New insights into the morphology, fill, and remarkable longevity (>0.2 m.y.) of modern deep-water erosional scours along the northeast Atlantic margin

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ABSTRACT

A series of large-scale erosional scours are described from four modern deep-water canyon and/or channel systems along the northeast Atlantic continental margin. Regional-scale geophysical data indicate that most scours occur in zones of rapid flow expansion, such as canyon and/or channel termini and margins. High-resolution images of the scours cover ~25 km² at 2 × 2 m pixel size, and were obtained at depths of 4200–4900 m using Autosub6000, an autonomous underwater vehicle equipped with an EM2000 multibeam bathymetry system. Sedimentological and microfossil-based chronological data of scour fills and interscour areas were obtained via accurately located piston cores that targeted specific sites within imaged areas. These core data reveal a number of key findings. (1) Deep-water scours can be very long lived (>0.2 m.y.) and may undergo discrete phases of isolation, amalgamation, and infilling. (2) Deep-water scours can develop via a composite of cutting and filling events with periodicities of between tens of thousands and hundreds of thousands of years. (3) Immediately adjacent scours may have strikingly different sedimentological histories and do not necessarily evolve contemporaneously. (4) Scour infills are typically out of phase with sedimentation in interscour areas, having thin sands internally and thick sands externally, or thick muds internally and thin muds externally. (5) Erosional hiatuses within scour fills may represent hundreds of thousands of years of time, and yet leave little visible record. Four distinct morphologies of scour are identified that range from 40 to 3170 m wide and 8 to 48 m deep: spoon shaped, heel shaped, crescent shaped, and oval shaped. Isolated scours are shown to coalesce laterally into broad regions of amalgamated scour that may be several kilometers across. The combined morphosedimentological data set is used to examine some of the putative formative mechanisms for scour genesis.

INTRODUCTION

Large-scale erosional scours are a key component of many deep-water channels and fans, and have been intensively studied in both modern (e.g., Normark, 1970; Normark et al., 1979, 2009; Shor et al., 1990; Kenyon et al., 1995; Wynn et al., 2002a; Fildani et al., 2006) and ancient submarine environments (e.g., Vicente Bravo and Robles, 1995; Elliott, 2000a, 2000b; Lien et al., 2003; Macdonald et al., 2011). Despite these studies, little is known about the genesis of deep-water erosional scours; direct observations of flow over scours are lacking, and there is very little information on sedimentation within scours. Consequently, the evolution and longevity of deep-sea scours are largely unknown. Similarly, the morphological variation within deep-sea scours has not been examined in detail, mostly due to a lack of sufficient image resolution.

Here we address these limitations through morphosedimentological studies of a number of key deep-water scour sites along the northeast Atlantic continental margin. The detailed morphology of scours in these areas has been measured at unprecedented depths (4200–4900 m) using high-resolution multibeam bathymetry collected using a deep-diving autonomous underwater vehicle (AUV). Accurately located cores were taken within and adjacent to scours, and coccolith stratigraphy was utilized to provide age control, enabling comparative studies of intrascour and interscour deposition to be undertaken for the first time. Sedimentological data demonstrate that scours may show prodigious longevity (>0.2 m.y.) and that scour evolution in the deep sea may be complex and multiphase. To put these new observations into a broader context, we synthesize existing studies and develop a morphological classification of scour types.

BACKGROUND

Scour Morphology and Environment

Research on deep-water erosional scours began in the 1970s, pioneered by Bill Normark and colleagues during their studies of the Navy Fan, offshore California (e.g., Normark et al., 1979). These studies recognized giant flute-shaped depressions more than 500 m wide and 15 m deep on the modern seafloor. Around this time, much smaller examples, as deep as 1.5 m, were documented in Late Cretaceous submarine fan deposits of the Cerro Toro Formation (Magallanes Basin), southern Chile (Winn and Dott, 1979). Even at this embryonic stage of
However, precise paleoenvironmental interpretations of scours in outcrop can be challenging, as exemplified by observations of the well-studied Carboniferous Ross Sandstone. In this system, scours have been interpreted as occurring in a channel-lobe transition zone (Chapin et al., 1994; Macdonald et al., 2011), on channel flanks via single high-magnitude channel-initiating flows (Elliott, 2000a, 2000b), and in spillover lobes at the bends of sinuous channels (Lien et al., 2003).

**Flow Processes**

Little is known about the underlying processes that form deep-water scours, or the longevity of these features. Most large-scale scours form in regions indicative of flow expansion (Mutti and Normark, 1987; Normark and Piper, 1991) induced by a lack of confinement or a change in slope. At these locations, turbidity currents are thought to frequently undergo a hydraulic jump, leading to locally increased turbulence and scouring of underlying sediments (Komar, 1971; Normark et al., 1979; Mutti and Normark, 1987; Lee et al., 2002). A linear scour array on the Monterey Fan has been interpreted in terms of repeated hydraulic jumps, so-called cyclic steps (Fildani et al., 2006), and this mechanism is thought to play a more generic role in deep-sea scour formation (e.g., Kostic and Parker, 2006). Information on scour longevity is limited, although Normark et al. (2009) estimated minimum ages for two scours in Redondo Canyon; one was directly dated (through an intrascour core) as being 950 yr old, and a second (based upon extrapolation of interscour accumulation rates to geophysical imaging of scour fill) was estimated as older than 4500 yr. However, these times largely indicate a period of stasis and mud infill, rather than active scour development.

Given the limited process data on large deep-water scours, some comparison has been made with much better studied small-scale erosional features such as flutes and tool marks. The flow processes of these small-scale erosional features have been recreated under laboratory conditions (Rücklin, 1938; Dzulynski and Walton, 1963; Dzulynski, 1965; Dzulynski and Simpson, 1966; Allen, 1969a, 1971, 1984) and studied in detail in outcrop (Eggenhuisen et al., 2010, 2011); however, these are typically several orders of magnitude smaller than scours documented on the modern seafloor. Allen (1971) linked the generation of small-scale erosional bedforms (i.e., flutes) to the presence of irregularities on the eroded bed, and Allen’s (1971) defect theory related the size, shape, and structure of erosional bedforms (i.e., flutes) to the number and character of these irregularities, and the nature of the erosive flow. To test whether Allen’s (1971) defect theory could be upscaled to large-scale modern scours, Shor et al. (1990) applied it to generation of a giant flute-shaped scour on the Laurentian Fan (100 m deep, 1000 m long), which was believed to have been generated by the 1929 Grand Banks turbidity current. Shor et al. (1990) performed calculations using both empirical parameters (from Allen, 1971) and measurements taken from the giant scour. However, both calculations produced durations of scour generation that were considered too short to realistically generate the observed scour; it was therefore assumed that the scour became unusually deep because erosion of seafloor surrounding the scour was hindered by a conglomerate veneer. It is critical that more recent work suggests that the scour may have existed prior to the 1929 event (Piper et al., 2007), and therefore it may have been the product of more than one flow. Allen’s (1971) theory assumed that flute formation was the product of single flows (in fact, just the head portion of these flows), and thus may not be transferable if scours develop under successive flows. It therefore remains unclear whether flow processes operating on both small-scale and large-scale scours are comparable, and whether experimental studies of erosion can be upscaled to natural examples on the modern seafloor.

**HIGH-RESOLUTION AUV IMAGING OF DEEP-WATER SCOURS**

Our understanding of deep-water scours has traditionally been restricted by a lack of high-quality bathymetric data; most previous studies relied on low- to medium-resolution sidescan sonar or hull-mounted multibeam bathymetry. However, recent technological advances in deep-water research are now enabling significant improvements in resolution. For example, Normark et al. (2009) utilized an AUV to obtain unprecedented images of deep-water scours on the Redondo Fan, offshore California. They obtained high-resolution multibeam bathymetry and subbottom profiles at water depths of as much as 700 m by flying the AUV at a height of ~70 m above seafloor. Their multibeam bathymetry data have 1.5 m lateral resolution and 0.3 m vertical accuracy, which is approaching outcrop-scale resolution (Normark et al., 2009). This pioneering study was a first step toward more detailed morphometric measurement of deep-sea scours, but still at relatively shallow depths. Here we utilized Autosub6000 (Huvenne et al., 2009) in order to image 4 examples of large-scale deep-water scours at water depths >4200 m. Autosub6000 is a newly developed AUV capable of operating close to the seafloor at water...
### TABLE 1. EXAMPLES OF LARGE-SCALE EROSIONAL SCOURS IN DEEP-WATER TURBIDITE SYSTEMS

<table>
<thead>
<tr>
<th>Fan name and reference</th>
<th>Imagery</th>
<th>Water depth (m)</th>
<th>Number of scours</th>
<th>Change in slope gradient (for CLTZ)</th>
<th>Scour depth (m)</th>
<th>Scour width (m)</th>
<th>Scour length (m)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Agadir Canyon Mouth</strong></td>
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<tr>
<td>Wynn et al. (2002a)</td>
<td></td>
<td>2500</td>
<td>Multiple, many tens</td>
<td>Changes from 0.2–0.04</td>
<td>n.p.</td>
<td>250–500 (isolated)</td>
<td>500 (isolated)</td>
<td>30-km-long erosional zone CLTZ extends 60 km from mouth</td>
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<tr>
<td>This study</td>
<td>EM2000</td>
<td>4265</td>
<td>Tens, plus regions of amalgamation</td>
<td>n.m.</td>
<td>8–20</td>
<td>50–225</td>
<td>150–600</td>
<td>CLTZ setting</td>
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<tr>
<td><strong>Albian Black Flysch, Northern Spain</strong></td>
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<tr>
<td>Vicente Bravo and Robles (1995)</td>
<td>Outcrop work; 3D sketches and photomontages</td>
<td>n/a</td>
<td>Not specified, probably several</td>
<td>1–5</td>
<td>5–50</td>
<td>Downstream exposures are poor or difficult to discern</td>
<td>Directly compared to Normark et al. (1979) Navy fan work. Composed of sands and gravels, must have formed under upper flow regimes CLTZ setting Shows multiphasic scour and fill</td>
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<tr>
<td><strong>Cerro Toro Formation, Magallanes Basin, Northern Chile</strong></td>
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<tr>
<td>Winn and Dott (1979)</td>
<td>Outcrop work</td>
<td>n.p.</td>
<td>Multiple, tens</td>
<td>1.5</td>
<td>n.p.</td>
<td>n.p.</td>
<td>Region forms channel margin deposits of proximal axial channel belt</td>
<td></td>
</tr>
<tr>
<td>Jobe et al. (2009)</td>
<td>Outcrop work</td>
<td>n.p.</td>
<td>Multiple, tens</td>
<td>n.p.</td>
<td>n.p.</td>
<td>Canoe flutes (no dimensions given) shown in photograph, meters in size</td>
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<td><strong>Eel Canyon</strong></td>
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<tr>
<td>Lamb et al. (2008)</td>
<td>15.5 kHz Hydrosweep system (echosounder?)</td>
<td>1000–1600</td>
<td>~7</td>
<td>Wavelength of steps = 2000 m</td>
<td>Step height ~150 m</td>
<td>Scours generated at cyclic steps by superelevated turbidity currents that escape a 90° bend in the Eel Canyon. Steps occur within larger channel-like feature extending from canyon bend</td>
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<tr>
<td><strong>Espirito Santo Basin, Offshore Brazil</strong></td>
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<tr>
<td>Heinlo and Davies (2009)</td>
<td></td>
<td>35–1800</td>
<td>Present-day water depth</td>
<td>Multiple, tens</td>
<td>1.5</td>
<td>200–600 m</td>
<td>300–1000 m across</td>
<td>Depressions develop as flume-shaped troughs and develop into more circular depressions as a result of deposition on the shallow, upslope-facing stoss flanks and erosion or nondeposition in the lee flanks and the troughs</td>
</tr>
<tr>
<td><strong>Northern Gulf of Patras (Onshore)</strong></td>
<td></td>
<td>Paleowater depths estimated at more than a few hundred meters</td>
<td>Multiple, tens</td>
<td>Few meters deep</td>
<td>1–3</td>
<td>n.p.</td>
<td>Eroded into pebbly mudstones, initially interpreted as channels</td>
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<tr>
<td><strong>Hueneme Fan</strong></td>
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<tr>
<td>Piper and Kontopoulos (1994)</td>
<td>Field study 7 kHz and 3.5 kHz profiles, piston cores</td>
<td>1000</td>
<td>Multi</td>
<td>n.p.</td>
<td>1–2 m deep</td>
<td>50–200 m apart</td>
<td>On scoured-lobe subelement Attributed to the passage of flows with a high proportion of silt but efficiency in sand, that erode sand as they pass down the fan. The low settling velocity of silt resulted in slow deceleration, permitting extended traction transport and scour. These flow therefore tended to locally bypass, scour, and/or deposit only thin and/or widespread beds on middle fan</td>
<td></td>
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<tr>
<td><strong>Horseshoe Valley</strong></td>
<td>AUV mounted EM2000 multibeam piston cores EM120 multibeam SBP120 and 3.5 kHz subbottom profilers</td>
<td>4570</td>
<td>1</td>
<td>1000</td>
<td>Multi</td>
<td>50–200 m apart</td>
<td>Single oval scour in channel mouth region Flanked by depositional chevrons and erosional (?) lineations</td>
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</tbody>
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(continue)
<table>
<thead>
<tr>
<th>Table 1. Examples of Large-Scale Erosional Scours in Deep-Water Turbidite Systems (continued)</th>
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<tbody>
<tr>
<td>Fan name and reference</td>
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<tr>
<td>------------------------</td>
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<tr>
<td>Laurentian Fan</td>
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<tr>
<td>Lisbon Canyon Mouth</td>
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<td>Makran Continental Slope</td>
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<td>Monterey Fan</td>
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<tr>
<td>Klaucke et al. (2004)</td>
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<td>Monterey East: Fildani et al. (2006)</td>
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<tr>
<td>Navy Fan</td>
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<tr>
<td>Vicente Bravo and Robles (1995)</td>
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TABLE 1. EXAMPLES OF LARGE-SCALE EROSIONAL SCOURS IN DEEP-WATER TURBIDITE SYSTEMS (continued)

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<th>Scour length (m)</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Placentia Bay</td>
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<tr>
<td>Potter and Shaw (2009)</td>
<td>Multibeam: Kongsberg- Simrad EM1000, EM1002, EM710, EM3002</td>
<td>~20</td>
<td>Multiple, tens to hundreds</td>
<td>n.p.</td>
<td>Several meters</td>
<td>&lt;200</td>
<td>&gt;500</td>
<td>Contended origin, linked to 1929 Grand Banks earthquake, but other causes are &quot;more likely&quot; (none given)</td>
</tr>
<tr>
<td>Redondo Fan</td>
<td></td>
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<tr>
<td>Normark et al. (2009)</td>
<td>AUV mounted 200 kHz 1° × 1° multibeam sonar, and 2–16 kHz subbottom profiler (navigation aided by 300 kHz Doppler velocetry log at depths &lt;130 m, and GPS at surface) ROV Vibracores</td>
<td>650–700</td>
<td>&gt;10 on two different scales</td>
<td>n.p.</td>
<td>30 (giant scour)</td>
<td>200 (giant scour)</td>
<td>&gt;400 (giant scour)</td>
<td>48 cm mud fill in giant scour Linear sets of depressions (on two scales) formed adjacent to sediment waves Formation is attributed to recurrent cyclic steps due to recurrent overflow events</td>
</tr>
<tr>
<td>Ross Sandstone, County Clare, Ireland</td>
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<tr>
<td>Chapin et al. (1994)</td>
<td>Outcrop work: multiple vertical logs, analysis of photo-montages</td>
<td>n.p.</td>
<td>Multiple, tens</td>
<td>n.p.</td>
<td>0.3–3.5</td>
<td>1.5–6</td>
<td>Some are &gt;30 m</td>
<td>np Scour types include bedding-plane scours, megafaults, and stepped scours and form a continuum of erosive processes Generated by (1) hydraulic jump associated with slope change at CLTZ or overbank or (2) disturbances from vortices in flow induced by irregular topography Linked to widespread surfaces termed megafault erosion surfaces (MES) MES are indicative of powerful, single, large-volume turbidity currents that were nondepositional and initiated channels Erosion linked to the final stages of spillover at the bends of sinuous channels Channel-lobe transition zone setting on lobe-element scale Scouring associated with flow expansion at termination of lobe-element feeder channel</td>
</tr>
<tr>
<td>Macdonald et al. (2011)</td>
<td>Outcrop work: multiple vertical logs, correlative panels</td>
<td>n.p.</td>
<td>Multiple, tens</td>
<td>n.p.</td>
<td>&lt;1</td>
<td>3–15 or more</td>
<td>n/p</td>
<td></td>
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<tr>
<td>Rhone Neofan</td>
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<tr>
<td>Kenyon et al. (1995)</td>
<td>30 kHz sidescan sonar 5 kHz profiles</td>
<td>n.p.</td>
<td>Tens</td>
<td>Changes from 1 in 100 to 1 in 200</td>
<td>20</td>
<td>1000</td>
<td>np</td>
<td>CLTZ Flow expansion, hydraulic jump</td>
</tr>
<tr>
<td>Wynn et al. (2002a)</td>
<td>30 kHz deep-towed sidescan sonar (TOBI) 5 kHz profiles</td>
<td>~2300</td>
<td>Multiple, Tens to 100</td>
<td>Changes from 0.6° to 0.3°</td>
<td>20</td>
<td>n.p.</td>
<td>1000</td>
<td>CLTZ Scours seen up to 30 km beyond CLTZ.</td>
</tr>
<tr>
<td>San Lucas</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Normark (1970)</td>
<td>Sidescan sonar 3.8 kHz profiles</td>
<td>~2900</td>
<td>Not specified, figures suggest 7°</td>
<td>n.p.</td>
<td>Not specified, figures suggest 10°</td>
<td>Not specified, figures suggest dimensions of ~50 x ~200 m</td>
<td>Imagined steep-walled depressions and hummocky topography</td>
<td></td>
</tr>
<tr>
<td>Normark and Piper (1991, p. 220)</td>
<td>Sidescan sonar</td>
<td>8 large Many small</td>
<td>0.028°</td>
<td>50–60</td>
<td>np</td>
<td>500–600</td>
<td>Reinterpretation of Normark (1970), no new data obtained</td>
<td></td>
</tr>
</tbody>
</table>

(continue)
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<th>Scour length (m)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Setúbal Canyon Mouth</strong></td>
<td>AUV mounted EM2000 multibeam Piston cores EM120 multibeam SBP120 and 3.5 kHz subbottom profilers</td>
<td>4840</td>
<td>10–20</td>
<td>n.p.</td>
<td>14 (isolated)</td>
<td>~2000 (many are open)</td>
<td>1000 (isolated)</td>
<td>CLTZ</td>
</tr>
<tr>
<td>Morris et al. (1998)</td>
<td>30 kHz high-resolution sidescan sonar (MAK1) Gravity cores</td>
<td>~2800</td>
<td>Multiple, tens, chevron bedforms, linear bedforms, and megaflutes</td>
<td>Flat channel floor has slope of 0.17°</td>
<td>~2 (chevrons)</td>
<td>200 (chevrons and megaflutes)</td>
<td>70 (chevrons)</td>
<td>CLTZ</td>
</tr>
<tr>
<td><strong>Valencia Channel Margin</strong></td>
<td>High-resolution seismic-reflection profiles 3.5 kHz echo-sounder profile High-resolution sidescan imagery Piston cores</td>
<td>~2400</td>
<td>Multiple, tens</td>
<td>Average slope gradient 3°–4° on Var Sedimentary Ridge</td>
<td>1–15</td>
<td>200–1000</td>
<td>n.p.</td>
<td>Associated with sediment waves Scour spacing of 500–1500 m is equal to wave spacing</td>
</tr>
<tr>
<td><strong>Var Canyon Mouth–Middle Valley</strong></td>
<td>AUV mounted EM2000 multibeam Piston cores EM120 multibeam SBP120 and 3.5 kHz subbottom profilers</td>
<td>4600</td>
<td>Tens, plus regions of amalgamation</td>
<td>n.m.</td>
<td>30 (isolated)</td>
<td>890 (isolated)</td>
<td>550 (isolated)</td>
<td>-Scouring in overbank area of channel Four scales of scouring documented: proto, isolated, amalgamated, and fully amalgamated</td>
</tr>
</tbody>
</table>

**Note:** CLTZ—channel-lobe transition zone; AUV—autonomous underwater vehicle; 3D—three dimensional; n.d.—no data; n.p.—not provided; n.m.—not measured; TOBI—towed ocean bottom instrument; ROV—remotely operated vehicle; GPS—global positioning system.
New insights into modern deep-water erosional scours along the northeast Atlantic margin

STUDY AREA

This study investigates erosional scours in four deep-water canyon and/or channel systems along the northeast Atlantic continental margin (Fig. 1). These are, from south to north, (1) Agadir Canyon mouth, (2) Horseshoe Valley, (3) Setúbal Canyon mouth, and (4) Whittard Channel margin. These locations display a variety of shallow- to deep-water sediment transport regimes, due to their different climatic settings (semiarid in the south to temperate and glacially influenced in the north) and varying proximity to the tectonically active Africa-Eurasia plate boundary (Weaver et al., 2000). Horseshoe Valley and Setúbal canyons exhibit active faulting related to the Azores-Gibraltar Fracture Zone, and the headwaters of Agadir Canyon are affected by the seismically active High Atlas Mountains (Sébrier et al., 2006; Arzola et al., 2008; Duarte et al., 2010). In contrast, the Whittard Channel is in a passive margin setting. These differences link to significant variations in flow type; Agadir Canyon is dominated by infrequent, landslide-derived large-volume flows (>10 km$^3$ of sediment, 1/10 k.y.) sourced from the Morocco Shelf (Wynn et al., 2002b), whereas the Whittard Channel is dominated by frequent (as many as 130/k.y.) smaller flows, mostly during glacial lowstands when fluvioglacial outwash supplied sediments directly to the head of Whittard Canyon (Toucanne et al., 2008). While these broad differences are known, the exact nature of flow types and magnitudes are poorly constrained for several of the examples (cf. North American margin; e.g., Piper and Normark, 2009).

METHODS

Geophysical Data

The majority of geophysical data presented here were collected during a research expedition on RRS James Cook in August 2008 (JC27). The main data set presented here is high-resolution multibeam bathymetry, collected using an EM2000 system housed within the Autosub6000 AUV. Autosub6000 was able to cover an area of ~25 km$^2$ within a 24 h mission, and the EM2000 system was able to image seafloor features with a pixel size of 2 x 2 m. Data were subsequently processed using the IFREMER (Institut Français de Recherche pour l’exploitation de la Mer) software suite Caribea (http://www.ifremer.fr/fleet/equipements_sc/logiciels_embarques/caribea/index.html). Additional data collected using hull-mounted multibeam bathymetry (EM120) provide information on the overall planform of the seafloor, although these data are generally of insufficient resolution to image the studied scours.

Sedimentological Data

A series of shallow piston cores was collected from each of the four work areas, with a maximum penetration of 6.5 m. Core sites were chosen once high-resolution multibeam bathymetry images were downloaded and visualized, and were selected to hit targets >50 m across (50 m is our estimated coring accuracy at water depths >4 km). RRS James Cook is equipped with a dynamic positioning system, while any potential offset created by drift of the corer was monitored using an ultra-short baseline acoustic positioning system located on the coring wire at depths as great as 2.5 km.

Visual core logging included sediment facies, color, and grain size. All logged deposits were interpreted for their mechanism of deposition (identified as turbidite, debris, or hemipelagite) and used to infer a depositional subenvironment. Note that in this study we identify turbidite sands as being normally graded, well sorted, and deposited in an aggradational layer by layer fashion (with associated laminations and cross-laminations). Smooth green or graybrown turbidite sands can be separated from pale brown hemipelagic muds due to the latter containing randomly dispersed foraminifera. Debris deposits are identified as ungraded, poorly sorted, and clast rich, often containing evidence for mass flow, e.g., contorted remobilized sequences.

Dating Control

Microfossil-based dating of hemipelagic sediments in the studied cores was used to identify erosional hiatuses. Ratios of different coccolith species were identified and a combination of first and last appearance and overall abundance of dominant species was then used to develop a chronostatigraphy, tied into the oxygen isotopic stratigraphy at specific oxygen isotope stages (OIS) (Weaver and Kuipers, 1983; Weaver, 1994; Wynn et al., 2002b). Biotauration of hemipelagic sediments and other potential errors means that ages are accurate to within ~10%.

RESULTS

Agadir Canyon Mouth

Agadir Canyon extends northwestern 450 km from the Morocco Shelf (100-200 m water depth) to the eastern Agadir Basin (~4500 m water depth) (Figs. 1 and 2A). The canyon is as wide as 30 km and acts as a conduit for large-volume siliciclastic flows (Wynn et al., 2002b; Frenz et al., 2009). Previous studies, utilizing medium-resolution (30 kHz) sidescan sonar, mapped a major zone of erosion in the canyon mouth with kilometer-scale scours focused immediately downstream of an intracanyon slope break (slope change of 0.2° to 0.04°; Wynn et al., 2002a). Both isolated and amalgamated scours were imaged in the erosion zone (see inset in Fig. 2A), but the relationship between the two end members was not clearly resolvable on existing data.

Our new high-resolution imagery (Fig. 2B) confirms the presence of both isolated and amalgamated scours, covering an area of ~15 km$^2$ in the canyon mouth. The deepest erosion is focused within isolated scours along the northern margin of the broad, flat canyon axis; these scours cut into the gently sloping northern margin of the canyon floor. Isolated scours are spoon shaped and elongated downslope, with U-shaped cross-sectional profiles that shallow and taper downstream. Maximum scour depths and downhill slope angles are consistently located within the upstream 60% of the scours; the steepest slope angles (20°–50°) are largely confined to scour headwalls and sidewalls (see profiles A-A’ and B-B’; Fig. 2B). Scour dimensions are 150–600 m long, 40–225 m wide, and 8–20 m deep. Scours 1 and 2 (Fig. 2B) are the largest identified isolated scours. Scour 2 exhibits a rim opening and low sidewall slopes (0.5°–6.5°) along its southwest margin, where it borders a region of amalgamated scour. This amalgamated scour displays a broadly flat-bottomed morphology, but includes several erosional remnants within the scour floor and in cuspate rims at scour margins (see cross-section C-C; Fig. 2B). The imaged area of amalgamated scour extends across ~4 km$^2$ and can be subdivided into smaller zones of amalgamation that are bound by high-standing topography. The headwall of the amalgamated scour comprises a series of cuspate scars, similar in apparent dimensions and morphology to the headwalls of adjacent isolated scours.

Three piston cores, JC27–09, JC27–12, and JC27–11, were obtained from within the imaged region along a south-southwest–north-northeast transect (Figs. 2B and 3). Core JC27–09 targeted the floor of the amalgamated scour, and recovered...
Figure 1. Location map of the four study areas along the northeast Atlantic continental margin. White rectangles show areas covered by Figures 2A, 4A, 6A, and 8A. Inset shows the Autosub6000 vehicle, which is 5.5 m long and 0.9 m in diameter, during deployment.
Figure 2. Erosional scours at Agadir Canyon mouth, offshore northwest Morocco. (A) Regional EM12 multibeam bathymetry showing the morphology of lower Agadir Canyon. Black arrows show interpreted flow pathways (after Wynn et al., 2002a, 2002b). Inset shows TOBI (towed ocean bottom instrument) 30 kHz sidescan sonar profile of the scoured region (located by the red rectangle on EM12 data). Light tones are high backscatter. White rectangle shows location of Autosub6000 imagery. (B) High-resolution Autosub6000 image and cross-sectional profiles of isolated and amalgamated spoon-shaped scours (11× vertical exaggeration). Locations of piston cores shown in Figure 3 are provided.
Figure 3. Core data from Agadir Canyon mouth scours (for locations, see Fig. 2). Data include core photos, graphic logs and interpretations, and coccolith ratios (E.—*Emiliania*; G.—*Gephyrocapsa*) from hemipelagic sediments that provide dating control (see key for species). OIS—Oxygen Isotope Stage. Core JC27–09 recovered sediments from within a large amalgamated scour, JC27–12 was taken from within an isolated scour, and JC27–11 sampled sediments adjacent to the scoured zone. Note the marked variability in abundance, thickness, and grain size of turbidite deposits, across an area of just more than 2 km. Two hiatuses are identified in the isolated scour (JC27–12), one that covers a period of ~130 k.y. and ended ca. 60 ka, and a second below OIS 7 that covers >200 k.y. In contrast, only a single hiatus of >320 k.y. is located in the amalgamated scour JC27–09, ending ca. 130 ka. These hiatuses point to at least 3 separate erosive events, ca. 60 ka and ca. 200 ka in the isolated scour, and ca. 130 ka in the amalgamated scour.
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Horseshoe Valley

The Horseshoe Valley is located offshore southwest Iberia, and is a broad conduit for sediments transported southwestward from the Lagos and Portimao Canyons to the Horse-
shoe Abyssal Plain (Fig. 4A) (Terrinha et al., 2009). Hull-mounted multibeam bathymetry data reveal a series of giant scours on the floor of the central fairway, on an overall slope of ~0.5° (Terrinha et al., 2009; Duarte et al., 2010; Fig. 4A). The largest scours are as much as 5 km wide and 120 m deep, with long axes aligned parallel to slope. Seismic profiles of Duarte et al. (2010) suggest that scour locations are controlled by the underlying thrust fault morphology.

Our new high-resolution AUV data focus on a single large-scale erosional scour that is U shaped in cross section and is ~3 km wide and 50 m deep (crenscientic depression 1 of Duarte et al., 2010). The scour is oval in planform and, unlike the Agadir Canyon scours, is elongate along slope (i.e., perpendicular to downslope flow). The scour is at ~4600 m water depth and displays average headwall slope angles of 30°, with maximum angles locally reaching 56° (Fig. 4B). Profiles of the headwall slope vary across the scour, ranging from smooth and constant to stepwise with quasi-terraced mor-
phology (profiles A-A’ and C-C’; Fig. 4B). Two areas of morphologically distinct bedforms flank the scour: V-shaped chevrons to the west and lineations to the southeast and east (see insets, Fig. 4B). The chevrons are V-shaped positive relief features that are as much as 200 m across. Chevon limbs bound a hollow and flat-bottomed central region, and open out in a downstream direction. The lineations are nega-
tive relief features that may be fully isolated or amalgamated with other surrounding linea-
tions; they are 40–80 m wide, 250–460 m long, and as deep as 3 m. All lineations >80 m in length appear to be amalgamated.

Two piston cores were recovered from the area imaged by high-resolution data (Figs. 4B and 5). Core JC27–24, recovered from outside the scour ~700 m upslope of the scour head-
wall, contains 4.7 m of dominantly hemipelagic sediments interbedded with ~20 thin turbidi-
tes. Turbidite deposits are 0.2–12 cm thick, and comprise thinly laminated fine sand bases overlain by structureless muds. In some cases the basal sand is absent. Coccolith ratios reveal that these deposits range in age from OIS 1–3 (younger than 60 ka) to OIS 8–12 (450 ka), and do not appear to be separated by significant hiatuses (Fig. 5). In contrast, core JC27–25-3, recovered from the scour floor, is dominated by seven thick turbidites (50–180 cm or more) with characteristics very different from those outside the scour. The turbidites display textur-
ally mature, normally graded, fine- to medium-grained sand bases that are erosive, as much as 25 cm thick, and laminated or cross-laminated (Tb and Tc). Sand bases are overlain by as much as 1.5 m of structureless ungraded turbidi-
tes and bounding hemipelagites are thin or absent (Fig. 5). Coccolith dating shows that the turbidite sequence cored inside the scour is relatively young, with ages restricted to OIS 1–4 (younger than 75 ka). Net accumulation rates during the past 75 k.y. are therefore more than 3 times higher inside the scour compared to the adjacent seaﬂoor.

Setúbal Canyon Mouth

Setúbal Canyon is one of the largest canyons crossing the west Iberian margin, extending sea-
ward from the continental shelf near Lisbon to the Tagus Abyssal Plain at 4840 m water depth (Fig. 6A) (Lastras et al., 2009). Erosional features have previously been documented in the lower canyon and canyon mouth, using medium-resolution (30 kHz) sidescan sonar (see inset, Fig. 6A). New high-resolution images within the canyon mouth reveal irregular crescentic scours that are elongate perpendicular to flow, with widely flaring limbs that point downstream (Fig. 6B). These scours are as much as 1.0 km in length and width and display width:length ratios of ~1; amalgamated forms typically exhibit width:length ratios >>1. One large iso-
lated scour reaches a maximum depth of 14 m and has a steep headwall with slope angles as high as 30°; it shallows downstream over a dis-
tance of several hundred meters and has a steep step that accounts for approximately half of the
Figure 4. Erosional scours in Horseshoe Valley, offshore southwest Portugal. (A) Composite image of SWIM (surface waves investigation and monitoring) multibeam bathymetry data showing the regional morphology of Horseshoe Valley (Zitellini et al., 2009). Note the large scours in the central valley. Black arrows show interpreted flow pathways. Red box indicates the location of Autosub6000 data. (B) High-resolution Autosub6000 image and cross-sectional profiles across a giant oval-shaped scour in Horseshoe Valley (vertical exaggerations used: A-A′ = 11×, B-B′ = 3.1×, C-C′ = 15×). Additional depth information (pastel colors) is derived from autonomous underwater vehicle (AUV) depth profiler data. Inset images show depositional chevrons and erosional lineations adjacent to the scour. Locations of cores shown in Figure 5 are indicated.
New insights into modern deep-water erosional scours along the northeast Atlantic margin

**Figure 5.** Core data from Horseshoe Valley scour (for locations, see Fig. 4), including core photos, graphic logs and interpretations, and coccolith ratios (E.—*Emiliania*; G.—*Gephyrocapsa*) from hemipelagic sediments that provide dating control (see key for species). OIS—Oxygen Isotope Stage. Core JC27–24 recovered sediments from smooth seafloor upslope of the scour headwall, while core JC27–25*3 was taken from within the scour. Note the thick mud deposits within the scour, compared to the zone of dominant bypass outside the scour.
Figure 6. Erosional scours in Setúbal Canyon mouth, offshore west Portugal. (A) Regional EM120 multibeam bathymetry showing the morphology of lower Setúbal Canyon. Black arrows show interpreted flow pathways. Inset shows TOBI (towed ocean bottom instrument) 30 kHz sidescan sonar profile of the scoured region (located by the red rectangle on EM120 data and corresponding to the Autosub6000 image). Light tones are high backscatter. (B) High-resolution Autosub6000 image of crescent-shaped scours. Location of piston core shown in Figure 7 is shown. (C) Cross-sectional profiles across a series of crescentic scours (16× vertical exaggeration). Profile locations are shown in B.
shallowing of the scour (profile A-A’; Figs. 6B, 6C). Two other scours are partly amalgamated, with headwall slope angles as high as 35° and a maximum depth of 22 m (profiles B-B’ and C-C’; Figs. 6B, 6C).

Core JC27–39 sampled sediments from within the largest isolated scour (Figs. 6B and 7) and contains 50 cm of hemipelagite underlain by 3.35 m of chaotic facies, herein interpreted as debrite. The debrite comprises lithic clasts, mud clasts (of varying stiffness), sand lenses, lithic rich sands, and banded sands, which are inferred to represent remobilized lower canyon sediments. These canyon sediments include (1) thin-bedded turbidites, (2) canyon floor gravels (containing lithic clasts as large as 7.5 cm), and (3) coarse sands with rip-up clasts as much as 6.0 cm across. It seems likely that this debrite is the same as that identified by Arzola et al. (2008), that covers much of the lower canyon mouth area. The overlying uninterrupted hemipelagite suggests that no flows have passed through this location since the deposition of the debrite, which further indicates a shutdown of the system in the last few thousand years.

Whittard Channel Margin

The Whittard Canyon and Celtic Fan link the southern Irish Sea and English Channel paleoriver systems to the deep northwestern Bay of Biscay (Figs. 1 and 8A) (Droz et al., 1999; Zaragosi et al., 2000). Hull-mounted multibeam bathymetry data from the fan surface reveal the course of the main Whittard Channel, locally flanked by levees draped with fine-grained sediment waves (Fig. 8A). High-resolution AUV images across the western margin of the distal Whittard Channel reveal three distinct morphological features (Fig. 8B). These include (1) a portion of the active Whittard Channel with a smooth flat thalweg, (2) a heavily scoured channel margin, and (3) a pair of large-scale sediment waves in the overbank area of the active channel.

Four stages of erosional scour can be recognized in the overbank area: protoscour, isolated scour, early-stage amalgamated scour, and fully amalgamated scour. All of the scours have developed on lee slopes or in troughs of sediment

Figure 7. Core data from Setúbal Canyon mouth scour (for location, see Fig. 6). Data include core photo and graphic log with interpretation. Core contains a thick (3.35 m) mass transport deposit overlain by hemipelagic drape.
Figure 8. Erosional scours on Whittard Channel margin, northern Biscay margin. (A) Regional multibeam bathymetry showing the morphology of Whittard Canyon and Channel. Note the presence of large-scale sediment waves in overbank areas beyond channel bends. Red rectangle shows location of Autosub6000 image. (B) High-resolution Autosub6000 image of scours adjacent to Whittard Channel, in an area of fine-grained sediment waves. Location of piston core shown in Figure 9 is shown. Note morphological contrast between smooth channel floor and scoured channel margins and sediment wave troughs. (C) Cross-sectional profiles across isolated and amalgamated scours (profiles A-A’ and B-B’ 12x vertical exaggeration, C-C’ 19x vertical exaggeration). Profile locations are shown in B.
waves. Protoscours are zones of shallow erosion that are as much as 100 m long and 40 m wide; they are shallow and flat-floored, with internal slope angles <10° and a maximum vertical relief of 8 m. Isolated scours are wider than they are long (at their maximum limits), and are as much as 890 m wide, 550 m long, and 30 m deep. They have a uniform heel shape that does not exhibit any obvious signs of coalescing from smaller features; internal slope angles are generally low (<10°), with steeper slopes (22°–50°) confined to the outer limits of the scour (profiles A-A′ and B-B′; Figs. 8B, 8C). One early-stage amalgamated scour has a distinctive scalloped headwall rim and low-relief interior hummocks that are characteristic of scour remnants following amalgamation (profile C-C′; Figs. 8B, 8C). This scour is as deep as 18 m, and is 750 m wide and 480 m long; internal slope angles range from 23° to 56°. The largest erosional feature within the imaged area is a late-stage amalgamated scour that extends for >2500 m in the across-slope direction and >1300 m downslope. Of all the scour types documented in this area, this region of amalgamated scour displays both the deepest level of scour and the steepest slopes (23°–56°) confined to the outer margins of the scour. Their downslope profile is asymmetric, with a steep headwall and more gradual downslope opening. The examples of isolated scours presented here reveal four distinctly different types of scour shape and size.

**Scour Morphologies and Sizes**

The high-resolution images presented here provide detailed insight into the dimensions, morphology, and infill of erosional scours in a variety of deep-water environments. Based upon these morphologic data, we are able to identify the following categories of scour (Fig. 10).

**Isolated Erosional Scours**

Isolated erosional scours have a smooth and continuous outer rim with a regular internal morphology and a broadly symmetrical U-shaped across-slope profile. They are relatively flat bottomed, with steeper slopes of 20°–50° confined to scour margins. Their downslope profile is asymmetric, with a steep headwall and more gradual downslope opening. The examples of isolated scours presented here reveal four distinctly different types of scour shape and size.

**Oval Scours**

Oval scours have an elliptical shape in planform, and are elongated in the downslope direction (e.g., scours 1 and 2 in Fig. 2B). Spoon-shaped scours are the only type of scour that narrows; it is important that they close in the downslope direction (Fig. 10). Their elliptical planform produces a low width:length ratio of ~0.4. Other examples of spoon-shaped scours include the Cerro Toro Formation of northern Chile (Winn and Dott, 1979; Jobe et al., 2009), Albion Black Flysch of northern Spain (Vicente Bravo and Robles, 1995), Ross Formation of Ireland (Elliott, 2000a, 2000b; Lien et al., 2003), and the modern Valencia Channel mouth in the western Mediterranean Sea (Palanques et al., 1995; Morris et al., 1998).

**Heel-shaped Scours**

Heel-shaped scours have outward-flaring limbs that originate at a central upslope location (Fig. 8B). The downslope termination of the scour develops via gradual shallowing across the scour width; scour limbs continue to flare out until this termination (Fig. 10). Heel-shaped scours are wider than they are long, resulting in width:length ratios of as much as 1.6. Other published examples of scours exhibiting a heel-shaped morphology occur on the Rhone Neofan off southern France (Kenyon et al., 1995; Torres et al., 1997; Wynn et al., 2002a; Bonnel et al., 2005) and on the Redondo Fan offshore California (Normark et al., 2009).

**Crescentic Scours**

Crescentic scours have broadly lunate shapes with two downslope-pointing limbs (Fig. 6B). The downslope profile varies across the width of the scour, with more rapid downslope shallowing in the center of the scour compared to the limbs (Fig. 10). Unlike heel-shaped scours, the area between the terminations of the two limbs is positive relief. They are as wide as, or wider than, they are long, with a resultant width:length ratio of ~1.3. Crescentic scours have previously been described from the canyon basin transition zone off west Portugal (Wynn et al., 2002a) and the Valencia Channel mouth (Palanques et al., 1995; Morris et al., 1998).

**Oval Scours**

Oval scours have an elliptical planform that is elongated in the across-slope direction (Fig. 10). The large oval scour imaged in this study (Fig. 4B) displays a more irregular rim than spoon-shaped scours; this may be due to a significantly steeper headwall resulting in small-scale retrogressive mass wasting. Oval scours can be very large; the example documented in the Horseshoe Valley is the widest and deepest isolated scour in the study area. Oval scours have also been documented in Eel Canyon, offshore California, where they were described as quasi-circular topographic depressions (Lamb et al., 2008).

The original controls on morphology of isolated scours remain poorly understood, especially as some examples show lateral variations in scour morphology within the same system, e.g., the Valencia Channel mouth (Palanques et al., 1995; Morris et al., 1998). In addition, as seen in this study, scours in comparable environments can look very different, e.g., the Agadir and Setúbal Canyon mouths (Figs. 2B and 6B).

We speculate that a complex interplay of substrate character (e.g., sand/mud ratio, consolidation rate), seafloor morphology (e.g., slope angle, degree of channelization), flow character (e.g., volume, velocity, density), and flow frequency are important factors contributing to scour morphology and dimensions.

**Amalgamated Erosional Scours**

Regions of amalgamated scour develop via lateral coalescing of isolated scours; consequently, the overall size of amalgamated scours exceeds that of the isolated scours that form them. The morphology of amalgamated scours is defined both by the character and number of isolated scours that have been amalgamated. The upslope portions of amalgamated scour rims are cuspatc (Figs. 2B and 8B), where each cusp is a relic of a former isolated feature that has since been incorporated into the amalgamated region. Erosional remnants of former isolated scour margins are commonly preserved on the floor of amalgamated scours, and take the form of irregular topography, hummocks, or elongate ridges of positive relief (Figs. 2B and 8C).

Of the types of isolated scours characterized here, spoon-shaped, heel-shaped, and crescentic scours all develop into broad regions of amalgamated scour (Figs. 2B, 6B, and 8B). In each case, the nature of the amalgamated region
Figure 9. Core data from Whittard Channel margin scours (for locations, see Fig. 8). Data include core photos and graphic logs and interpretations. Core JC27–62 recovered sediments from a sediment wave crest just north of the imaged area, while core JC27–63 was taken from within a scour. Note the thick mud deposit, within the scour, that is not present in the sequence recovered from outside the scour.
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Figure 10. Morphology and dimensions of the four isolated and amalgamated scour types documented in this study. Examples of comparable scours from both modern and ancient systems are also listed.
becomes highly irregular, although some key characteristics remain that allow the character of former isolated scours to be identified. In the case of spoon-shaped scours, the outer margins and inner remnant topography of the amalgamated region are aligned in the downslope direction, while the irregular upslope rim comprises a number of narrow, steep, and tightly rounded cusps (Fig. 2B). In comparison, the rims of heel-shaped or crescentic amalgamated scours comprise gently rounded cusps and maintain their widely flaring character (Figs. 6B and 8B). Amalgamated regions that grow via the coalescing of crescentic scours continue to shallow downslope more rapidly toward the center of the scour than at the margins, therefore retaining the overall crescentic shape.

It is notable that the oval isolated scour in the Horseshoe Valley is ~3 km wide (Fig. 4B), wider than any region of amalgamated scour documented in this study. It is a fully isolated scour, with no evidence for amalgamation and no comparable isolated scours visible on the adjacent seafloor (Fig. 4B). This has been interpreted to result from structural control (Terrinha et al., 2009; Duarte et al., 2010). However, it is also possible that amalgamation is partly controlled by spacing of isolated scours, whereby this example has developed to a scale rarely achieved by isolated examples because it is located many kilometers away from adjacent scours. Overall, it appears that the point at which amalgamation occurs is controlled by the spacing, rate of lateral expansion, and longevity of original isolated scours.

Sedimentary Deposits within and Adjacent to Scours

Sedimentary deposits of the studied scours reveal some remarkable results. First, they demonstrate the longevity of some deep-sea scours, with those in Agadir being active over a period of at least 0.2 m.y. (since the oldest turbidites preserved in the scours are 190–245 ka) and possibly older than 450 ka (the age of the oldest hemipelagite). As a result of erosion, it is not possible to further determine whether the scour has been continuously active since before 450 ka, or whether it only initiated ca. 0.2 Ma and eroded down through ~200 k.y. of sediment (see Fig. 3). This longevity is in sharp contrast to scours in river systems, which are typically active over periods of months to years (e.g., Lunt et al., 2004; Sambrook Smith et al., 2005; Hooke and Yorke, 2010). Our results therefore overturn the associated paradigm that states that scours are largely transient features. Scour deposits also indicate that erosion and deposition within some scours may be cyclical, with a periodicity of tens of thousands to hundreds of thousands of years (Fig. 3). This repeated cut and fill has fluctuations in the vertical on the order of several meters.

In all cases, the sedimentary infill of the scours is out of phase with sedimentation outside of the scours. In the Agadir example, sedimentation inside the scours over the past 60 k.y. is represented by a series of muddy turbidites with thin (~5 cm) sandy bases; in contrast, just outside the scoured area is a sequence of sand-rich turbidites as thick as 50 cm (Fig. 3). In the Horseshoe Valley example, the opposite occurs; recent sedimentation (younger than 75 ka) inside the scours is represented by very thick muddy turbidites with thin (~15 cm) sandy bases, whereas outside the scour there is little or no deposition (<12 cm of mud; Fig. 5). The character of deposits can also vary greatly between scour fills and associated inter scour areas. For example, scours may be filled with thick (0.7–1.7 m) ungraded structureless muds (e.g., Agadir Canyon, Horseshoe Valley, and Whittard Channel), but can also contain thick debris (e.g., Setúbal Canyon).

In addition to the marked differences between intra and inter scour sedimentation style and associated thicknesses, there is evidence for large-scale variations in the infill of adjacent scours. In Agadir, the deepest isolated scour displays two significant hiatuses, the youngest of which occurs between OIS 3 and 7, representing at least 130 k.y., while for much of this period, the adjacent amalgamated scour shows deposition of a conformable sequence of mud-dominated turbidites (Fig. 3).

Insights into Scour Genesis and Evolution

High-resolution multibeam bathymetry data integrated with cores provide new insights into scour genesis and evolution. A key observation is that isolated scours merge laterally from the higher gradient flanks to the north of the channel flanks. The history of the channel flanks may also act to focus erosion in this position. However, given that the type of flow expansion in Agadir is so broad, it is difficult to see how small-scale variations in the primary zone of erosion can lead to such marked changes in scour infill between adjacent scours.

Migration of the Primary Zone of Erosion

Well-defined isolated scours are present on the higher gradient flanks to the north of the main channelized zone (Fig. 2). This may suggest that the initiation of erosion has been more recent on the northern flank, with insufficient time for scour to amalgamate and for the channel floor transverse gradients to be reduced, and that consequently the primary zone of erosion has migrated laterally. The higher gradients on the channel flank may also act to focus erosion in this position. However, given that the zone of scour expansion in Agadir is so broad, it is difficult to see how small-scale variations in the primary zone of erosion can lead to such marked changes in scour infill between adjacent scours.

Hydraulic Jumps

Deep-sea scours have long been linked to the formation of hydraulic jumps (Mutti and Normark, 1987; Normark and Piper, 1991), given their positions in zones of flow expansion and with rapid changes in basal slopes. Numerical and physical modeling of hydraulic jumps have reproduced scour formation (Kostic and Parker, 2006; Postma et al., 2009), and in certain cases scour trains can form (cyclic steps), each associated with a hydraulic jump (Taki and Parker, 2005; Kostic and Parker, 2006). The cyclic step concept has subsequently been utilized to interpret scour trains in deep-sea environments.
New insights into modern deep-water erosional scours along the northeast Atlantic margin

Scour Genesis: Summary

The origin of the scours cannot be specifically determined; however, the sedimentary fill of the scours provides evidence for periodic large-scale scouring in some cases. The marked differences in sedimentary infill between adjacent scours in the mouth of Agadir Canyon are difficult to interpret in terms of spatial variations in turbidity currents. Instead, they suggest that different scour types may interact with the overlying flows in contrasting ways, leading to juxtaposition of erosion and deposition in adjacent scours. Given the likely flow depths in Agadir, it is not clear that bed topography is sufficient to trigger localized hydraulic jumps over specific scours. Consequently, it may be the case that flow-topographic interactions may account for the observed local variations in scour erosion and deposition. Note that other factors such as underlying structure, e.g., sediment waves or thrust faults, may also locally influence location of individual scours (e.g., oval scour in Horseshoe Valley; Terrinha et al., 2009; Duarte et al., 2010).

Scour Fill

When currents are insufficient to cause net erosion of scours, then the scour fill appears to be a function of flow type. When flows are carrying significant amounts of coarse-grained sediments, they appear to have sufficient energy to largely keep the scours free of sediment (thin sandy turbidites), while interscour areas may exhibit large-scale deposition and the development of thick sands (e.g., Agadir Canyon; Fig. 3). Mechanistically, scours likely exhibit local flow acceleration and turbulence enhancement. In contrast, when flows are carrying large volumes of mud but little sand, then scours are preferentially filled compared with interscour areas (e.g., Horseshoe Valley; Fig. 5). We suggest that the thick muds observed in some scour fills are not the products of the tails of dilute turbidity currents, but are instead the products of higher concentration mud-rich basal flow components (Talling et al., 2004; Amy et al., 2005; Baas et al., 2009). This is further supported by the presence of associated thin clean sands at the base of the thick muds, giving a bipartite distribution characteristic of many hybrid flows (e.g., Talling et al., 2004).

Scour Abandonment

Scour abandonment and infilling may occur in response to a general system shutdown, e.g., during sea-level highstand, represented by Holocene hemipelagic drape in Setúbal Canyon mouth and Whittard Channel scours (Figs. 7 and 9). Scours may also be partially infilled by debrites, possibly from canyon and/or channel margin failures, e.g., the debris fill in Setúbal Canyon mouth scour (Fig. 7). Muddy scour fills may therefore be generated by both allocyclic factors, e.g., changing and/or reducing sediment supply, and autocyclic factors, e.g., canyon thalweg migration or canyon margin failure.

Morphologic Features Associated with Scours

The V-shaped chevrons imaged alongside a giant oval scour in Horseshoe Valley (Fig. 4B) morphologically resemble erosional chevrons described from the seafloor beyond the Setúbal Canyon mouth, offshore west Iberia (Wynn et al., 2002a). However, the limbs of chevrons imaged in Horseshoe Valley are positive relief features, indicating that they are depositional in origin. They are therefore comparable to depositional chevrons, also as much as 200 m across, reported from beyond the mouth of Valencia Channel, where they are thought to be composed of coarse sand-sized sediments moving over a muddy substrate (Palanques et al., 1995; Morris et al., 1998).

Erosional lineations were also imaged adjacent to the oval scour in Horseshoe Valley (Fig. 4B). These features closely resemble longitudinal streaks identified by Wynn et al. (2002a) and Morris et al. (1998) from modern canyon and/or channel mouth environments. However, those documented here are significantly smaller and more closely spaced. Isolated erosional lineations are as much as 80 m long, while lineations that exceed 80 m in length are coalesced with adjacent features.

IMPLICATIONS

This work demonstrates that deep-water erosional scours can be dynamically long-lived features with multiple cut-and-fill stages. In addition, they may exhibit marked variability, both between adjacent scours and between intrascour and interscour areas. Consequently, scours add much spatial variability into deposits, with implications for existing simple architecture models of submarine channels and canyons (Mayall et al., 2006; Wynn et al., 2007). Furthermore, the recognition of multiple cut-and-fill stages in large (km wide) scours will make them very difficult to recognize in outcrop or core, where they are likely to be recognized as the primary conduits, rather than as components of much larger scour surfaces.

The complexity observed herein also indicates that simple approaches such as estimating scour longevity based on measurements of interchannel sedimentation and geophysically derived depths (e.g., Normark et al., 2009) may...

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not always be appropriate. This same complexity also limits application of processes determined from smaller, better-studied erosional features such as flutes. It is clear that, unlike flutes, both erosion and infill may take place over multiple flows, and that these features, despite occasional morphological similarities, are not simply upscaled versions of flutes. In this respect the widely used term megaflute is potentially misleading. Flutes are cut and filled by single flows, while scours are features that persist on the seafloor during multiple flows.

CONCLUSIONS

In this study the detailed morphologies of deep-water scours have been combined with sedimentological and chronological data to provide new insights into scour morphology, sedimentology, and genesis, as follows.

1. Deep-water scours can be very long-lived (>0.2 m.y.). This overturns the paradigm that scours are merely transient features.

2. Scours can show multiple cut-and-fill cycles with periodicities of tens of thousands to hundreds of thousands of years.

3. The infill of scours is shown to be typically out of phase with interchannel deposits, with thin sands internally and thick sands externally, or thick muds internally and thin muds externally.

4. Adjacent scours can have markedly different sedimentary infill.

5. Different scour types may interact with overlying flows in contrasting ways, leading to this juxtaposition of erosion and deposition in adjacent scours.

6. Isolated scours documented in this study are associated with canyon and/or channel termini and margins, and display four different morphologies: spoon shaped, heel shaped, crescent shaped, and oval shaped.

7. Isolated scours may coalesce into broad areas of amalgamated scour; evidence for the presence of isolated scours is often preserved within the region of amalgamation as a series of scour rims on the scour headwall, or as remnants on the scour floor. Taken together, these points demonstrate both the range of different types of scour and the associated high spatial variability in sedimentary deposits within these depositional settings.

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REFERENCES CITED


