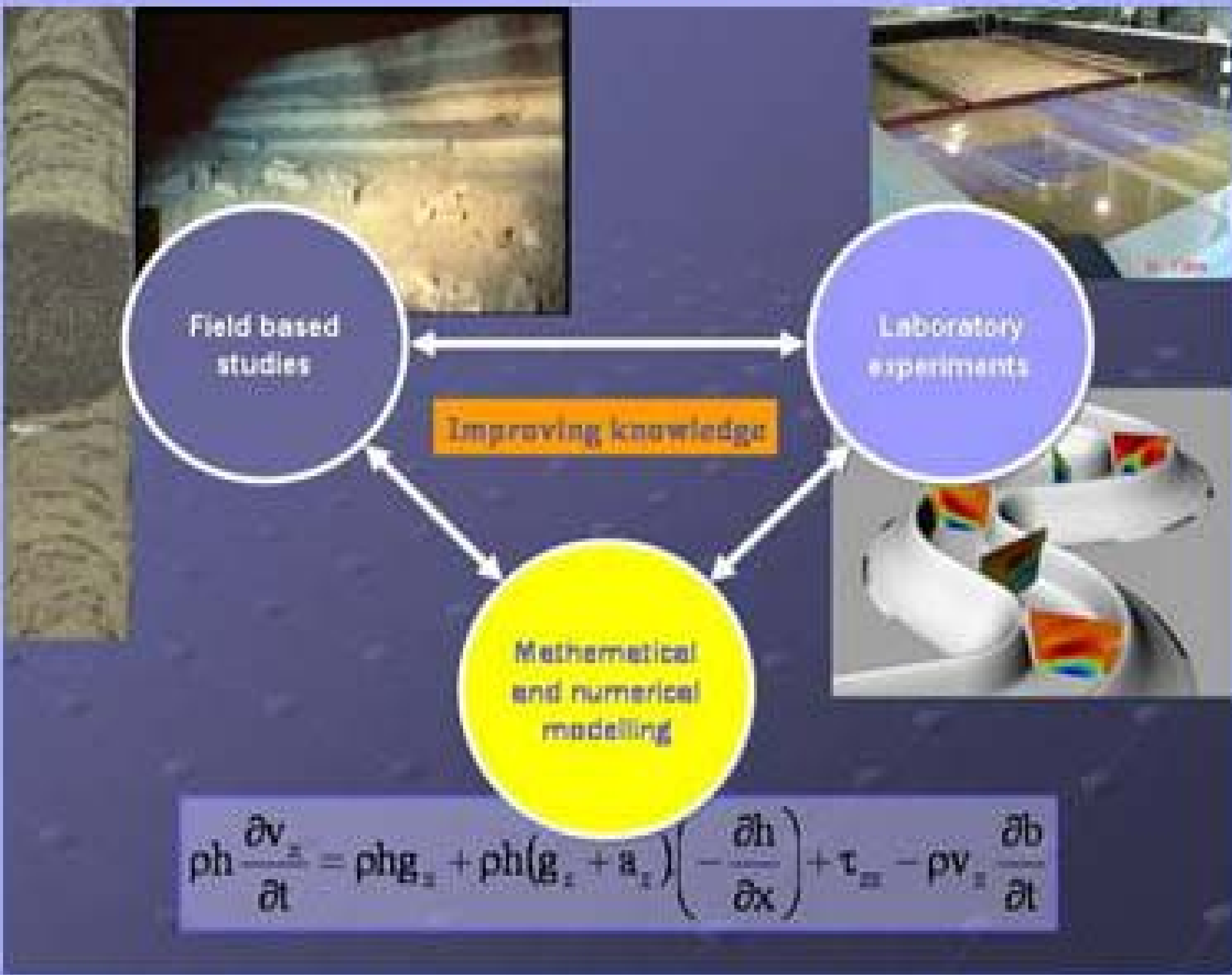
Variatis

Var: integrated assessment of turbidites in situ



EU-specialist teams of various science disciplines federate manpower, software development and flume tank facilities for accurate modeling continental slope- and deep-sea turbidite sedimentary systems.

The teams work together on the same scientific questions, share the same calibration data sets and aim to develop an integrated European knowledge center, which can act as training and advisory board for both government and industry.

Teams
Ifremer (France)
Utrecht University (Netherlands)
University of Leeds (United Kingdom)
Delft Hydraulics (Netherlands)
University of Oslo (Norway)
Complex Flow Design AS, Trondheim (Norway)

Variatis

Var: integrated assessment of turbidites in situ

EU-specialist teams of various science disciplines federate manpower, software development and flume tank facilities for accurate modeling continental slope- and deep-sea turbidite sedimentary systems.

The teams work together on the same scientific questions, share the same calibration data sets and aim to develop an integrated European knowledge center, which can act as training and advisory board for both government and industry.

Teams

Ifremer (France)

Utrecht University (Netherlands)

University of Leeds (United Kingdom)

Delft Hydraulics (Netherlands)

University of Oslo (Norway)

Complex Flow Design AS, Trondheim (Norway)

Contacts

Bruno Savoye Bruno.Savoye@ifremer.fr (Ifremer, France)
Ricardo SILVA JACINTO Ricardo.Silva.Jacinto@ifremer.fr (Ifremer, France)
George Postma gpostma@geo.uu.nl (Utrecht University, Netherlands)
Jeff Peakall j.peakall@earth.leeds.ac.uk (University of Leeds, United Kingdom)
Dick Mastbergen mastber@wldelft.nl (WL Delft Hydraulics, Netherlands)
J.C. Winterwerp h.winterwerp@wldelft.nl (WL Delft Hydraulics, Netherlands)
Anders Elverhoi anders.elverhoi@geo.uio.no (University of Oslo, Norway)
Snorre Heimsund snorre@cfd.no (Complex Flow Design AS, Trondheim, Norway)

Variatis

Var: integrated assessment of turbidites in situ

To federate teams working on modelling of turbidites systems at an European scale, it is important to federate manpower, software development, tank facilities and to avoid dispersion, to make geologists, physicists, modellers and engineers work together on the same scientific questions, share the same calibration data sets.

This proposal presents what could be a starting project to develop a European platform for integrating field detailed sedimentary mapping and in situ monitoring and modelling studies of turbidite systems with the purpose of training and set up a counterpart for governments and industry and to compete with modellers groups at a global scale.

1 Project summary

Scientific context

In the complex geological cycles of erosion, transport and deposition undergone by sediment particles, turbidite-canyon-system is one of the most probable ultimate destinations. The canyons collect, by a series of single, energetic and catastrophic events, a significant amount of the continental erosion products. Much of the material that accumulates at the shelf break or on the upper continental slope is in an instable situation and likely to move down the slope. Such movements impact on the slope and the deep-sea environments (i.e. HERMES project of FP6), determine the depositional architecture and evolution of deep-sea sedimentary systems. One of the distinctive features of these turbidite systems is the concentration and channeling of the terrigenous bed load from the mouth of large rivers (or the edges of platforms) to the abyssal plain. Processes involved in sediment transfers appear to be very efficient for particle grain size segregation and are a way to create huge sand accumulations in the deep-sea, providing in that way high quality reservoirs of high interest for the oil industry as it is moving deep offshore. These processes are also a major source of geohazards and damage for infrastructures lying on the sea floor and on coastal areas.

Submarine canyons and channels are also important conduits for the transport of fluids and pollutants across the shelf and into the deep-ocean. The flows that are responsible for these fluxes are typically of large magnitude, have high flow velocities and are highly destructive, and therefore pose a significant hazard for sub-sea engineering structures. As many of these flow events are linked to large-scale river flooding in high gradient terrains, and with climate change predicted to produce more extreme weather events, the frequency and magnitude of such flows may be anticipated to increase.

Because of the continental slope, it is on ocean margins where the majority of submarine slides occur due to a complex cause-effect relationship between increasing stress and decreasing resistance of the sediment in relation to seismicity, sedimentation, tectonics and anthropogenic overloading. In Europe, the Mediterranean and the Atlantic area adjacent to it are vulnerable to earthquake activity and, hence, submarine slides and tsunamis generation.

The interconnection among the main geological factors determining submarine slides and related geohazards remain on the edge of knowledge. Facing the dramatic development in coastal population and human activity on the sea bed, integrated approaches are essential to improve understanding of turbidite-canyon systems and associated geohazards.

The topic proposed here has been fascinating geoscientists for more than 30 years. Only recently (in the 90's) technological advances led to a major breakthrough on the understanding on how turbidite systems evolve. Efforts have been made to establish links at national, European and international level between different research institutions, to build partnerships with industry, and to encourage the transfer of knowledge at different levels. Simply based on the scientific programs of major international conferences (AAPG, EGU, EAGE, IAS, and SEPM to mention only a few organizations) it is evident how turbidite systems are extremely fashionable at the moment and offer immense opportunities in terms of future research. Based exclusively on field work in early times, the research has rapidly moved to more remote areas. Studies conducted onshore on outcropping fossil systems are limited as outcrop conditions govern the quality of geometric, facies, climatic and paleogeographic reconstructions Advances in sub-sea exploration techniques, in particular high resolution multi-beam echo-sounders, sonar imaging, HR seismic profiling and the development of multiple parameter core measurements (true logging on cores) and much improved integration of research disciplines (micropaleontology, tephro-chronology, bio-stratigraphy, palynology, sequence stratigraphy, etc.) allowed the scientific community to make a giant leap in the understanding of marine environments. But we are still at the early stages of the process and although the study of deep sea fans generated abundant literature over the last twenty years, there is a strong need for research in this area.

Since late 80's, Ifremer has been studying several modern deep-sea sedimentary systems located in different and various geological settings and oceans, collecting a series of high resolution data sets including swath bathymetry, side-scan sonar imagery, HR seismic lines, cores and submersible observations. In some case studies, the resolution of data sets helped to show depositional structures ranging several spatial scales comparable with those of on land outcrops.

On the other hand, physicists and engineers in several European countries, in US, and in Japan developed flume tank facilities for physical experimenting at different scales for calibration of numerical model studies of submarine processes. Yet to date, there were only just a few attempts integrating true deep-sea submarine data sets and modelling efforts. They were limited in time and in terms of human means and in terms of level of collaboration.

Scientific objectives and approach

This project intends to be a first step of an integrated scientific approach to provide predictive knowledge and assessment tools for a quantitative understanding of canyon and slope related turbidite processes and systems at field scales. The chosen approach is the convergence to the same in situ data sets and experimental data sets along three different scientific approaches: geological description of natural systems, physical experiments in laboratory and deterministic process-based numerical modelling.

The chosen approach here is clearly multidisciplinary and based on a full integration of field and experiments data. This approach would provide i) an identification of the key processes that determine the morphodynamical evolution of turbidite systems, ii) a physical and mathematical formulation of those identified processes, iii) the integration of these processes in deterministic numerical models, iv) a calibration and validation of those models in relation to laboratory and field observations and v) a strategy to use the models, to develop teams interactions, to interpret results together and to make the results available to the European scientific community and industry.

Expected impacts

Understanding the depositional processes occurring in marine environments is also extremely important in terms of prevention or at least partial control of natural disasters. Turbidity currents, or more generally sediment gravity flow deposits, are catastrophic events and the fossil stratigraphic record indicates that they can occur in many distinct geologic settings (not only in deep water environments) and can affect large areas. But they can also have a profound impact on human activities, as demonstrated by recent examples of communication cables disrupted by deposition of turbidity currents along the Algerian margin in 2003 and, more sadly, casualties caused by relatively small episodes probably triggered by man activity (Nice airport (France) disaster of 1979).

The results of this project can be used by the scientific community to better understand the evolution of continental margins and the processes controlling deposition of slope and rise settings, an area of strategic importance. A precise knowledge of the geometry, architecture, flow processes are extremely important for the scientific community, but also for industrial partners. The oil industry would benefit from a more precise characterization of sand bodies formed at relatively great water depth. Considered that petroleum exploration is rapidly moving to ever greater water depths with enormous financial efforts, it seems extremely important to undertake studies that can help minimizing investments and make them more affordable, even to companies with limited human, technical, and financial resources.

Secondly, one of the factors limiting the interpretation of datasets are not their sedimentological information content but: (1) how to interpret the large quantities of data in a reasonable cost-effective time frame, and (2) how to provide access to specialists in, for example process sedimentology. This project aims to strengthen collaboration between new associations of researchers that will be advantageous to both industrial and academic partners.

The project will contribute to enhance the European scientific excellence by combining the ‘savoir-faire’ (scientific, experimental and algorithmic) of renowned institutions or laboratories sharing their high level of expertise with each others. It will also strengthen the scientific and technological bases of European industry and encourage its international competitiveness while promoting research activities in support of other EU policies, two of the strategic objectives of 6th Framework Program.

A rapid dissemination of the research progress is one of the objectives of the project and hopefully the followed integrated approach would make possible to answer questions arising from potential end users such as hazard prediction teams, oil companies, earth-science research teams, governments and public entities.

2 Scientific and technical objectives and innovation

Scientific knowledge related to turbidite systems has been increased in the frame of different approaches and methodologies, mainly and broadly by *in situ* data collection, observation and interpretation, physical modelling in laboratory facilities and numerical modelling based on the mathematical expression of physical processes. Great improvements, partially associated with technological evolution, have been done in each of these scientific approaches.

Despite the importance of gravity currents, the understanding and modelling of such flows within channelised systems is poorly constrained. In particular, the role of physical modelling, which has been so influential in our understanding of open-channel (river) flows, has been restricted by a number of key technical challenges. This in turn has meant that the underlying assumptions of numerical models have been difficult to constrain, and there have been very limited datasets for the validation of numerical models.

In this project, the integration of different methodologies will provide innovation and a better understanding of turbidite systems in two ways. In the first place, different approaches will provide quantitatively and qualitatively more information: a more coherent and well constrained interpretation of turbidite systems will arise. At the same time each methodology "behaves" as a scientific analysis of the others and in that way a critical tool pointing out necessary innovation. In a second place, each methodology and its technical supporting solutions have to be adapted to usefully exchange information with the others.

The Var and Zaire turbidite systems are relatively well known for the high quality of the collected data. The recent development of sub-sea monitoring facilities in both the Var and the Zaire channel systems provide an outstanding opportunity to measure turbidity flows at multiple locations an in precedent detail. Nevertheless, these observations do not provide correlations in space and time between the data. Data information, as vertical profiles, bed forms, grain size distributions, at broad spacing cannot address all of the key questions concerning flow properties, erosion and deposition. Modelling results of density currents through the system at event time scales may provide cartographic information of fluid dynamics, erosion and deposition. These results are an important new input to data interpretation such as, for instance, the identification of active and fossil parts of the system.

Physical experiments provide a key intermediate step in developing numerical models of turbidity currents, by providing detailed datasets at a small scale which can be used to validate two and three-dimensional flows. Physical models can provide excellent input and output boundary conditions. Once validated and refined, numerical simulation of field data can be run with fewer degree of freedom and correspondingly greater confidence.

Numerical models validated against field and laboratory data will provide excellent tools to link spatially dispersed in-situ data and to validate synthetic interpretation of the turbidite systems. Being versatile "numerical laboratories", numerical models can simulate very simplified experiments in order to calibrate singular processes, in one hand, and be applied to more complex flows and morphologies, in the other hand. Being developed on a deterministic basis, numerical models are a quantified expression of the interpretation obtained from field and laboratory experiments. They would be as good as the scientific understanding one may have.

3 Project work plan

The project is divided in three different work packages (WP) organized by scientific approach: field data, physical modelling and numerical modelling. This provides the required scientific validation of the different tasks and deliverables. Meanwhile special attention will be paid for providing effective connection and collaboration between partners and tasks of the different work packages. This linking work will be identified as tasks and managed in a constrained way to assure the interdisciplinary objectives of the project. An interconnection flow diagram is presented together with the associated tasks Fig. 1.

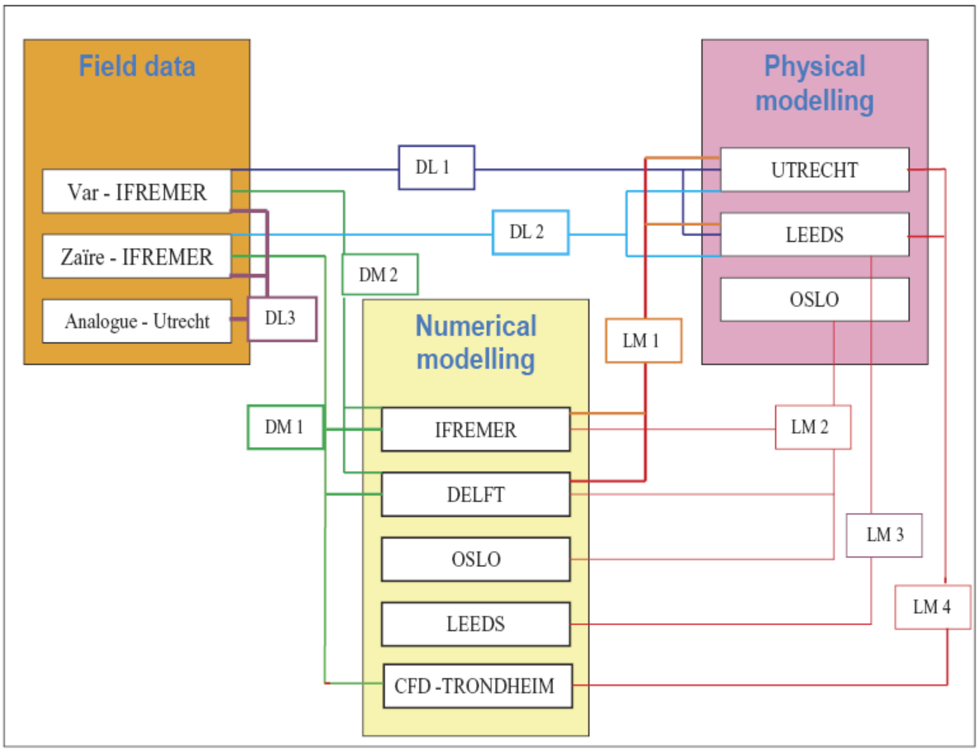


Fig. 1 Interconnection diagram: represented are the main connections between work packages that are identified tasks by themselves. Connections inside work packages are not represented. Other tasks will be associated with partners' boxes.

WP1: Field data

Partners: Ifremer and Utrecht

Geological background

As field analogue we have chosen two modern systems (Var and Zaire) and several fossil systems: the Tabernas Basin in Southeastern Spain, the Hecho Basin in the central Pyrenees, and the Cerro Toro Formation in the Torres del Paine National Park, southern Chili. The Var and the Zaire turbidite systems are permanently and therefore still connected to a river, on the contrary of most of the turbidite systems all aver the world that are presently disconnected and sediment starved due to the present high sea-level. Therefore they still undergo active, dominantly river driven, turbidite processes, erosion and deposits.

The Var system is under a temperate climate dominated on the seasonal scale by fall-winter storms and heavy rains, on the geological scale by the 100 kyr glacial-interglacial variability. The Var turbidite system is about 250 km long with a rather straight channel. It is divided in 5 morphological areas (Piper & Savoye, 1993; Migeon et al., 2006), (1) four coalescing canyons among which the Var canyon, connected to the Var river, incises up to 200 m the Var delta late glacial deposits and widens downstream from 1 to 3 km up to 1650 m water depth, (2) the Upper Valley extends 12 km south-east from the confluence of the Var and Paillon canyons to the base of the continental slope at about 2000 m, (3) the Middle Valley extends 50 km eastward to a water depth of 2500 m and bends to south-east. The northern or left-hand levee is low and discontinuous while the south or right-hand levee is voluminous and with height decreasing from west to east from 400 m to less than 30 m, (4) the lower valley extends 100 km southeastward to a water depth of 2700 m and is only 20 m high, (5) the terminal lobe is 80 km long and 40 km wide. The Quaternary Var fan has a steep concave longitudinal profile and pebble-floored fan valley that is essentially a bypass zone. This is a consequence of the constant supply of coarse sand, gravel and pebbles to the fan (Piper & Savoye, 1993). According to the classification of Reading & Richards (1994) the Var system is in between the range of mud/sand rich fan point source systems and sand rich ramp although the presence of a unique overgrown levee is not really considered in this classification.

The Zaire system is under a tropical climate dominated on the seasonal scale by the monsoon driven by the position of the Intertropical Convergence Zone (ITCZ), and on the geological scale by the glacial-interglacial migration of the ITCZ. The Zaire turbidite system is one of the largest modern deep-sea turbidite systems and extends over 760 km from the Congo-Angola continental shelf down to more 5100 m water depth in the abyssal plain with a very sinuous channel. It is divided in 5 morphological areas (Babonneau, 2002), (1) the Zaire canyon, about 130 km long, deeply incises the shelf and the continental slope with a relatively straight ESE-WNE orientation. The width and height of the canyon increase seaward up to 15 km and 1300 m respectively at the shelf break at 2000 m water depth, (2) the upper fan valley, about 130 km long on the lower continental slope, forms a large curving segment down to 3300 m water depth bounded at the south by a diapiric (salt) domain. The width of the valley is rather constant around 6-7 km and the relief gradually decreases from 800 to 250 m. Several flat terraces are located at distinct levels on both sides of the meandering thalweg. The average sinuosity strongly increases downslope, (3) the lower valley extends about 200 km long across the continental rise to the abyssal plain. The channel width is relatively constant at around 1.5 km and the relief gradually decreases downstream down to 4100 m. The channel is intensively meandering and the channel relief is comprised between 150 and 250 m, (4) the lower valley extends about 260 km long down to 4800 m. The channel width remains constant at around 1 km and the relief gradually decreases down to 20 m. The apparent moderate sinuosity gradually disappears downstream, (5) the distal lobes area comprises at least five discrete lobes characterized by a wide topographic bulge and a short network of superficial channels extending from the mouth of the lower valley. The present channel is deeply entrenched and floored with fine to coarse sand and locally gravel in the distal channel. Turbidite levees are dominantly mud rich, even in the terminal lobes. According to the classification of Reading & Richards (1994) the Zaire system is within the range mud rich submarine fan point source systems.

Recent advances in outcrop collection techniques allow collection of accurately digitized surfaces, collected from rectified photo panels, GPS, total station or laser scanning techniques. These techniques allow outcrop data to be readily assimilated into high resolution and highly deterministic 3D geologic models (Rogerson et al. 2006; Kleverlaan, 1989). The main bulk of the data can be acquired from three, already extensively studied, field work sites: The Tabernas Basin in Southeastern Spain, the Hecho Basin in the central Pyrenees, and the Cerro Toro Formation in the Torres del Paine National Park, southern Chili. Gravelly canyon fills will be mainly studied from the Tabernas fans (Late Miocene) in SE Spain. Gravelly canyon fills crop out over more than 3 km's in the Tabernas Basin and have already been crudely mapped and studied for large scale internal organization. The same basin allows study of aspects of channel bend deposition including in channel deposition, backset bedding and in channel point bar like deposition ('solitary channel complex'). In the Eocene Hecho Group superb outcrops of the Banastón turbidite systems (Lutetian) provide excellent examples of the rarely described relationships between coarse-grained channel-fill units and their related fine-grained overbank deposits and transitions from these channels into their lobe deposits. The Cerro Toro Formation contains a series of deep-water channel complexes with essentially continuous depositional record of migrating, leveed-channel complexes, which form a channel belt of approximately 5 km (3 mi) wide and several hundred meters thick. The outcrops will be studied with help of local experts.

Methodology

Detailed, up to field scale, knowledge of modern and fossil turbidite systems is a necessary step towards modelling of turbidity currents and deposits. Modern analogues give access to non-deformed morphologies and offer the possibility to choose the sampling areas. An exhaustive dataset covering several scales and ranging from swath bathymetry to submersible observation give a good overview of the whole system up to small sedimentary bodies.

Outcrop studies are used as analogues to aid subsurface interpretations and help us predict facies distribution. Hence, outcrop analogues provide a bridge between the seismic and core studies from modern analogues. Recent advances in outcrop collection techniques allow collection of accurately digitized surfaces, collected from rectified photo panels, GPS, total station or laser scanning techniques. These techniques allow outcrop data to be readily assimilated into high resolution and highly deterministic 3D geologic models. The main bulk of the data can be acquired from three, already extensively studied, field work sites: The Tabernas Basin in Southeastern Spain, the Hecho Basin in the central Pyrenees, and the Cerro Toro Formation in the Torres del Paine National Park, southern Chili.

Objectives of WP1:

- To investigate with more details (morphology, lithologies) selected key areas in the turbidite systems such as 1) gravelly canyon fills, 2) channel and levees, 3) channel-bend deposition (including in and out channel facies), 4) and channel-lobe transitions. **Gravelly canyon fills** will be studied from the Tabernas fans (Late Miocene) in SE Spain and from the Var turbidite system. Gravelly canyon fills crop out over more than 3 km's in the Tabernas Basin and have already been crudely mapped and studied for large scale internal organization. Gravelly canyon fills have been described in the Var upper valley and detailed observation from side-scan sonar and submersible is available. **Channel bend deposition** including in channel deposition, backset bedding and in channel point bar like deposition ('solitary channel complex') will be studied from the Tabernas Basin and from the very sinuous Zaire system.
- **Relationships between coarse-grained channel-fill units and their related fine-grained overbank deposits** and transitions from these channels into their lobe deposits will be studied in the Eocene Hecho Group superb outcrops of the Banastón turbidite systems (Lutetian) and on the Zaire turbidite system.
- **To provide detailed facies models** that serve as basis for validating the physical model studies herein proposed, which in turn are being used for calibration of the numerical models that are being developed.
- The Cerro Toro Formation contains a series of deep-water channel complexes with essentially continuous depositional record of migrating, leveed-channel complexes,

which form a channel belt of approximately 5 km (3 mi) wide and several hundred meters thick. The outcrops will be studied with help of local experts.

Tasks

- To compile the existing dataset including swath bathymetry, side-scan sonar, seismic and lithological logs.
- To organize fieldwork on outcrops of the Tabernas turbidite system
- To provide quantitative data such as sediment composition, grain-size and accumulation rates at chosen areas in agreement with objectives from physical and numerical modelling work packages.
- To provide conceptual models of the turbidite systems up to bed scale, including a qualitative identification of erosion, transit and deposition areas.
- To provide conceptual models on selected key areas such as gravely canyon, channel, levees, bends and channel-lobe transitions, including high resolution stratigraphical architectural highlighting characteristic depositional feature at a scale that satisfies core and modeling studies.
- To compare studies from fossil analogues and modern analogues

Deliverables

D1.1: Reporting of the fieldwork on the Tabernas turbidite system

D1.2: Dataset on the composition and grain-size, including detailed fabric studies of the gravel and sand portions

D1.3: Conceptual models for the Var, Zaire and Tabernas turbidite system, including detailed selected key areas.

WP2 : Physical Modelling of Canyon and Channel Systems

Partners: Utrecht and Leeds

Background

New advances in facilities and measurement technology now enable us to produce high-resolution, spatial and temporal datasets in these multi-phase, frequently opaque and high concentration flows. This enables a step-change from the largely qualitative assessment of bulk flow properties to the quantitative measurement of two- and three-dimensional flow fields in terms of velocity and concentration, which are required for numerical model validation. Purpose-built large-scale facilities now also enable currents to be run for longer time periods and for the evolution of channel conduits to be observed and measured. These changes have recently enabled the first physical modelling studies of sinuous submarine systems to be undertaken, and for the underlying methodologies to be proven. Sinuous studies to date have only examined generic plan forms rather than scaled versions of natural prototypes. This work package will utilise the bathymetric datasets from the Var and Zaire channel systems, integrate flow measurements from instrument arrays within these systems, and compare the experiments back to sedimentological observations.

The work to be carried out will build upon the major advances in facilities and the developments of measurement techniques and methodologies, many pioneered by the

Universities of Leeds, Oslo and Utrecht, to examine the processes and evolution of flows through submarine channelised systems, and their impact on channel evolution and resultant deposits.

Objectives of WP2:

1) Improving the understanding of the fluid dynamics of gravity currents in the context of flow rheology;
2) Gaining insight into the processes of down slope flow transformation that occur in canyons and channels;
3) Assessing the importance of hydraulic jumps on sedimentation and flow development.
4) Elucidating flow processes in sinuous channelised submarine systems, both as a function of flow parameters and of bend geometry;
5) Establishing the sedimentary architecture of submarine channel bends, and the linkage between depositional and flow processes;
6) Detailing the processes and morphodynamics of submarine conduits and channel-lobe transitions;
7) The production of spatially and temporally detailed datasets of gravity current flow in straight and sinuous channels, and at a range of scales, for the validation of numerical models.

The physical modelling will be synthesised to enable construction of a suite of models at different spatial and temporal scales, from the physics of flows of differing rheology, through flow dynamics of bends and channel reaches at the event-scale, to the morphodynamics of individual system elements over longer time-scales. The objectives and measurement strategy of WP2 are closely coupled to the numerical modelling (WP3) in order to allow maximum integration between the physical and numerical approaches. The physical models and associated quantitative datasets will be used to inform numerical modelling assumptions and for subsequent model validation (WP3).

Task 1 – Sedimentation and morphodynamics of submarine canyons and channels: with emphasis on the Var

University of Utrecht

1.Objectives

To examine and quantify deposition and erosion processes for gravelly subaqueous slopes in relation to internal hydraulic jumps and supercritical flow in turbidity currents and to study depositional phenomena related to channel-bends and channel-lobe transitions. The channel-bend experiments are complementary to those at Leeds and include a few experiments that focus on various degree of overspill of turbidity currents to investigate consequences for in-channel sedimentation (e.g. back-set bedding (“plastering”) in the outer bends). In particular, focus will be given to: 1) bed form (antidune and backset bedding) generation from gravelly suspensions; 2) overall flow properties to provide appropriate spatial and temporally resolved data for the validation of numerical modelling studies; 3) fabric development of the coarse fraction for comparison with Var cores; 4) channel bend processes; 5) channel lobe transitions as analogues for the Var and Zaire sandy fans, and; 6) comparison of resultant model stratigraphies with real-world systems.

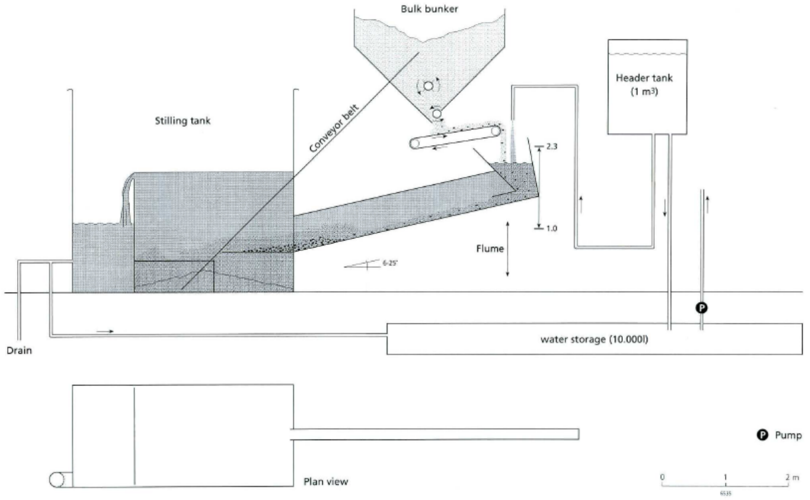


Figure 1. Design of tilting flume.

2. Methodology

The Eurotank facilities of the Sedimentology Laboratory of Utrecht University shall make available two different setups in order to meet the objectives: 1) an 8 m long tilted flume (8-25 degrees) that will be used for very high concentration (up to 40% solids/vol), high velocity (Fr>1) cohesionless flows, and 2) a 6.5 m x 13 m x 1.4 m basin for scaled process experiments that serve to produce analogues for the spatial variation in erosion and deposition produced by initially supercritical turbidity currents. In particular, the supposition that after the jump turbidity currents accelerate again once having passed their own-made obstruction and return to the supercritical condition is relevant for the Var slope – fan transition is a feature we shall explore by monitoring flow evolution in a wide pre-shaped canyon (a few metres in width) of sufficient slope. The suspension-driven flow will start with supercritical (Fr ~ 2-3) conditions and consist of a dense, fine-silt or clay suspension (~1200 kg/m^3). Flow will be maintained for approximately 10-15 minutes to produce sufficient canyon fill for morphological and stratigraphic studies. In order to simulate natural erosion conditions the ratio of bed shear stress to the critical value of grain motion is not scaled. To achieve this, a low density powder (e.g., bakelite; 1280 kg/m^3) will be used as a bed material. The produced canyon fill, channel bends and channel lobe transitions will be studied on the basis of lacquer peels.

Measuring equipment for Fig. 2 models will be shared with Leeds and will include Ultrasonic Doppler velocimetry profiling (UDVP) that can operate in multi-phase and particle-laden opaque flows, and Ultrasonic High Concentration Meters (UHCM), while for the Fig. 1 tank the new high tech Electro Magnetic Flow (EMF) velocity meters, Conductivity Concentration Meters (CCM) will be used. All experiments are monitored with time laps and high-speed digital film cameras that allow detailed flow-bed interactions to be monitored and examined

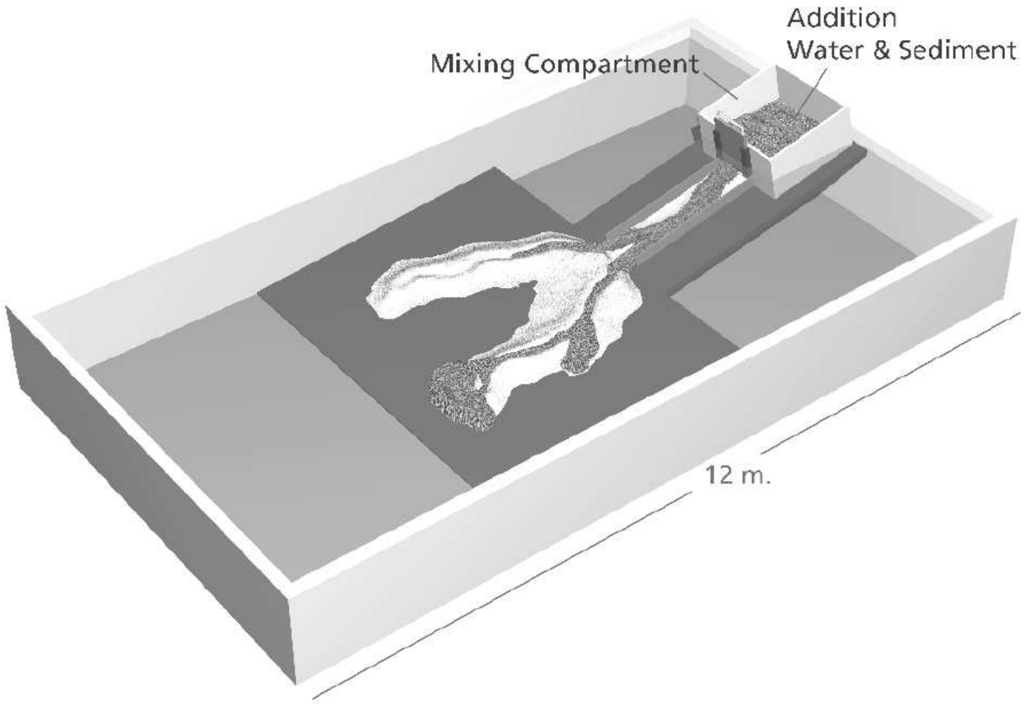


Figure 2. Test design in Eurotank with artist view of an evolving turbidity flow on a submarine fan topography.

3. Deliverables

1. Establishment of bed features produced at various relative velocities (u/u*);
2. Establishment of bedforms produced in relation to suspended sediment concentration and grain size over the flow depth and;
3. Visualization of the flow structure by video images;
4. Fluid entrainment data at hydraulic jumps;
5. Establishing equilibrium slopes as a function of flow rate and density;
6. Relationship between excess shear stress (τ/τ_c) and produced morphology in terms of aspect ratios;
7. Establishment of the 3-dimensional architecture that can serve as an analogue for field examples. Also these results will be presented in dimensionless form.

Task 2 - Physical modelling of flow dynamics and sedimentation in submarine channels: simulation of the Var and Zaire channels, and channels of simple geometry.

University of Leeds

1. Objectives

The primary objective of this task is to provide detailed physical modelling derived datasets of flow dynamics and sediment patterns for a range of submarine channel geometries. Secondary objectives are to utilize these datasets to: i) elucidate flow processes such as helical bend flow and the interaction of overbank and intra-channel flow; ii) examine the influence of key controlling variables including bend geometry and flow parameters, and; iii) interpret sedimentation patterns, both overbank and intra-channel. A further key objective is to provide appropriate spatial and temporally resolved data for the validation of numerical modelling studies (WP3).

2. Methodology

The physical modelling programme will concentrate on analysing the fluid dynamics within reach-scale models of the Var and Zaire systems, on event time-scales. These datasets will be supplemented by comprehensive datasets from a number of simple geometries that can be used for initial testing of numeric models. The physical modelling will be undertaken in two specially designed gravity current flumes at Leeds, and in the case of the Var will be undertaken in conjunction with Utrecht University. Pre-formed channel geometries will be used to enable boundary conditions to be precisely measured, and supplied for CFD validation (WP3). Models of channel reaches from the Zaire and Var will be built from high resolution bathymetric datasets.

Saline or sediment laden flows (or combinations thereof) will be pumped through the channel models. A mobile bed will be incorporated into some of the experiments in order to simulate bedload transport and sedimentation. Velocity flow fields will predominantly be measured using Ultrasonic Doppler velocimetry profiling (UDVP) that can operate in multi-phase and particle-laden opaque flows. Higher resolution and higher frequency data for the lower part of the gravity current flow (below the mixing zone) will be obtained using Particle Imaging Velocimetry (PIV), enabling parameters such as turbulence and the temporally varying flow structure to be measured in much greater detail. Concentrations will be recorded with ultrasonic concentration meters, constant flux peristaltic pump controlled siphons, and a high-frequency salinity probe. These flow measurements will be allied to topographic measurements of the sediment accumulations collected with ultrasonic depth gauges mounted to automated XY traverses.

The physical modelling programme will build on the pioneering work of the Leeds group, which has demonstrated that detailed flow measurements can be collected from sinuous submarine channels, and has indicated that the three-dimensional flow field is of critical importance and very different from that in meandering river channels which have in the absence of such data been considered by many workers to be strongly analogous.

3. Deliverables

- Improved models of fluid flow and sedimentation in submarine channel bends (with WP3T4)
- Comparative assessment of bend dynamics in open-channel and subaqueous systems
- Validation datasets for the full range of numerical modelling approaches including 3D CFD (required for WP3)
- Papers in leading scientific journals

Task 3 - Flow dynamics in debris flows and turbidity currents as a function of rheology

University of Oslo

1. Objectives

The principal objective of this work is to establish the changes in behaviour when gravity current flows are modified from cohesive (clay-rich) to granular, non-cohesive (sand-rich). Initial work has been undertaken on high-concentration flows (debris flows), and here we plan to extend this to lower concentrations (turbidity currents). Such a study is a key requirement for modelling the downslope transformation of sediment flows, as occurs in canyons like the Var.

2. Methodology

Recently, we have started collaboration with the University of Pavia (Italy) to analyze data from debris flows and turbidity current experiments making use of the PIV technique, where information on the velocity field is extracted automatically from high-speed camera shots. The group in Pavia works in strict connection with the St. Anthony Falls Laboratories in Minneapolis (SAFL), where we also have strong links. The Italian group has analyzed the data from a number of experiments we had run a couple of years ago at SAFL. The analysis provided a new glance at an old problem, demonstrating the extreme richness of fluid-dynamical effects at play inside an artificial debris flow. This new technique has proven very innovative in the capability of visualizing details that went unnoticed with previous methods. For example, the analysis has revealed the existence of ample zones of high speed alternated with more tranquil water flow, in a much more impulsive mode that previously thought. We believe that progress in physical and numerical simulations should also be based on the results of this new analysis.

Our research group in Oslo in collaboration with SAFL recently made some experiments on debris flows with variable sand-clay composition. The aim of these experiments was to establish the changes in behaviour when the slurry was modified from cohesive (clay-rich) to granular, non-cohesive (sand-rich). Clay-rich slurries (clay content over 20 %, sand less than 36%) did not disintegrate significantly during the experiments. Eroded material from the surface of the debris flow forms a clay suspension that can be interpreted as the experimental counterpart of a turbidity current. In such cohesive debris flows, the front is found to flow rigidly and at high speed. This occurs because beyond a threshold velocity dictated by Froude criteria, a water layer of a few millimeters thickness intrudes at the base of the debris flow front. The water layer lubricates the front of the debris flow, boosting the front and causing a marked stretching that may lead to detachment of frontal parts of the debris flow, a result closely resembling the out-runner blocks seen at the front of many subaqueous debris flows.

The dynamics is completely different for clay-poor debris flows (clay content less than 10 %, sand more than 46% by weight in our experiments). After release, the front mixes efficiently with ambient water, a process leading to complete disintegration. Sand grains freed from the matrix settle to form a sand layer, whereas clay remains suspended for a long time. As sand settles, water is expelled from the lower layers and flows upwards. This helps maintaining the sand in a fluidized state, a process called hindered settling. Velocities have been measured with precision by direct tracking of black coal slag particles introduced in the slurry, and for the sand layer they were of the order 10 cm/s. The otherwise tranquil flow of the sand layer is at times suddenly broken by the arrival of sand waves, traveling faster than the layer itself. We have seen that successive waves form a stacked sequence of normally graded layers with sand at the bottom and a clay veneer at the top.

The experiments with low clay content demonstrate high mobility of these flows, even if they do not hydroplane like the clay-rich flows. The thorny problem of extrapolating the experimental results to the field scale is still open, and will need more thorough investigations. This question is particularly relevant for the understanding of the origin of deep water sand bodies. We also plan to analyze these experiments with new automatic techniques.

The experience and analysis techniques gained with the previous experiments at SAFL will be applied to a series of new experiments on turbidity currents. These experiments will analyse changes in flow properties and velocity profiles of mixtures depending on original concentration and composition.

3. Deliverables

- Improved models of gravity current dynamics in a rheological framework
- Insights into the downslope transformation of gravity currents
- Validation datasets for numerical modelling
- Papers in leading scientific journals

WP3 : Numerical modelling

Partners: Ifremer, Delft, Oslo, Leeds and CFD Trondheim

Background

The numerical modeling of submarine, gravity induced sediment suspension flow dynamics and sea bed channel interactions hydrodynamics of turbidity currents forms an essential part in this proposal. Hydrodynamics are difficult to study in the natural environment, while laboratory experiments are limited to small-scale flows and relatively time-consuming to accomplish. Computational fluid dynamics is one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. These can be used to upscale laboratory datasets and to integrate the data from nature and experiments.

Objectives

The main objective of the present task is to provide to the European partners a well validated numerical model, capable of simulating the complex three-dimensional fluid and sea bed sediment dynamics in submarine channels and canyons.

This will provide a tool in full understanding of river and coastal sediment transport distribution to the deep sea, the resulting depositional sea bed texture with respect to oil and gas exploration and the risk on geohazards in coastal and off shore area.

Methodology

A number of specific physical key processes will be formulated and implemented in existing numerical 3-dimensional flow modeling software in order to simulate in a deterministic way the initiation, flow and deposition of a suspended sediment gravity induced turbidity current . The model will be calibrated with experimental data, applied to the full Var and Zaire submarine channel system and validated with available field data.

Input from other WP's

Experimental data on key processes such as erosion, deposition, hydraulic jumps, bend flow (Utrecht University, Leeds University), Field data bathymetry, flow events, river sediment redistribution (Ifremer)

Output to other WP's

Integrations of results, application on Zaire and Var submarine system

Deliverables for all task forces

- Innovative numerical routines for key physical processes;
- Detailed computations of turbidite events as recorded in Zaire and Var submarine systems, and detailed comparison with analogues from the fossil record (outcrop studies);
- Report with presentation of results in graphs and animations and papers in leading scientific journals.

Task 1 - Numerical simulation of gravity driven flows and flow-bed interactions of complex (multi-class grain size) suspensions across the Var and Zaire systems at event time scale

Ifremer

The main objective of the present task is to provide a numerical model integrating by accurate mathematical formulation the physical processes determining the morpho-dynamics of 3D turbiditic systems in a highly efficient way with simple operation. This deterministic model should allow for features as non-hydrostatic and anisotropic internal stress distributions controlled by complex rheology and different from basal stresses. It should allow entrainment/erosion of under-laying sediment and ambient water along the flow-path. It should allow differential deposition of different class/grain-size material.

The solver of this model is based on the Smooth-particles hydrodynamics (SPH). It provides a Lagrangian meshless solution, which avoids problems related to mesh distortion for long displacements. This type of modeling is well suited to simulate flows across extended domains. The computational effort is always within the current, independently of where the current is at a given moment. The SPH technique allows the branching and decoupling of the flowing mass which can be of great importance through 3D complex channel systems.

The model solves a vertically integrated momentum equation of the suspension coupled with a transport equation for each class of sediment.

The model will be applied to simulate physical experiments and to reproduce depositional features in the Var and Zaire. These applications will consist of several steps. Identified key processes will be reformulated and/or integrated as necessary. Single processes modeling will be calibrated and validated against literature and from-project experiments.

Application to real systems will provide flow characteristics (current velocity, sediment concentration), erosion and deposition at an event time scale. The importance of morpho-dynamics will be stressed by modeling a characteristic event with and with out morpho-dynamical (fluid-bed) interactions.

Task 2 - Numerical modelling of the 3-dimensional non-stationary turbidity flow and sediment transport processes applied on the Zaire (and / or Var) submarine canyon and channel system

WL | Delft Hydraulics:

The objective of our task is to develop specific physical / mathematical routines to be implemented in the present DELFT 3D numerical modeling environment, in order to be fully equipped to simulate the initiation, flow and sediment deposition patterns of a turbidity current for a specific 3D bathymetry, calibrated with laboratory experiments and field data from the Zaire (and / or Var) submarine systems provided by our European research partners.

A number of key processes required for the numerical modeling of turbidity currents are already available in the present DELFT 3D software such as 3D bathymetry with varying bed properties in bends and fan channels with flow stripping, tidal currents and waves, density effects by temperature, salinity and turbidity differences, detailed turbulence modeling, thixotropic properties of bed and suspension flows (fluid mud), various sediment transport-, erosion and deposition expressions for multiple sand and cohesive sediment fractions.

Some relevant new developments are currently being implemented in DELFT 3D in the framework of the Belgium / Netherlands Western Scheldt works, such as Generic Σ-Transformation, enabling high resolution sub layer modeling of density induced mud flows and the development of a Process based Mud-Sand transport model. Alternative detailed process modeling is available with 1DV point model and two-layer modeling; however, these models are not suitable to simulate the full Var or Zaire prototype.

In the framework of the present European 7th Framework program the development of the following mathematical-physical extensions are foreseen that are still essential to achieve the objectives, namely non-hydrostatic plume flow modeling, sub- to supercritical flow transitions and internal hydraulic jumps, the interaction of a mud suspension with the bed (hindered erosion) and soil mechanical initiation processes on steep slopes such as slumping, liquefaction, retrogressive erosion and breaching.

When the extensions are implemented, the numerical model will be applied to simulate experiments performed at Utrecht and Leeds University and observed events at Zaire and / or Var submarine system.

Task 3- Numerical modeling of debris flows and turbidity currents

University of Oslo

Oslo plans to study the flow of an ensemble of particles immersed in a moving fluid using fluid dynamical codes. This problem has been tackled earlier in relation to bed fluidization, where a granular bed is maintained suspended by a fluid injected from below. However, in contrast to most existing calculations, the simulated particles will not move in clean environment, but in clay-rich water. We will need to include both the effect of cohesion between particles and the change of viscosity of the medium owing to suspended clay.

These calculations should provide indications on the run out, flow patterns, and emplacement of sand in turbidity currents, and give hints on the geometry of the final deposit. Clearly, the problem of flow-bed interaction (erosion and deposition) and the possibility of multi class grain sizes would be also an important problem to consider in the simulations.

Task 4 - Numerical modelling of submarine channel fluid and sediment dynamics: with application to the Zaire and Var systems

University of Leeds:

The main objective of the present task is to provide a well validated numerical model capable of simulating the complex three-dimensional fluid dynamics of submarine channels and canyons. In particular, the modeling will concentrate on simulating the internal helical flow structure of submarine bend flow, the interaction of overbank (above the height of the levee / confining topography) and intra-channel flow, and sedimentation around bends. We will extend our present FLUENT based numerical models of gravity currents through the incorporation of a sediment erosion algorithm, adaptive meshing, and new turbulence closure schemes; and apply the model to laboratory experiments of, and field data from, the Zaire and Var submarine systems.

The gravity current model developed at the University of Leeds uses FLUENT as the primary solver, with user defined functions added to this in order to more accurately reproduce the dynamics of the currents. Validation against detailed small-scale physical experiments has enables the model to be optimized to a far greater degree than comparable models. To date work has centered around lock exchange and lock release currents, and flows have been modeled in both straight and curved geometries. Work is currently focusing on extending the model through the incorporation of boundary roughness and optimization of sediment stratification within flows.

The FLUENT based model will be extended and modified to allow improved modeling of flow and sedimentation in complex sinuous geometries, and the incorporation of 'continuous' currents. A key modification will be a re-examination of the applicability of different turbulence closure schemes and grid-independence criteria in these systems. To extend the model to handle erosion and deposition, and the resultant changes in bed elevation with time, a sediment erosion algorithm will be added, and adaptive meshing implemented.

The model will initially be applied to simulate physical experiments of simple channel geometries, enabling the modeling of specific morphological and physical parameters to be tested. The numerical model will then be used to extend the knowledge gained through the physical experiments by exploring the parameter space, through changing geometric and physical parameters. Subsequently, simulations will be made of the physical experiments of the Zaire and Var systems, and observed events in the Zaire and / or Var systems. Comparison of the simple and complex geometries will allow the importance of complex topographic forcing, and within-channel / overbank interaction, to be assessed. The results of the numerical simulations will be used to extend the knowledge of the three-dimensional fluid dynamics of submarine channels, an area that the Leeds group has pioneered.

Task 5 - Flow-3D simulation of the Var submarine canyon system

Complex Flow Design, Trondheim

Turbidity currents may respond to the topography in different ways, with an erosional or non-erosional sediment bypass in some areas, local spilling over basin-floor highs, ponding in local depressions, flow deflection and/or flow reversal on an opposing slope. Therefore, it is crucial to monitor the 3-D flow behavior in order to understand the resulting spatial patterns of sediment dispersal on the basin-floor. As the depositional system evolves, its topography will inevitably change and so will also the spatial behavior of the successive flows. This feedback phenomenon can be studied and its effects on sediment dispersal can be recognized by an incremental, step-by-step simulation of successive flows. In this way, the zones of erosion and sand-on-sand deposition, the non-erosional zones and the sand-starved zones of turbidite pinch-out can be recognized and mapped.

The main objective of this project is to analyze, by numerical CFD simulations, the sensitivity of turbidity currents to the bathymetric configuration in the Var submarine canyon system and the ancient Tabernas Fan system. The simulations will use the commercially available CFD software Flow-3D to study the influence of substrate topography on the spatial pattern of sediment dispersal. Flow will 3-D will use physical flume experiments from Leeds and Utrecht in addition to observational data from outcrops and sea floor morphology for constraining some of the variables and for validation and verification of numerical models. Delft WL Hydraulics will provide erosion tests on sediments over a wide range of conditions. The Trondheim group collaborates closely with the Flow-3D developer, Flow Science (USA), on the development of physical sub-models to simulate turbidity current dynamics.

Flow-3D is a general purpose CFD program that employs specially developed numerical techniques to solve the governing equations of fluid flow to obtain transient, three-dimensional solutions to multi-scale, multi-physics flow problems. The Flow-3D approach is to subdivide the flow domain into a computational mesh that provides the means for defining the flow parameters at discrete locations, setting boundary conditions and for developing numerical approximations of the fluid motion equations. Finite difference and finite volume methods from the core of the numerical approach used in Flow-3D and they are applied to obtain numerical solutions to partial differential equations on such meshes. In addition, Flow-3D is equipped with a range of user customisable models that expand its capabilities beyond those of many other CFD programs, including the physical models needed to simulate turbidity current dynamics. The methodology is particularly valuable when it comes to understanding the complexity of the systems' controlling variables and related feedback mechanisms operating in turbidity currents. In most cases, there are more variables than governing equations, and many mathematical models thus rely heavily on various simplified assumptions to circumvent this problem.

Interconnection between work packages

In order to assure the necessary integration of different methodologies, which is one of the main objectives of the project, different tasks are identified to manage and control the effective interconnection between the main work packages.

Field data and Physical modeling connections (DL)

DL 1: Provide data from the Var system to design modeling experiments at Utrecht and Leeds. Carry out experiments. Analyze results and inter-compare real and model systems.

DL 2: Provide data from the Zaire system to design modeling experiments at Utrecht and Leeds. Carry out experiments. Analyze results and inter-compare real and model systems.

DL3: Outcrop study of ancient analogues of elements of Var and Zaire systems on a bed scale focusing on depositional processes and facies. Compare with cores.

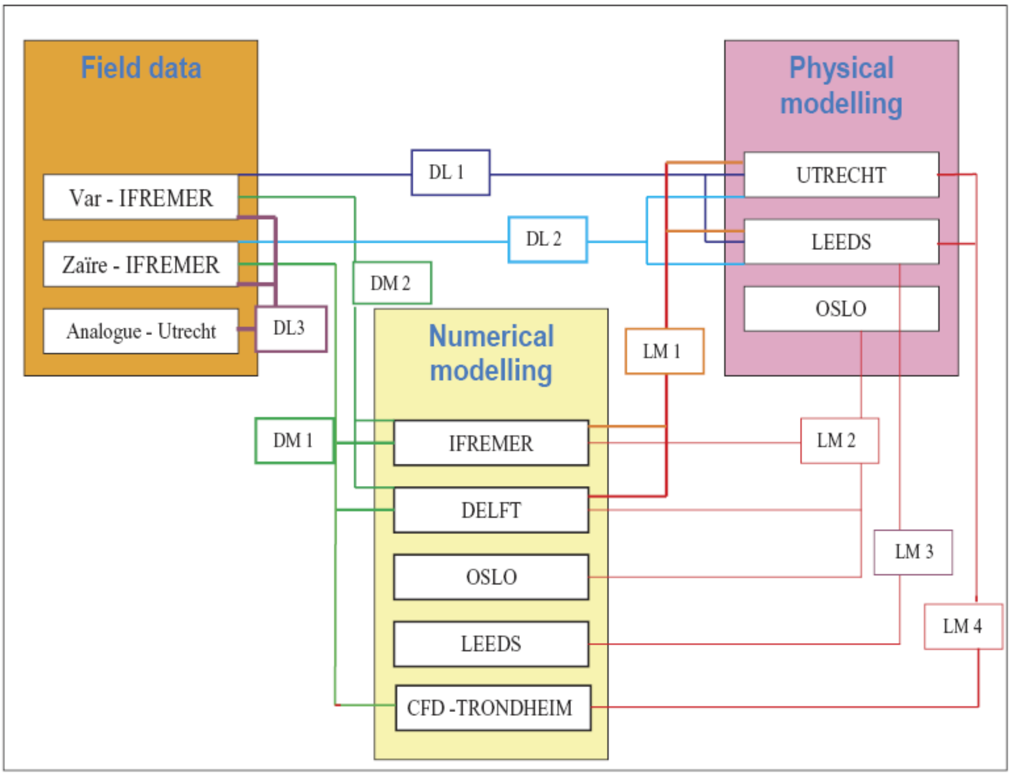


Fig. 1 Interconnection diagram: represented are the main connections between work packages that are identified tasks by themselves. Connections inside work packages are not represented. Other tasks will be associated with partners' boxes.

Physical modeling and Numerical modeling connections (LM)

LM1: Provide relevant information from experiments to numerical modeling; simulation of the physical modeling experiments of the Var and the Zaire systems (Calibration, validation); interpretation of numerical and laboratory results.

LM2: Reproduction by numerical modeling of processes oriented laboratory experiments; integration (or improvement) of these processes in the large scale numerical models.

LM3: Small scale modeling of the 3D hydrodynamic flow in highly instrumented parts of the Leeds physical models.

LM4: Provide relevant information from experiments to numerical modeling; Simulation of the physical modeling experiments of the Var and the Zaire systems (Calibration, validation); interpretation of numerical and laboratory results.

Numerical simulation of the Var and Zaire systems

DM1: Compile necessary data for numerical modeling; application of the numerical models to the Zaire system; develop a strategy to use the models and interpret the results.

DM2: Compile necessary data for numerical modeling; Application of the numerical models to Var system; develop a strategy to use the models and interpret the results.

4 Contribution to objectives of the 7th FPRD

This proposal will integrate a number of major objectives of the FP7 Environmental theme (Fig. 2). It will provide a key Assessment Tool that will link data collected from present (e.g., ESONET) and future seafloor observatories such as the proposed FP7 ESFRI European Multidisciplinary Seafloor Observatory (EMSO), to critical policy areas such as hazard prediction and mitigation, and the modeling of pollutant transfer and other anthropogenic affects. We will utilize the seafloor observatory data to validate numerical simulations of channelised gravity currents, and therefore provide a new Environmental Technology that can be used for hazard prediction, modeling and mitigation. This technology will be a key to the optimum design and deployment of sub-sea engineering structures such as pipelines, cables and seafloor hydrocarbon production facilities, and will be a major advance over existing models which are unable to fully assess and model the nature and magnitudes of these risks (e.g., Niedoroda et al., 2000; Reed et al., 2000). The potential for large-scale environmental impact from damage to sub-sea structures, notably hydrocarbon facilities, is considerable.

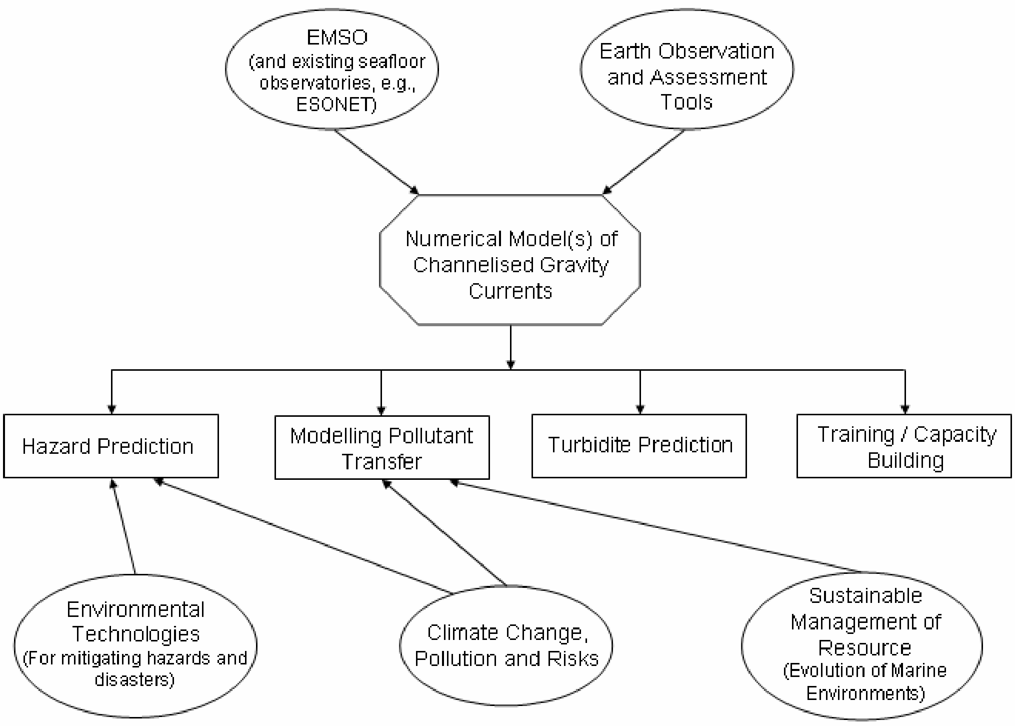


Figure 2. Linkages between project outputs and objectives of Framework 7

This project will also provide an Assessment Tool for modeling pollutant fluxes through submarine channelised systems and into the deep ocean. In particular, the tool will be critical for modeling those gravity current flows that develop directly at the river mouth during river flooding (so called hyperpycnal flows) and transport pollutants directly to the deep ocean, without any residence time on the shelf. With climate change causing more 'extreme' weather events (IPCC, 2001) then it is not unreasonable to suggest that these hyperpycnal flow events will become more frequent, and possibly of greater magnitude. The modeling approach to be developed here provides a tool that will enable the impacts of such changes to be assessed. Climate change will similarly alter the nature and magnitude of seafloor hazards, and again models are required that can assess potential impacts and factor these into risk analysis.

Sustainable Management of Resources and the evolution of marine environments requires knowledge of gravity current pathways and the resultant impact on the seafloor, as well as pollutant fluxes, sedimentation, and the role of gravity current events as providers of oxygen and nutrients to deep-sea communities. This project will therefore provide key inputs for future work on resource management issues in deep-sea environments.

The proposal will also enable capacity building in the field of environmental modelling through training of staff involved in the project. Such capacity is urgently required in the EU.

The modelling approaches will certainly have value for turbidite prediction and, therefore, the optimum recovery efficiency of hydrocarbon fields.

Cited References

Babonneau N, Savoye B, Cremer M, Klein B (2002) Morphology and architecture of the present canyon and channel system of the Zaire deep-sea fan. Mar Petrol Geol 19(4):445–467Kleverlaan, K. (1989) Three distinct feeder-lobe systems within one time slice of the Tortonian Tabernas fan, SE Spain. *Sedimentology*, **36**, 25-45.

Migeon S., Mulder T., Savoye B., Sage F. (2006) The Var Turbidite System (Ligurian Sea, northwestern Mediterranean): morphology, sediment supply, construction of turbidite levee, sediment waves and potential reservoirs, Geo-Marine Letters, Special Issue on Deep-Sea Turbidite Systems on French Margins, Mulder T., ed., v. 26 (6), 361-372.

Niedoroda, A.W., Reed, C.W., Parsons, B.S., Breza, J., Forristall, G.Z., Mullee, J.E., 2000. Developing engineering design criteria for mass gravity flows in deepsea slope environments. Offshore Technology Conference, Houston, 1-4th May 2000. OTC 12069, 10pp.

Reading H.G. and Richards M., 1994. Turbidite systemsin deepwater basin margins classified by grain size and feeder systems. J. Geol. Soc.London 148, 427-430.

Reed, C.W., Niedoroda, A.W., Forristall, G.Z., Mullee, J.E., 2000. Mass-gravity flows pose major hazards for deepwater pipelines. Oil & Gas Journal, Nov., 78-85.

Rogerson, M., Kouwenhoven, T.J., van der Zwaan, G.J, O'Neill, B.J., van der Zwan, C.J., Postma, G., 2006, Kleverlaan, K. and Tijbosch, H. Benthic Foraminifera of a Miocene Canyon and Fan. Micropaleontology, 60, 295-318.

Piper, D.W.J. and Savoye, B., 1993, Processes of late Quaternary turbidity current flow and deposition on the Var deep sea fan, northwest Mediterranean sea.