Particle-Driven Gravity Currents*, Int. J. of Multiphase Flow 28, 279).

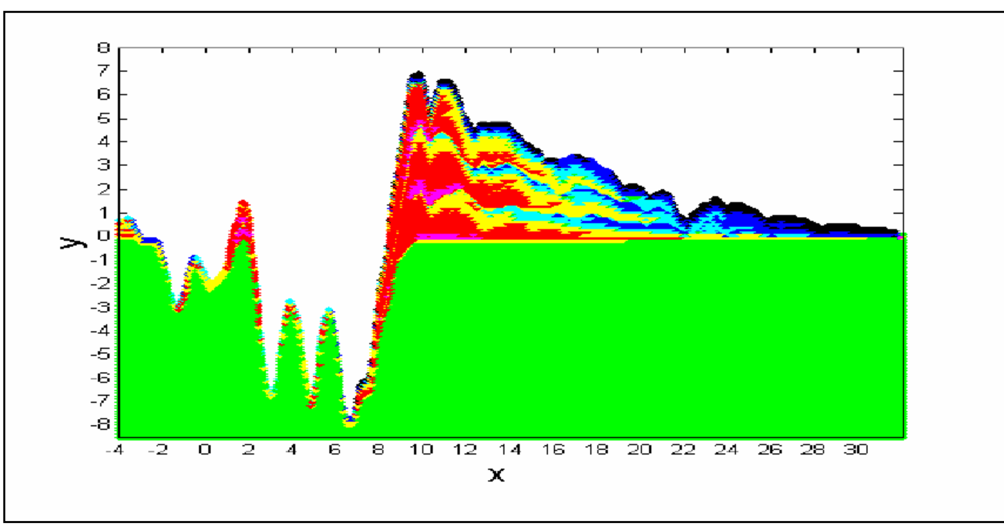


Figure 13. Local average grain-size in the deposit built up by a succession of three flows in 2D numerical simulation with erosion and deposition.
From Strauss, M., Meiburg, E., Kneller, B., Glinsky, M and Blanchette, F. Multi-flow effects on grain sorting by resuspension and deposition in turbidity currents. Unpublished research report.