SEDIMENT FAILURE PROCESSES IN ACTIVE GRABENS: THE WESTERN GULF OF CORINTH (GREECE)

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Abstract

On steep (2-6^o) offshore fan deltas of Western Gulf of Corinth medium to small scale (10^6-10^7 m^3) debris flows and avalanches are the prominent slope features. Loose sands, gravels and pebbles are observed in the lower fan while silty/sandy turbidites/tsunamites detected in cores, implying sediment dissociation during failure and downslope transport. These failures are associated with significant upslope retrogression that has caused coastal retreat with important human and economic impact. All the events were estimated to have occured during the late 4-5 kyr after or during the deposition (progradation) of the HST fan delta. Recent (late 0.1-0.15 kyr) prodelta failures in the Gulf of Corinth are evidenced by the destruction of telecommunication cables, coastal collapse and the initiation of destructive tsunami waves (i.e. 1963AD). The frequency of major failure events in the Western Gulf of Corinth is estimated to 2-3 events/0.1 kyr, usually associated with strong earthquakes and tsunamis (i.e. 1817, 1861, 1917?/,1963 1995AD events)

Keywords: Offshore sediment failure, Fan delta, geotechnical properties, active graben, Gulf of Corinth, NE Mediterranean

1. Introduction

The western Gulf of Corinth is one of the more seismically active areas in Europe due to its proximity to the Hellenic trench (Jackson et al., 1982; Armijo et al., 1996; Clarke et al., 1997; Davies et al., 1997; Moretti et al., 2003) (Fig. 1). The greater area includes the Gulf of Corinth (graben) and the Ionian margins with high river run-off and terrigenous sediment supply. Intense shallow earthquake motions particularly pronounced in Western Gulf of Corinth are expected to generate peak ground accelerations of 25-35%g (Makropoulos and Burton, 1985; Papoulia et al., 1998). Within this region frequent sediment mass failures during the late century have been responsible for numerous cable breaks (Heezen et al., 1966) and catastrophic tsunamis (Papadopoulos and Chalkis, 1984).

From the late Pleistocene stage, the Gulf of Corinth basin was filled up by a thick sequence of gravity deposits (turbidites, debris flows, mudflows etc.) (Heezen et al., 1966; Brooks and Ferentinos, 1984; Poulos et al., 1995; Lykousis et al., 2007a). Fan delta prograding deposits during Pleistocene sea-level changes coupled by extensive slumping, are the predominant sedimentary processes in the steep flanks of the gulf (Ferentinos et al., 1988; Lykousis, 1990; Lykousis et al., 1995; Perissoratis et al., 2000; Lykousis et al., 2007b). These processes are mostly related to seismically triggered mass-gravity failures that initiated in the coastal zone and/or the uppermost slope

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(Perissoratis et al., 1984; Lykousis, 1990; Piper et al., 1990; Ferentinos et al., 1988; Papatheodorou and Ferentinos, 1997). Slope stability calculated using the Normalised-Soil-Parameter (NSP) method (Lee and Edwards, 1986) indicates that instabilities could be induced by earthquake ground accelerations of 26.6-29.6 %g (Lykousis et al., 2007b). Since the expected ground accelerations over the next 100 yrs are 25-35% g (Papoulia et al., 1998) the fan delta slopes of the Western Gulf of Corinth are potentially unstable.

The purpose of this paper is to study the mass failures and associated processes, related to the prograding sedimentary sequences in the steeper fan delta slopes (mean gradient 2^0-6^0) of the Western Gulf of Corinth.

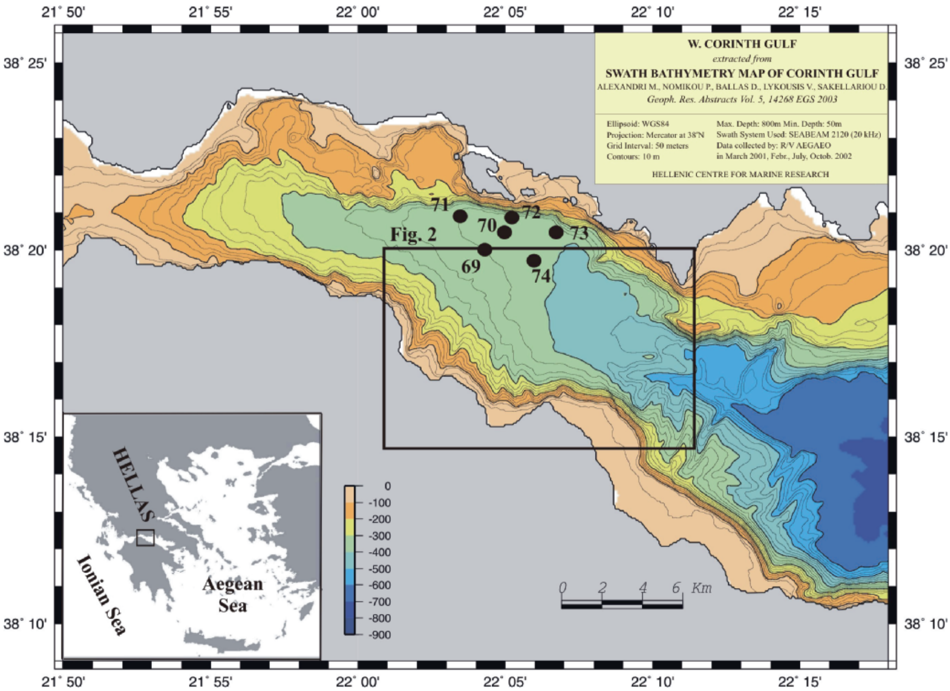

Figure 1: Multibeam bathymetric map of Western Gulf of Corinth extracted from Alexandri et al. (2003). The black box indicates the location of the 3D view shown in Fig. 2. Approximate location of box-core samples is indicated by full circles.

2. Methods

High resolution seismic reflection profiles taken from various surveys during the last decade (3.5 kHz and Air Gun) with the R/V AEGAEO were used to identify the sediment sequences and the associated instabilities. Sediment cores (2 - 5m long) were recovered using a BENTHOS INSTR. gravity corer that provides relatively undisturbed samples. Grain-size analysis was performed with the Sedigraph laser technique (Micrometrics 5100) at 5 cm intervals along the split cores. The multibeam mapping was conducted using the SEABEAM 2120 and 2200 models operating at 20 kHz and

200 kHz respectively. Recent sedimentation rates (late 0.1 ka) were calculated by measuring the ^{210}Pb activity via its α-particle-emitting granddaughter ^{210}Po, and assuming secular equilibrium with ^{210}Pb (Appleby and Oldfield, 1978) and following the methodology described by Sanchez-Cabeza et al. (1998) and Radakovitch (1995).

3. Fan delta slope failures

Extensive Gilbert –type fan delta deposits were developed along the Gulf of Corinth steep, faulted slopes. The offshore fan deltas are well pronounced along the southern slopes which are characterised by high sediment fluxes and rapid tectonic uplift (Brooks and Ferentinos 1984; Ferentinos et al. 1988; Papatheodorou and Ferentinos 1997; Lykousis et al. 2007a). The dip of the slope ranges between 3^0-6^0 and is locally higher, close to fault or slump scarps.

Small-medium size sediment failures with volumes of 10^6-10^7 m^3 have been imaged with the high resolution (200 kHz) multibeam mapping of the Western Gulf of Corinth particularly along its southern margin (Fig. 2).

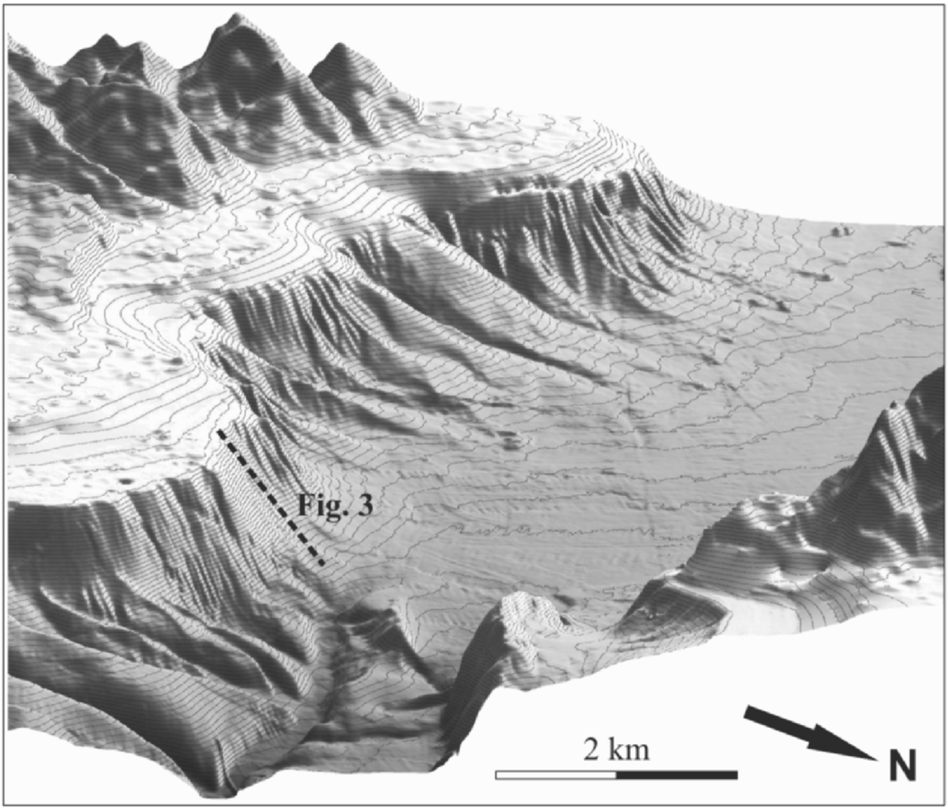

Figure 2: 3D view of fan delta failures (debris flows) along the southern flanks of Western Gulf of Corinth (imaged from ENE). Note the “floated” sediment block debris in the lowermost fan. For approximate location see figure 1. Location of figure 3 is also indicated.

The majority of the observed failures are downslope debris flows/avalanches (Fig 3). Slab (translational) slides occur also (locally) along gently dipping slopes (2^0-3^0 HST prodeltas (i.e. Mornos delta) (Lykousis, 1990). The failure scarps are shallow (10-50m depth), located close to (100-200 m) the coastline and are usually associated with coastal zone retreat and submergence, due to upslope (cross shore) retrogression. Although more difficult to locate in offshore fan deltas, failure planes are expected to be basal muddy layers (flooding surface-MFS??) and/or biogenic methane gas charged sediment horizons (Lykousis et al., 2007b).

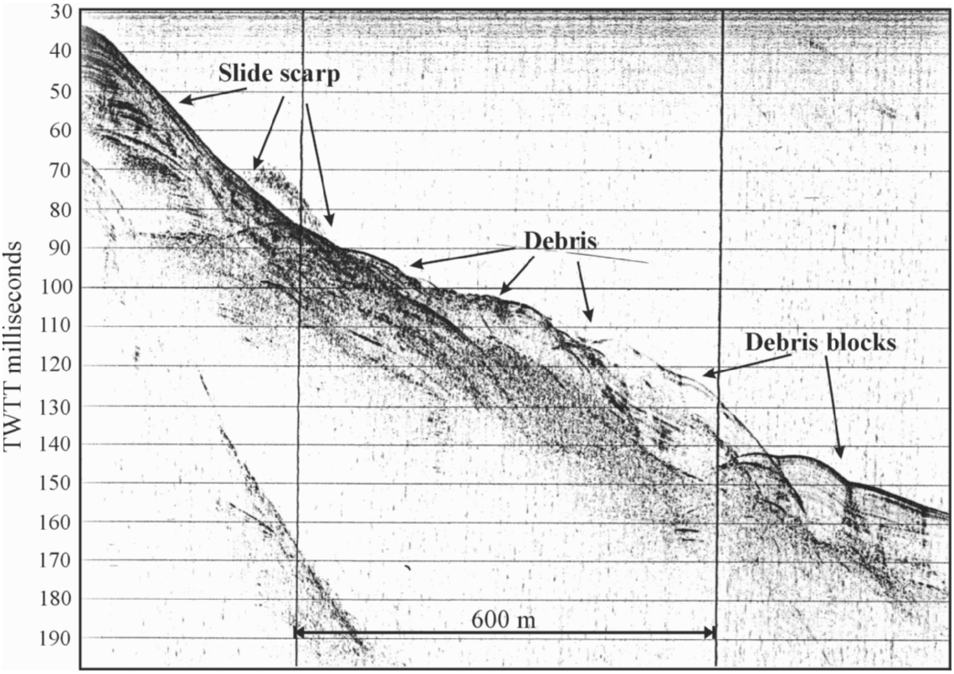

Figure 3: 3.5 kHz subbottom profile showing debris flows off the fan deltas of Western Gulf of Corinth. For approximate location see figure 2.

Since the fan deltas have been developed (prograded) during the late high sea level stand (HST fan deltas) all the events are younger than 4-5 ka BP. The majority of these failures are associated with strong earthquakes, although major failures initiated without seismic activity (Papadopoulos and Chalkis, 1984). The repetition rate of major failure events is estimated to 2-3events/100yr and is coincident with occurrence of tsunamis in the Gulf (ie 1817, 1861, 1917, 1963, 1995AD etc). At least five cable brakes have been reported from the westernmost part of the Western Gulf of Corinth (Mornos delta) for the period 1890-1920 (Heezen et al 1966). Successive surveys with subbottom acoustic profiling and sediment sampling revealed that cable brakes were due to different types of slope failures, including turbidite flows (Lykousis, 1990; Lykousis et al., 2007b). Repeated dives with submersible and ROV deployments upslope the evacuated zones displayed loose sands, gravels and pebbles dispersed in the lower fan and numerous downslope small channels (0.5m wide and 0.4 m deep) indicating sediment (turbidity?)

flows. Towards the steeper scarp zone repeated arcuate (crown) cracks with 10-20 cm offset are evidence of the frequent small scale failures that promotes the upslope erosion and the oversteepening of the uppermost slope (Figure 4).

In a long term basis, this process play important role in the upslope and inshore retrogressive failures, with ultimate result the costal failure and subsidence of significant coastal zones. Shallow gravity normal faults recorded on 3.5 kHz profiles between the failure scarp and the coastline support this interpretation. Consequently, smaller scale events occur very often as indicated from indirect approaches (cable brakes, small tsunamis without seismic shock, local ground tremors and sounds etc) but also from repeated direct ROV/submersible observations. At least one medium-big failure event (2-3 km^3 in volume) (Lykousis et al., 1995) has been determined in the Western Gulf of Corinth and may be associated with the regional coastal submergence (drowning of ancient Helike and destruction of ancient Voura) and the giant tsunami which followed the 363 BC earthquake.

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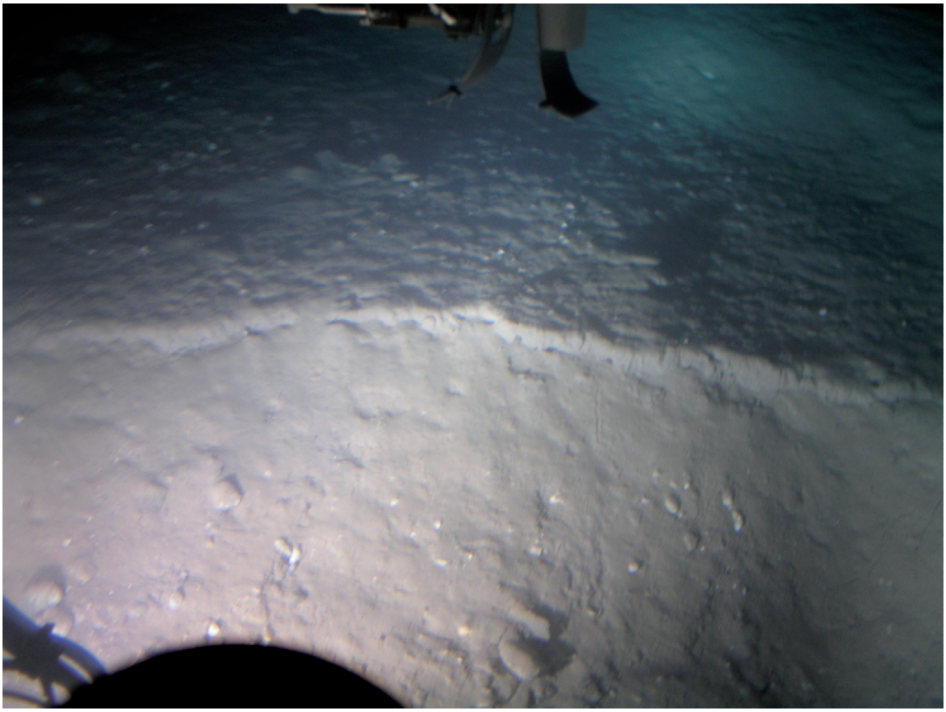

Figure 4: Arcuate (crown) crack with small offset, observed on the southern slope of the Western Gulf of Corinth, is interpreted as a precursor of a forthcoming small failure. Approximate scale of the frame 2m x 2m.

4. Basin turbidites/tsunamites?

A series of sediment cores (box and gravity) were recovered from the basin of the Western Gulf of Corinth between Trizonia Island and the south slope. All the cores systematically display two distinct coarse grained layers with sharp upper and lower contacts and comparable thickness among the sediment cores (Figure 5). The predominant layer, that occurs basin-wide, ranges in thickness from 6-10 cm (mean 8 cm) and the total volume of this coarse-grained deposit is estimated to 0,5 x 106 m^3.

This is comparable to a single failure event in the Western Gulf of Corinth based on the estimation from the detailed multibeam bathymetry. Microscopic analysis showed that it consists almost exclusively of relatively well rounded terrigenous coarse silt-fine sand. The grains are mostly feldspars, quartz and minor amount of terrigenous calcite. There was a lack of shell debris and foraminifera. These characteristics, the basin wide spread and the uniform thickness probably implies tsunamigenic derivation rather than gravity flow (turbidite) deposition (i.e. distal turbidites from debris flow along transport dissociation), although, this late assumption should not be excluded.

The mean accumulation rates for the last 100-120 yrs obtained by the ^{210}Pb radiometric method from two short sediment box cores are shown in Figure 6. The obtained ^{210}Pb activity profile versus depth below sea floor displayed, irregularities which can be directly related to episodic deposition of gravity driven mud flows or mud turbidites on the seafloor. Apart from the internal structure of the core, the calculated mean accumulation rates for the last 100-120 yrs, according to the downcore distribution of the excess ^{210}Pb activity, were 20-30cm 100 yr^{-1}. This also indicates that the turbidites have been deposited at the margin before 100-120 yrs or earlier (about 150 yrs). The region experienced two very intense seismic events the late 100-200 yrs followed by destructive tsunamis and extensive coastal collapse that indicated significant offshore failures (1817AD and 1861 AD). We conclude that the coarse grained layers were deposited during the 1861 AD stronger and more recent event either as tsunami deposit or as a distal end member of debris flow.

5. Summary and conclusions

Multibeam, seismic profiling, submersible dives and sedimentological data (cores, x-ray images, AMS and Pb^{210} dating) provide new information regarding the mass failure processes in one of the most active rifts among the European margins. The Gulf of Corinth, Greece is characterized by a complex set of natural hazards, (earthquakes, slumps, tsunamis, fluid escape etc) mainly associated with its strong neotectonic and seismic activity. The seismicity, the steep slopes of the basin, together with the large amount of sediments deposited by the several rivers (sedimentation rates about 3 m/kyr) is the key factors of sediment failure. The latter explains why the sliding masses were found offshore the major delta plains of the western part of the Gulf of Corinth. The submarine slope failures are characterized by relatively small-medium volumes (up to $9x10^7$ m^3) but of high number of events and aerial extension on the slopes of the Western Gulf of Corinth. The sediment slides are initiated from very shallow depths (20-40 m) and sometimes from the coastal zone (i.e. 1963 AD slump and associated tsunami). During the failure most of the slumped sediment masses are disintegrated to debris flows (muddy sands with gravels) in the mid-lower slope and probably sandy/silt turbidites in the proximal basin. These coarse-grained layers may also have been derived from deposition of material resuspended by tsunami (tsunami deposits).

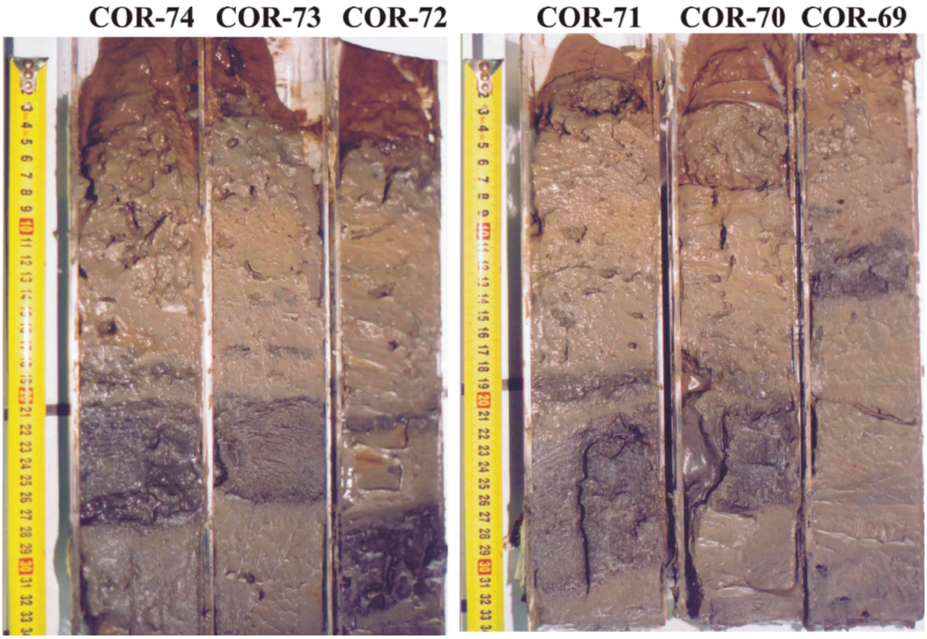

Figure 5: An 8cm-thick coarse-grained layer (turbidite/tsunamite?) occurs at ca. 20-30 cm depth below the seafloor of the Western Gulf of Corinth basin.

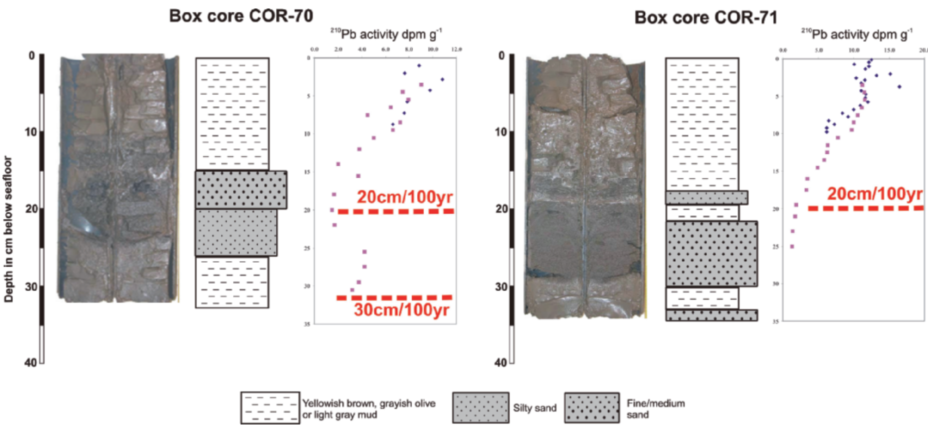

Figure 6: Photographs and sedimentological description of two box cores (COR-70, COR-71) from the Western Gulf of Corinth. The ^{210}Pb downcore activity profiles and the calculated actual sedimentation rates are also shown (from Sakellariou et al., 2004).

The upper slope and the scarp of the failure zone undergo active retrogression as indicated by the upslope (up to the coastal zone) shallow gravity faults and the arcuate (crown) cracks that have been observed by submersible dives. This process is responsible for the coastal zone subsidence during major, mass failure events. Estimated reoccurrence of major failure event is at least 5 events/100yr (based on cable brakes and Pb^{210} dating of successive turbidite events). Smaller and minor failure events, mostly due to retrogression and gravity faults activation, are often and continuous as evidenced by submersible observations, local ground vibrations and sounds due to offshore slumping. One of the greater, recent, extensive offshore and coastal failure occurred during and after the 1861AD strong earthquake. The sandy-silt turbidite layer deposited on the flat basin of the Western Gulf of Corinth because of this event is 8 cm thick, extends basin wide and display total volume of about 0,5 x 10^6 m^3.

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