A giant catastrophic mud-and-debris flow in the Miocene Makran

Jean-Pierre Burg,1 Daniel Bernoulli,1 Jeroen Smit,1 Ashgar Dolati1,2 and Abbas Bahroudi2,3
1Geological Institute, ETH-Zurich, 8092 Zurich, Switzerland; 2Geological Survey of Iran, Tehran, Iran; 3Tehran University, PO Box 11365-4563, Tehran, Iran

ABSTRACT
We challenge the former interpretation of the 'sedimentary mélangé' of the Makran accretionary complex as a tectonic mélangé diapirically emplaced from below and provide evidence for its sedimentary gravitational emplacement from the north during Tortonian–Messinian times (between 11.8 and 5.8 Ma). It is an olistostrome that includes blocks of ophiolites and oceanic sediments derived from the 'coloured mélangé' of the north, and reworked chunks of the turbidites on which it rests with an erosional truncation. The chaotic scattering of blocks of any size and lithology and the weak, soft-sediment deformation of the matrix argue against a tectonic emplacement of the chaotic formation. Its size and internal structure, together with the size of the individual blocks, make the olistostrome a fossil equivalent of the large, gravitationally emplaced debris flows observed along present-day continental margins and unstable volcanic edifices.

Terra Nova, 20, 188–193, 2008

Introduction
Massive mass-wasting events are common along both the passive and active continental margins (e.g. Canals et al., 2004; Haflidason et al., 2004; Medialdea et al., 2004) and large volcanoes (e.g. Masson et al., 1998; Coombs et al., 2007). The disastrous effects that already small mass-wasting events produce (e.g. Rahn, 1996), and the size of many examples from the geological record make us aware of catastrophes of magnitudes beyond those historically documented. On the basis of new geological observations at regional, outcrop and hand-specimen scales, we argue that the 'sedimentary mélangé' in the Iranian Makran is an olistostrome emplaced as a huge mass flow during Tortonian–Messinian times (between 11.8 and 5.8 Ma), or shortly thereafter. This event may reflect the initiation of a new tectonic regime along the Arabia–Eurasia collision zone.

Geological setting
The geological Makran is the best exposed accretionary complex on Earth. It extends between the Minab dextral transform fault to the west, and the sinistral Chaman transform fault to the east, and results from the convergence between the Arabian and Eurasian plates since at least the Cretaceous (Byrne et al., 1992; Dercourt et al., 1993). More than 150 km in profile of the accretionary complex are exposed on land, from the coast to the north and to the contact with the Jaz Murian Depression, to the south (Fig. 1). This contact is delineated by obducted ophiolites overlying a 'coloured mélangé', an imbricate zone of ophiolite fragments and oceanic sediments. The frontal southern half of the wedge developed below sea level since the late Miocene (Platt et al., 1985). The oceanic basement dips regularly 2–3°N up to the Jaz Murian Depression, where it is 30 km deep (White and Louden, 1982; Kopp et al., 2000). Further north, it dips approximately 30° beneath the Lut and Afghan microcontinents and the Pleistocene volcanic arc. Shortening and abundant sediment supply led to the seaward growth of the accretionary complex by frontal accretion and underplating of trench fill sediments (Platt et al., 1985). Since mid-Pliocene times, uplift and normal faulting produce tilted and faulted terraces (Platt et al., 1988). The active subduction zone absorbs the oceanic part of the Arabian plate at nearly 2 cm yr⁻¹, in an approximately N–S direction (Bayer et al., 2006; Vigny et al., 2006).

Lithologies of the accretionary complex essentially comprise turbidites representing relatively distal base-of-slope and slope deposits with channel, fan and lobe facies. These sediments range in age from latest Paleocene to early Miocene without major non-conformity or hiatuses (McCall, 1997, 2002). The turbiditic sequence is spectacularly folded by E–W-trending chevron folds plunging shallowly either direction. The progradation from deep marine to slope-shelf and coastal plain sedimentation with neritic fauna occurred rapidly, producing growth structures, however, without a regional non-conformity, from the mid-Miocene onwards (Harms et al., 1984). Coarse fanglomerates of Pleistocene age are unconformable over wide areas of southern Makran. The Holocene comprises cemented coastal and fluvial sandstones and unconsolidated sand dunes.

The topic of this contribution, the 'sedimentary mélangé', is inserted within the Miocene sequence: it overlies the Eocene to Lower Miocene turbidites to the north and is intercalated in the Upper Miocene deposits to the south. The erosive contacts with the underlying folded turbidites attest its sedimentary origin.

Olistostrome
The olistostrome is a chaotic, non-metamorphic formation of dissociated turbidites with a muddy, shaly matrix containing randomly mixed blocks of various compositions (limestones, sandstones, shales, chert, schist, pillow lava, gabbro and serpentinite), shapes (rounded and angular) and sizes (mm to km across). The olistostrome is mainly matrix supported and assumes the texture of pebbly mudstone and, at places, displays only sedimentary signatures (Fig. 2). It overlies Paleo-
cene to Oligocene turbidites in the north, and Lower to Upper Miocene turbidites farther south (McCall, 1983).

Unconformable lower contacts are exposed in many places. The lowest levels of the olistostrome cut the layering of underlying turbidites and contain sandstone blocks comparable to sandstone layers of the eroded sequences. This situation is common in the north (Fig. 3). Faulted contacts represent later thrusts and faults. In the south, where the substrate is Miocene slope deposits, the contact is nearly parallel to the sediment layers with apparently limited or no erosion. The basal contact does not bear prominent slickensides; however, the shales of the olistostrome matrix present a strong, but soft-sediment scaly fabric (Fig. 4). There is a polarity in the lithological and size distribution of the blocks. Kilometre-size blocks of ophiolites and radiolarian cherts and smaller blocks of Cretaceous pelagic and Eocene shallow-water limestones are more abundant to the north, whereas most blocks in the south are sandstones similar to those of the underlying turbidites.

Some block-matrix contacts are faulted (expectably, late tectonic faulting will be concentrated between strong blocks and weak matrix); yet, many contacts are sedimentary and matrix structures are typical of soft-sediment deformation (Fig. 2) (Allen, 1982; Mills, 1983). Although the olistostrome locally shows tectonic overprint, it meets all criteria that distinguish it from tectonic mélanges (Pini, 1999). The weak cleavage, without stretching lineation, does not represent a deformation event pervasive enough to be responsible for the hefty scattering of blocks of various sizes and, more importantly, various compositions along the same strike direction: boudins would be more regular, interboudins would display neck structures that are inexistent, and some sort of 'stratigraphy' would be preserved. The scaly fabric of the matrix, which looks like a wavy, phacoidal to anastomosing spaced cleavage, is independent of fold axes and does not prominently wrap around the hard blocks as would be expected for a tectonically induced foliation (Fig. 5). Instead, it merges into isolated and locally anastomosing high-strain zones and planes identified from the intensified fabric, ridge-and-groove striations and slickensides. The scaly fabric is therefore interpreted as the flow fabric developed, while the ductile matrix and the blocks were emplaced. The fabric has been emphasized by later compaction/deformation, as indicated by minor deflection against hard blocks of any size.
The different morphologies of this fabric and associated higher strain zones and planes can be related to rheological variations mirroring variations in water content as reported from experiments in variably water-saturated argillaceous rocks (Maltman, 1977; Dehandschutter et al., 2005). This interpretation is consistent with abundant and coherent flow directions deduced from displacement features (offset markers, ‘extensional’ shear bands) and local structural asymmetry (drag folds, sigmoidal scaly fabric, clast rotation in non-lithified matrix) recorded throughout the area. Structures such as open to isoclinal folds of disrupted sandstone beds floating in the non-folded matrix, ball-and-pillow structures and contorted laminae also point to soft-sediment deformation.

The olistostrome is absent in the Pakistani Makran, to the east (Fig. 1). In Iran, we estimated the extent of the olistostrome using published geological maps and new field and satellite mapping on high-resolution multispectral Landsat7 images. The general map and the composition of the blocks suggest a source area to the NE of the studied area.

The olistostrome covers today an area of approximately 10 000 km$^2$ in a polygon of $< 70 000$ km$^2$. The maximum thickness we could measure was 600 m, which rounded to as the largest average would make a volume of $< 42 000$ km$^3$. There are large uncertainties in this approximation, yet the figure is not extraordinary for submarine mass movements (e.g. Hjelstuen et al., 2007). By contrast, it matches the dimensions of the olistostrome associated with the Gibraltar accretionary wedge (at least 50 000 km$^3$, Torelli et al., 1997).

Age of the mass flow

In the south, the olistostrome laps onto Langhian (NN5) turbidites and slope deposits that provide a lower age bracket. The foraminiferal content of the youngest of the blocks had led (McCall, 1983) to date the ‘mélange’ as late middle Miocene. A maximum age can be inferred from the presence of Neogloboquadra acostaensis (first occurrence at 11.78 Ma, Hilgen et al., 2000) and Globoquadra dehiscens (last occurrence at 5.8 Ma, Berggren et al., 1995) in a shaly matrix sample taken a few meters above the erosive basis (GPS: 26°28’45.6”N; 61°14’39.6”E).

The olistostrome nature of the unit is further confirmed by mixing of shallow-water benthic foraminifera (Spezzaferri et al., 2001), with deep water species (Boersma, 1974). Both pelagic and benthonic foraminifera are Tortonian to Messinian in age.

Discussion

Despite a weak deformation cleavage in regional, E-W-trending fold-hinge zones, the sedimentary origin of the ‘mélange’ and redeposition of blocks of various lithologies and sizes within a muddy matrix is evident. We disagree with the interpretation of McCall and Kidd (1982) and McCall (1983) that the ‘blocks were all
emplaced tectonically, being squeezed up from the basement like pips’. The system was certainly very chaotic as suggested by remobilization and injection of clastic material, soft-sediment deformation and the inclusion of coherent blocks of all sizes and shapes into a non-lithified, argillaceous matrix. However, there is a clear polarity from proximal to distal with an erosional basal contact in the north, conformity in the south, and a southward reduction in block dimensions. The large extent of the olistostrome and its preservation in synelines and outliers above older turbidites argue against emplacement from below by mud diapirs and mud volcanoes as inferred by McCall and Kidd (1982).

We interpret the chaotic unit to be a huge submarine, gravity-induced mass flow that was transported for over 100 km: debris flows are known to travel hundreds of kilometres on the sea floor, even along very gently dipping slopes (e.g. Masson et al., 1998). The whole formation was emplaced very rapidly, probably during one catastrophic event, because we were not able to separate different episodes of emplacement and nowhere are there undisturbed sedimentary layers between individual debris flows or draping of the more coherent blocks. Although the occurrence of reworked packages of pebbly and non-pebbly mudstones may suggest polyphasic sediment flow, they are not separated by sediments that would indicate major time discontinuities. Finally, the extremely chaotic aspect and the lack of large and intact slump units seem at odds with slow creep. The flow direction determined from sense-of-shear criteria is south–southwestward, with local variations, a regional consistency that favours the interpretation of rapid movement of the mass. This transport direction is consistent with a bulk trench-ward slope of the margin, whose proximal portions were to the north at that time. The extra-formational blocks of ultramafic and mafic igneous rocks and deep-sea sediments (radiolarites) must have been in an uplifted, allochthonous position already at the time of the emplacement of the flow, i.e. cropping out sub-aerially or at the sea floor, in an area to the north. Other blocks represent debris probably derived from the slope and from older carbonate platforms incorporated into and floated in the fluid matrix. The originally southward inclination of the slope makes that the folded basal unconformity of the olistostrome that has an envelope surface near the present-day topography. Therefore, previous estimates of the olistostrome thickness have been overestimated.

The area covered by the olistostrome and the km size of some blocks suggest that it is a Late Miocene counterpart of a large submarine-debris flow similar to those reported from the Bay of Bengal (Moore et al., 1976), the Gibraltar Arc (Medialdea et al., 2004) and to the Holocene slides on the Norwegian margin (Hafldason et al., 2004; Bünz et al., 2005). Like the chaotic unit of the Gibraltar Arc accretionary wedge, in particular, the Makran olistostrome is inserted within the Miocene sedimentary sequence of the wedge. Although the chaotic unit of the Gibraltar Arc has been overprinted by later deformation, its primary emplacement within the sedimentary sequence along a seaward-dipping surface has been by lateral gravitational transport (Medialdea et al., 2004). We draw the same conclusion for the Makran olistostrome.

Conclusions
Most giant submarine mud and debris flows have been identified from seismic reflection profiles of passive continental margins (Hjelstuen et al., 2007) and volcanic islands (Masson et al., 1998); however, there are an increasing number of examples from accretionary wedges (Moore et al., 1976; Medialdea et al., 2004). The Makran offers exceptionally clear exposures where the size, the mor-

Fig. 4 Limestone block in the scaly mud matrix. Note that the fabric of the matrix does not wrap around the block as would a tectonically induced foliation. Outcrop at 26°44′04.3″N; 61°05′34.1″E.

Fig. 5 Scaly matrix of ‘pebbly mudstone’, 10 m from Fig. 2. Outcrop at 26°28′45.6″N; 61°14′39.6″E.
Giant mud-and-debris flow in the Miocene Makran


References


Received 14 November 2007; revised version accepted 17 February 2008