Morphological analysis of the upper reaches of the Kukuy Canyon derived from shallow bathymetry

Nicolas Le Dantec[1,2], Nathalie Babonneau[1], Marcaurélio Franzetti[1], Christophe Delacourt[1], Yosef Akhtman[3], Alexander Ayurzhanaev[4], Pascal Le Roy[1]

[1] Université Européenne de Bretagne Occidentale, UMR-6538 Domaines Océaniques, UBO-CNRS, Plouzané, France

[2] Centre d'Etudes et d'Expertise sur les Risques, l'Environnement, la Mobilité et l'Aménagement, DTechEMF, Margny Lès Compiègne, France

[3] Geodetic Engineering Laboratory, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

[4] Baikal Institute of Nature Management, Siberian Branch of the Russian Academy of Sciences, Ulan-Ude, Republic of Buryatia, Russian Federation

Abstract

We present preliminary results on the morphology of the upper reaches of the Kukuy Canyon and Selenga shelf in front of Proval Bay (Lake Baikal), derived from newly acquired, high-resolution bathymetry. Numerous and varied erosional and transport features provide an interpretation framework for source to sink transfer and gravity flow processes in this shallow and active tectonic environment, suggesting on-going gravity instabilities and sediment-laden flows. Scarps in the canyon head are likely signatures of retrogressive incision of the western tributary and eastward lateral migration of the western tributary, the latter coming within about 1 km of the shoreline. Immature gullies incising the upper-slope feedings of the Kukuy Canyon indicate gravity flows with low erosional power. Large arcuate scarps on the break of the narrow shelf east of Proval Bay reveal gravity instabilities. The morphological connection between the Selenga Delta and the Kukuy Canyon suggests a direct pathway for fluvial sediment focused through breaches in the Sakhalin sand shoal, with likely occurrence of hyperpycnal flows into canyons heads during high sediment discharges. The neotectonic activity affects both the accommodation space around the prograding delta via earthquake-induced subsidence of coastal ar-

eas, and the location of incisions through slope instability triggering. Subsequent surveys allowing diachronic analysis would help determining the influence of tectonic and climatic factors controlling sediment transfer across the land-lake continuum and interpreting the morphological signature of the associated gravity processes shaping the delta and surrounding shelf and canyons.

1. Introduction

Sediment transfer from land to deep basin is a major process in the formation of landforms and sub-aquatic morphologies like submarine canyons. It mainly occurs during extreme climatic or geological events (floods, earthquakes...), supplying large quantities of sedimentary material to basins during brief and repetitive episodes (Korup, 2012). In deep environments, gravity flows as turbidity currents are mostly responsible for canyons incision in the continuity of the main rivers. The triggering of turbidity currents remains a topical research question in marine environments (Piper and Normark, 2009). Scientific issues include the continuity at sea of hyper-concentrated stream flows generating hyperpycnal flows into canyons, mass wasting and re-suspension of sediment deposits under the influence of oceanographic factors (waves, currents). The interface between fluvial and submarine sedimentary systems is a key area to understand the morphological evolution and transformation associated with sediment transfer processes. In recent years, high-resolution bathymetric data acquired with latest-generation multibeam technologies in shallow-water environments provides advances in outlining detailed morphological features, and in understanding the sedimentary processes at canyon heads (Smith *et al.*, 2007; Yoshikawa and Nemoto, 2010; Casalbore *et al.*, 2011; Lastras *et al.*, 2011; Babonneau *et al.*, 2013).

Lake Baikal in Siberia is among the best examples of a large tectonic lake. It occupies the central part of the presently still active Baikal Rift Zone. It is the world's largest and deepest freshwater lake. Morphologically, it is subdivided into three deep basins, the South, Central and North Baikal Basins, which are separated by inter-basin highs: the Selenga Delta accommodation zone (or Buguldeika Saddle) and the Academician Ridge accommodation zone. The development of the Baikal basin results from earthquakes, which are accompanied by considerable vertical displacements of the lake bottom, collapses and landslides in the coastal zone (Shchetnikov *et al.*, 2012). Contrary to the pronounced morphological structure (tectonic escarpments) observed on the northwestern side, the more gently sloping eastern side of the rift shows major lithospheric extension associated with rearrangement of blocks in the upper lithosphere slab.

The Selenga River is a major river in Asia and forms a large delta on the southeast shoreline of Lake Baïkal. The mean discharge of the Selenga River into Lake Baikal in winter is approximately 100 $m^3.s^{-1}$, which increases to 1,700 $m^3.s^{-1}$ in spring as the snow melts. The Selenga Delta consists of a multibranch fan-like channel structure. The northern shelf of the delta is incised by a deep NE-SW oriented canyon (the Kukuy sub-aquatic canyon) feeding a large turbiditic fan. The morphology of this fan is characterized by a network of sinuous turbidite channels, as observed in deep-sea fans, which suggest active and frequent sediment transfer from the deltaic channels to the deep lake via turbidity currents or hyperpycnal flows into the canyon.

Proval Bay, to the East of the Selenga Delta, was formed by a large seismic dislocation event: the 1862 earthquake caused subsidence (up to 7-8 m) of the former Tsagan steppe below the water surface. This seismotectonic phenomenon constitutes an example of scaled subsidence of crustal blocks in coastal zones (Shchetnikov *et al.*, 2012). On the south and the east, the littoral zone of the bay is controlled by the Delta fault, which has a defined scarp up to 10-12 m high. Comparison of old charts with modern maps shows that the boundary of the Selenga River delta has shifted considerably eastward (Vologina *et al.*, 2010) due to intense progradation from the Selenga River delta plain (66 mm/yr). Sedimentation rates vary greatly across Proval Bay depending on proximity to the Selenga River. Seismotectonics thus plays a role of buffer mechanism in the sediment transfer through the land-sea interface, as subsidence events generate accommodation space. Sediments prograde into the recently formed coastal embayments instead of being delivered directly to the Baikal basin through the canyon and shelf break. Before the rise of water level when the Irkutsk hydropower station of Angara dam was put into operation, Proval Bay was separated from Lake Baikal by the oblong Sakhalin island.

The remnants of this sand ribbon still exist as an underwater sand shoal consisting of numerous bars bordering most of the bay. The entire system of underwater bars is active, with a general eastward and offshore drift on the order of 50 m/yr (Rogozin, 1993).

We have acquired high-resolution bathymetry in the shallower section of the lake in front of Proval Bay, on the upper reaches of the Kukuy Canyon. Here, we are presenting preliminary results on the morphology of the canyon and shallow shelf. We describe erosional features and infer sediment transport pathways. The main scientific issues are : (1) to identify the potential activity of turbidity currents initiated in the canyon heads by the observation of active bedforms and fresh erosional structures ; (2) to understand the continuity of the sedimentary processes between the delta and the canyons (morphological continuity, transformation of the flows, sediment instabilities…) and (3) to determine the influence of tectonic factors in the triggering of gravity instabilities, and in the control of the location of morphological incisions. This initial study highlights the interest in extending the survey to cover the entire shelf in front of the delta, possibly with repeated surveys to develop a multi temporal approach (Franzetti *et al.*, 2013, Babonneau *et al.*, 2013).

2. Data and methods

A high-resolution bathymetric dataset of the Northern Selenga Delta was collected in August 2014 during the SELENGA 2014 survey, using a shallow-water multibeam echosounder Kongsberg EM3002. This high-resolution 300 kHz multibeam system was temporarily set up on a lake survey boat, which allowed acquisition of bathymetric data in water depths ranging from 2 m up to 250 m with a vertical resolution of up to 10 cm. Sound velocity profiles were carried out twice a day in the vicinity to correct sound refraction errors. Multibeam soundings were edited with QINSy software to provide a 4-m grid DTM. Figure 1 shows the surveyed area.

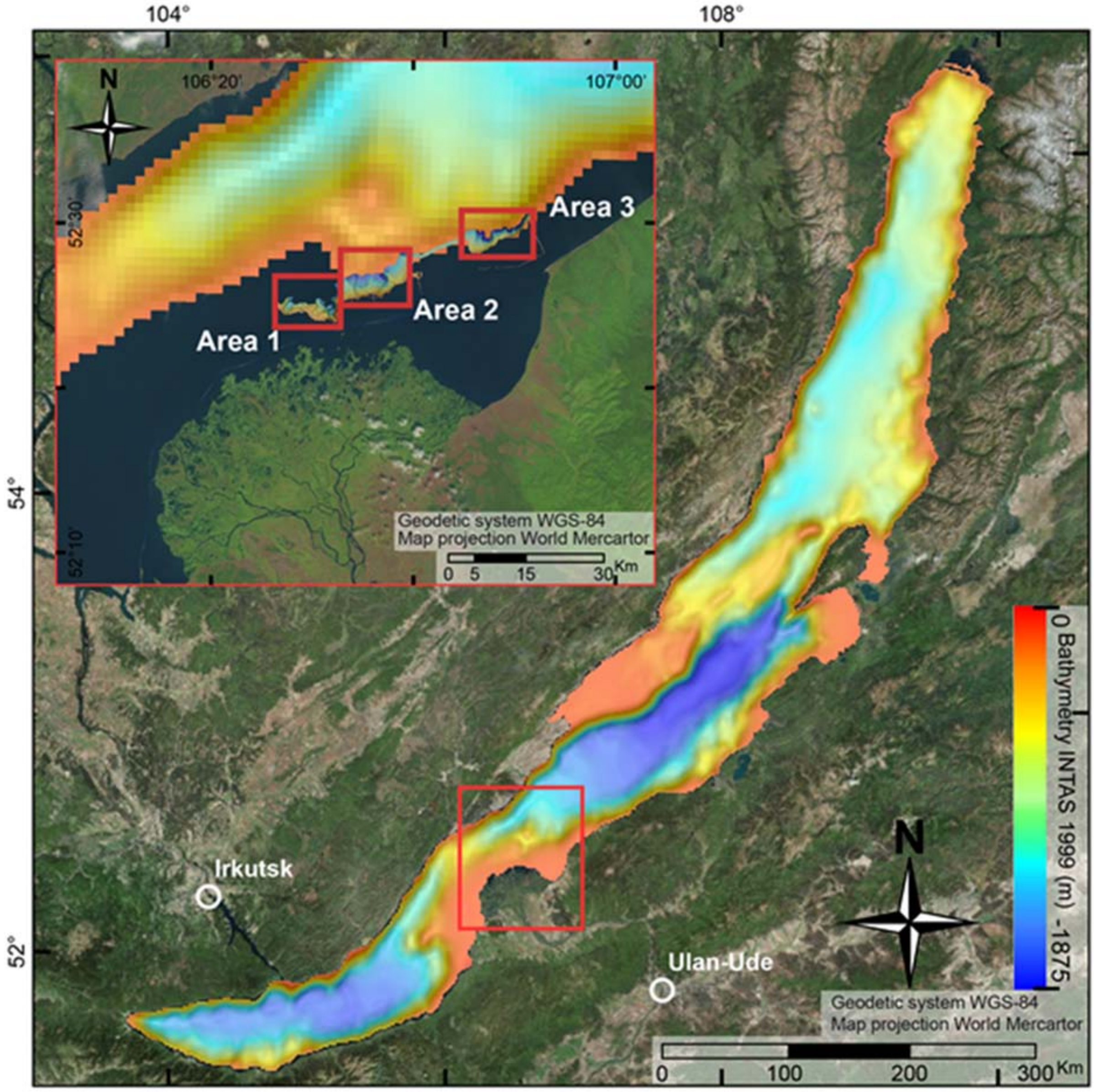

Figure 1: Bathymetric map of Lake Baikal (INTAS, 2002; Sherstyankin et al., 2006). Insert: Location map showing the Selenga Delta and the study area (3 boxes indicating the new high-resolution bathymetric data).

3. Results

The derived bathymetry is decomposed in 3 areas for the presentation of the results (Figure 2). Survey planning was devised to focus on the upper reaches of the canyon, off the Western side of Proval Bay, and on the shelf break of the Eastern side of the bay. In the first of the 2 zones, the delta shows significant focusing of the sediment discharge through the sand bar, which is visible on satellite images (Figure 2). The head of the canyon exhibits a bifurcation, with the main branch turning toward the shore and coming within about 1 km of the shoreline. The second branch is mainly in the same orientation as the canyon itself but it is much less deeply incised. In the results description, the canyon head will constitute area 1. Near the shelf break, the Kukuy Canyon exhibits a sharp lateral jog, where the orientation of the thalweg abruptly turns at 90° and back. The section of the canyon up-canyon of this lateral shift and down-canyon of the canyon head runs nearly parallel to the shelf break. Along this section, secondary channels incised along the upper shelf feed the main canyon beyond the head. This sector will be area 2. While the lake has a mostly narrow shelf (5 km wide on the South shore and 10-15 km wide on the North shore), in the Selenga accommodation zone in front of the delta, the shelf extends over 30 km into the lake. Data collected off the Eastern side of Proval Bay, where the shelf becomes much narrower after a sharp inshore turn of the shelf break (300m isobath), is presented as area 3.

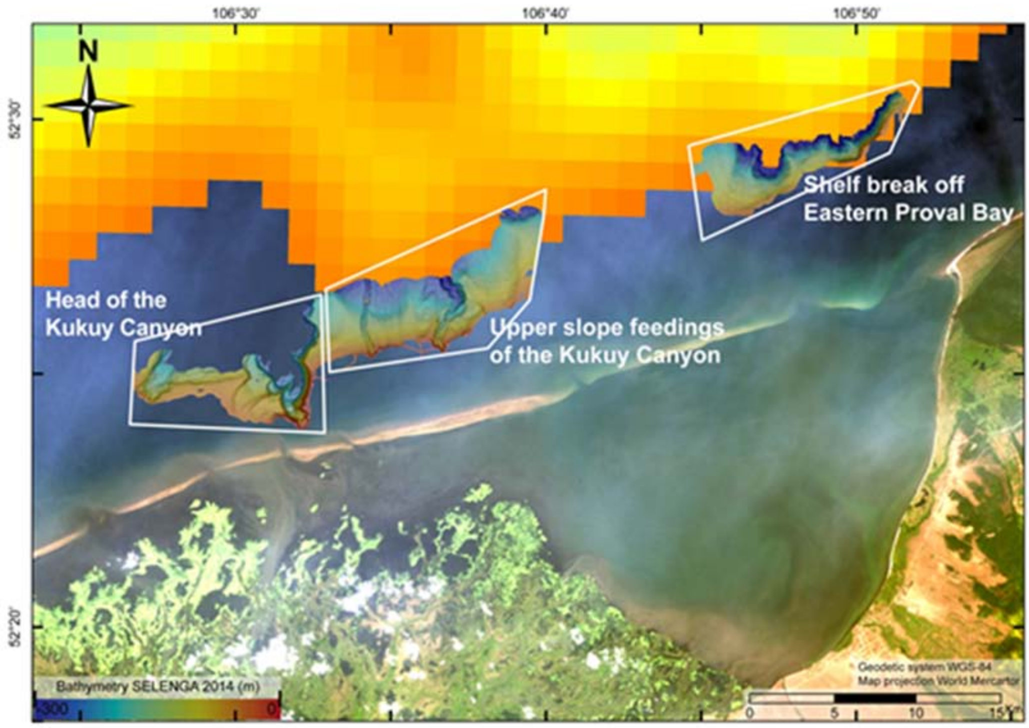

Figure 2: High-resolution bathymetric map at the mouth of the Selenga delta and Proval Bay (Satellite Image: Landsat 8 from August 18th, 2014).

Area 1: Head of the Kukuy Canyon

Of the two tributaries composing the head of the Kukuy Canyon, the western tributary canyon is slightly asymmetric and bounded by a steep and rectilinear left side in the continuity of the canyon side. The NE-SW rectilinear orientation suggests a strong morphological control by a major fault, matching with the main rift structures. The canyon head is characterized by several rounded scarps at less than 50 m of water depth, which can be interpreted as local slope instabilities generating a retrogressive incision of this canyon head. The canyon floor is about 1 km wide and shows irregular bedforms and erosional features. It is not draped by muddy sediment but shows relatively fresh sedimentary features indicating a recent activity of gravity processes.

The eastern tributary canyon is the most incised. Its morphology is highly asymmetric with a steep eastern side oriented N-S and an arcuate morphology. This arcuate morphology is consistent with the sinuous path of the thalweg in the deeper part of the canyon. The presence of current and abandoned meanders along the thalweg indicates a mature canyon incised and active for a long time. The morphology of the western side of the tributary canyon shows several rounded erosional structures suggesting the lateral migration of the canyon head from West to East. The present canyon head shows very fresh scarps initiated at less than 20 m of water depth. The longitudinal depth profile in the canyon axis shows a succession of small steps suggesting active processes of slope instabilities.

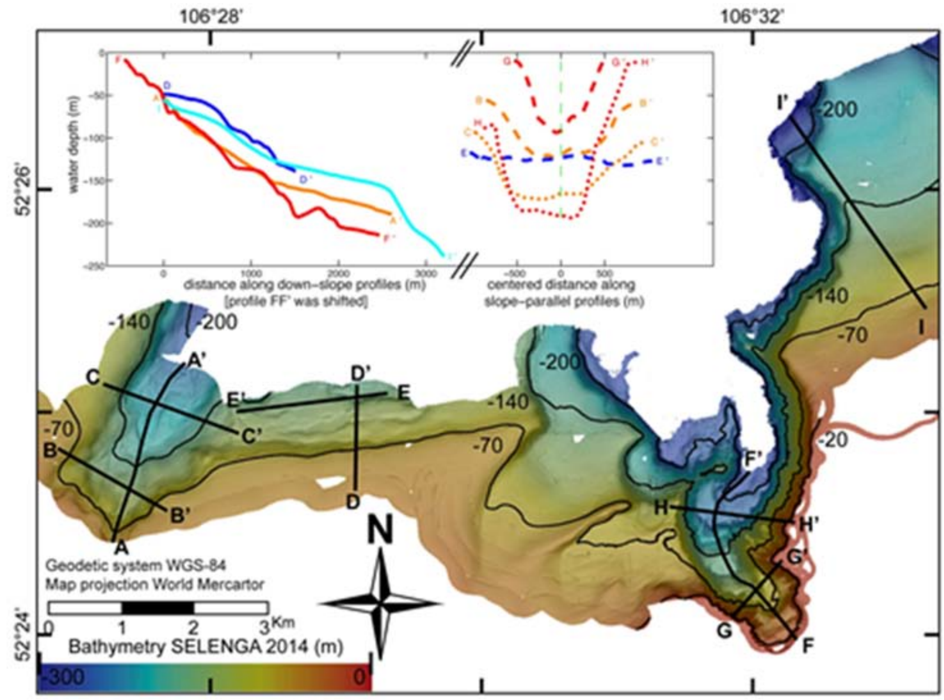

Figure 3: Zoom of the bathymetric map focused on Area 1, western feeding of the Kukuy Canyon (isobaths at 20, 50, 100 and 200 m water depth and location of the bathymetric profiles). Insert: Bathymetric profiles.

Area 2: Upper slope feedings of the Kukuy Canyon

The central area also corresponds to a sector with smaller tributary canyons and gullies incising the upper slope and feeding the Kukuy Canyon. In this area, two small canyons are distinguished with incision about 25 m deep and width about 200-300 m. The sinuosity of these small canyons is low and suggests more immature morphology. Other erosional features are visible. They are straight and their incisions are superficial, corresponding to immature gullies suggesting gravity flows with low erosional power.

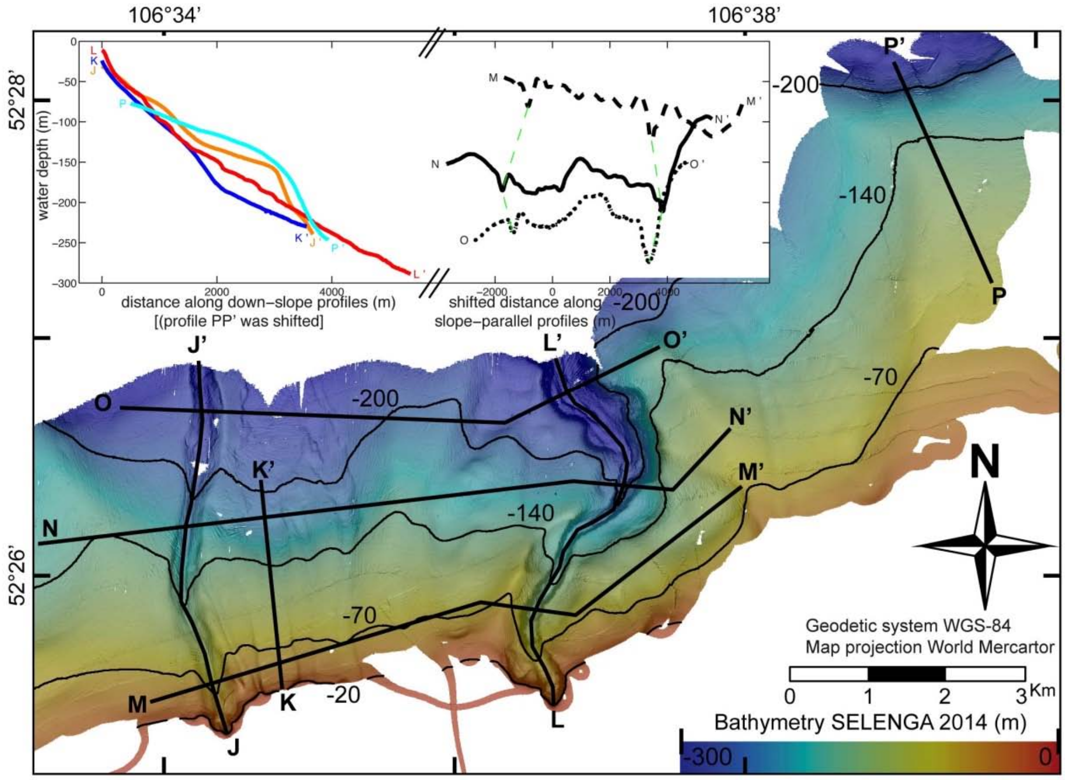

Figure 4: Zoom of the bathymetric map focused on Area 2, eastern feeding of the Kukuy Canyon (isobaths profiles location as in Figure 3). Insert: Bathymetric profiles.

Area 3: Shelf break off Eastern Proval Bay

Shallow bathymetry illustrates the morphology of the shelf break and the upper slope at the eastern extremity of the delta. The eastern area is not directly linked to the Kukuy Canyon. In this area, the submarine slope is steeper eastward and shows large arcuate scarps. Such morphology probably corresponds to gravity instabilities of the shelf break, which contribute to mass transport through the canyon, generating slump, debris flow or turbidity flow. Earthquakes as well as sediment overload are likely trigger mechanism for slope failure. The absence of morphological evidence of sediment-laden, bottom flows in the shallow bathymetry between the delta and the shelf break, contrary to the 2nd area, can be explained by the earthquake-induced creation of Proval Bay offering accommodation space for the prograding delta.

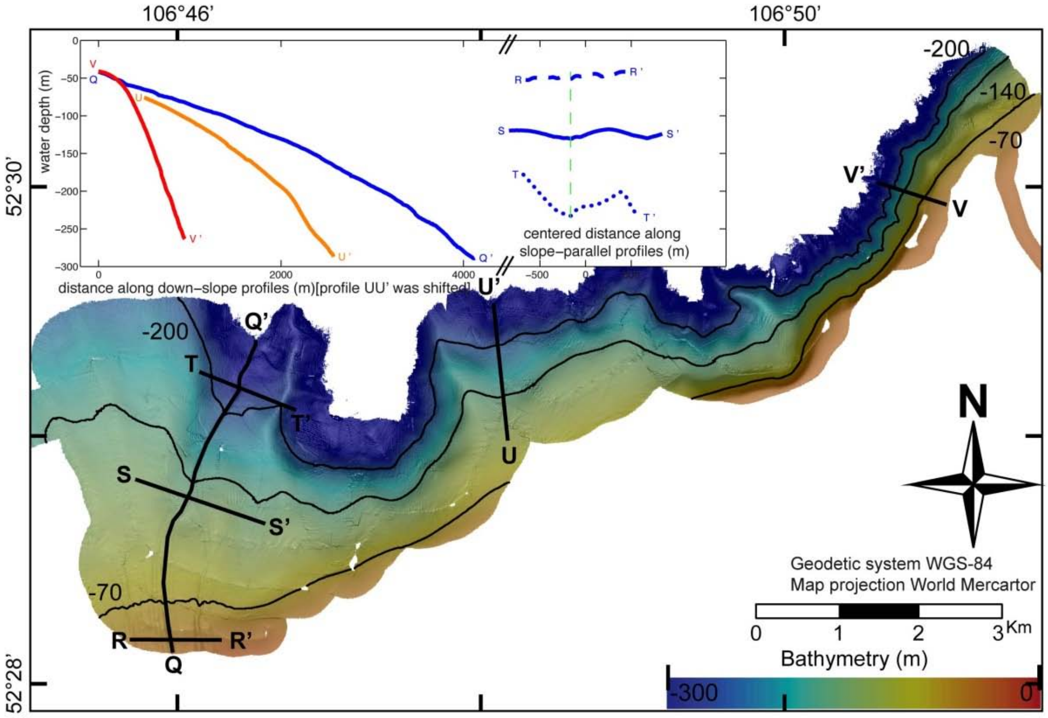

Figure 5: Zoom of the bathymetric map focused on Area 3, Shelf break and upper slope of the eastern part of the delta (isobaths profiles location as in Figure 3). Insert: Bathymetric profiles.

4. Conclusions and perspectives

The interpretation of shallow bathymetric data aims to show the detailed structure of the upper reaches of the Kukuy Canyon. Preliminary results provide new elements on the issues of source to sink transfer and gravity flow processes in this shallow and active tectonic environment. The number and varieties of sedimentary features and the recently-generated morphologies (scarp, bedforms ...) observed in shallow water suggest active gravity instabilities and gravity flows as turbidity currents. The morphological connection and close proximity between the delta channels breaching the sand bar and the upper reaches of the Kukuy Canyon suggest a direct pathway for fluvial sediment. It is likely that high sediment discharge volume of the delta during snow melt periods generates hyperpycnal flows feeding the Kukuy canyons heads. Moreover, the active seismic setting both affects the accommodation space around the prograding delta, with morphological changes of the lake basin through earthquake-induced subsidence, and is also a very likely predisposing factor for slope instability triggering, with a strong tectonic control on the location of incisions and scarp failures by rift faults. Multitemporal bathymetric surveys will be carried out in the next years, providing new measurements in order to better understand the relationships between variation of sediment discharge and gravity processes, and the links between shallow and deep gravity processes.

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