# INITIATION AND EVOLUTION OF TURBIDITY CURRENT SEDIMENT WAVES IN THE MAGDALENA TURBIDITE SYSTEM

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## Abstract

This study describes an extensive sediment-wave field in the Magdalena Turbidite System, which occupies an area of at least 15,000 $km^2$ on the continental slope (3330 - >3800 m). The waves display wavelengths up to 1.9 km, wave heights up to 18 m, and crestlines that are aligned roughly parallel to the regional bathymetric contours. Preferential deposition on the upslope wave flank has led to upslope migration, in the manner of antidunes. The Magdalena sediment waves are interpreted as forming beneath unconfined turbidity currents, which may result from the downslope evolution of slumps and mass flows. The unconfined turbidity currents are derived from several point sources along the continental slope and spread laterally as they flow downslope. This has led to the formation of a laterally extensive sediment-wave field. Simple numerical modelling estimates that the turbidity currents responsible for wave generation were near- or super-critical, with flow thickness and velocity estimated at 40-160 m, and 36-82 cm $s^{-1}$ respectively.

However, later phases of wave growth were not dependent on specific flow conditions.

The most important aspect of this study is that the entire sediment-wave unit, from the basal boundary to the present-day seafloor, has been investigated using ultra high-resolution seismic profiles. The sediment-wave unit rests upon an irregular discontinuity that marks a recent change in the sedimentary regime of the Magdalena Turbidite System, from channelised to unchannelised gravity flows. Above this boundary, the sediment waves display a growth pattern characterised by an increase in wave dimensions. In addition, the wave dimensions appear to become more regular through time. However, breaks of slope in the lower bounding surface of the wave field have produced variations in wave morphology that are still visible at the present-day seafloor. This indicates that there is a close relationship between variations in slope angle and turbidity current flow characteristics, which in turn leads to variations in wave morphology.

*Keywords:* Magdalena Turbidite System; turbidity currents; sediment waves; numerical models

## 1. Introduction

Most studies of deep-water sediment waves have concentrated on the qualitative and quantitative analyses of their surface or near-surface distribution and morphology (e.g. Normark et al., 1980; Wynn et al., 2000a, b; Ercilla et al., this volume). However, their temporal evolution has received little attention as the basal boundary of most sediment-wave fields is too deep in the subsurface to be imaged using shallow seismic profiles (Ewing et al., 1971; Tucholke, 1977; Richards et al., 1987; Carter et al., 1990; Nakajima et al., 1998).

This study investigates an extensive sediment-wave field, recently described from the eastern Magdalene Turbidite System (Fig. 1). The entire sediment-wave unit, from the basal boundary to the present-day seafloor, has been imaged using ultra high-resolution seismic-reflection profiles. The sediment waves occur across a broad area, and are not restricted to levee backslopes bordering turbidity current channels (Ercilla et al., 2000). Initially, we describe the location, plan view morphology, and geometry of the sediment waves. Secondly, a high-resolution seismic-stratigraphic analysis will attempt to establish the growth pattern of the waves since their initiation. The geological processes that are responsible for wave genesis also provide information on the factors governing sediment wave evolution through time.

## 2. Database

Ultra high-resolution acoustic data have been used for the detailed analysis of the sediment waves developed in the Magdalena Turbidite System. These acoustic data comprise multibeam bathymetry and seafloor backscatter, both obtained with the SIMRAD EM-12 echosounder, a 12 kHz and 120° opening multibeam echosounder, providing 81 values of bathymetry across the ship track, corrected for the geometric propagation of sound in the stratified water column. Ping rate was approximately once every 100 m, and the average sonar footprint was about 200x200 m. In addition, the system simultaneously recorded acoustic backscatter amplitude for each depth value. Ultra high-resolution seismic profiles were collected with the TOPAS PS 018 Simrad parametric echosounder. The system transmitted approximately every 2 seconds (~10 m at cruise speeds of 10 knots) with a beam angle of approximately 5º, and a modulated frequency sweep (chirp) between 1.5 and 4 kHz. The data were deconvolved and corrected for spherical spreading with a linear time varying gain prior to presentation. The vertical resolution of the TOPAS records is very high (less than one metre) and the penetration in this area ranges from a few metres to several tens of metres. Acoustic data obtained with both systems were registered simultaneously on long (up to 130 km) WSW-ENE and W-E transects across the turbidite system. These transects are connected by shorter (<5 km) NNW-SSE and N-S transects.

## 3. Geological Setting

The Magdalena Turbidite System is developed on the continental margin of Colombia, in the Caribbean Sea, in an area where convergence between the South American and the Caribbean tectonic plates takes place (Fig. 1). This river-fed turbidite system displays a fan bulge shape with an E-W trend, and is active at the present-day. This sedimentary activity is well-documented by the numerous breaks of submarine cables that have occurred since the 1950’s (Heezen, 1956; Heezen and Muñoz, 1965). Although the Magdalena Turbidite System is developed in a tectonically active region it presently remains undeformed, except in the westernmost sector where turbidite sediments are deformed and/or incorporated into the deformed prism (Ercilla et al., 2000).

The main sedimentary processes that have governed the most recent evolution of the Magdalena Turbidite System comprise different types of gravity-flow processes. Three large areas, up to 120 km long and 25 km wide, have been affected by mass-flow deposits. These areas are tongue shaped, with an E to W radial distribution that extends from the upper to the lower continental slope (down to 3700 m water depth) (Fig. 2). Slumping processes have produced striking scarps (up to 150 m high and 50 km long) that are distributed along a continuous E-W band on the middle continental slope (2500 to 3300 m) (Fig. 2). Gravity flows, dominantly turbidity currents, have contributed to the development of dendritic channel-levee systems, composed of major sinuous feeder channels and smaller meandering distributary channels (Fig. 2). The channel-levee systems erode the continental slope, extending downslope beyond 3800 m water depth. The morphology of the channel-levee systems is partially or totally destroyed by the large-scale mass-flow deposits, cut by slump scars and modified by the formation of a sediment-wave field (Ercilla et al., 2000) (Fig. 2).

The Magdalena sediment waves have previously been described as an architectural element of the Magdalena Turbidite System (Ercilla et al., 2000) (Fig. 2). Ercilla et al. (2000) mainly focussed on the sedimentary analysis of architectural elements within the turbidite system, but suggested that the development of the sediment waves may have contributed to destruction or modification of the turbidite distributary channels. Although Ercilla et al. (2000) did not establish the exact process responsible for wave generation, they did conclude that the waves have a primary sedimentary origin, and are not related to deformational processes (i.e., they are not folded or compressed).

**4. Location and morphology of the sediment waves**

The Magdalena sediment-wave field extends from the middle continental slope (3300 m water depth) to the lower continental slope outside the limits of the study area (>3800 m water depth). Therefore, the downslope limit of the sediment-wave field is not observed. The wave field covers an area of at least 15,000 $km^2$, which is just over one-third of the eastern Magdalena Turbidite System (39,650 $km^2$). The sediment waves extend downslope from the E-W band of slump scars and the area of large-scale mass-flow deposits. No waves are identified upslope of the middle continental slope, in the inter-channel areas of major feeder channels, or within the area affected by large-scale mass-flow deposits (Fig. 2).

The plan view morphology of the sediment waves indicates that crestline orientation is roughly parallel to the regional bathymetric contours (Fig. 3). The dominant orientation is WNW-ESE, although in the western sector crests with a WSW-ENE orientation are also observed. The backscatter images of the seafloor are generally of poor quality and are therefore not presented in this paper. However, they do show high backscatter sinuous lineations that are interpreted as images of the upslope flanks of sediment waves. Crests appear to be sinuous and show some evidence of bifurcation (Fig. 3).

Wave morphology, wave dimensions, and slope gradient based on cross-section, have been defined taking into account the orientation of the wave crests. Therefore, only the seismic lines that run perpendicular to the wave crests and the regional slope have been utilised in this study. The sediment waves display an asymmetrical profile, and in general the steeper and larger flank faces downslope (Fig. 4). Wavelength (WL) generally falls between 0.5-1.0 km, although it varies between 0.1-1.9 km. Wave heights (WH) are up to 18 m. The WL:WH ratio ranges between 70-240. The regional slope gradient is 0.3°-0.6°, and exhibits local variations without displaying any overall spatial (downslope) tendency. WL, WH and WL:WH also fail to show any spatial trends, probably resulting from the irregularity of the regional slope (Fig. 4).

## 5. Seismic characteristics and stratigraphy of the sediment waves

Analysis of the ultra high-resolution seismic reflection profiles of the sediment waves in the Magdalena Turbite System offers a temporal perspective of wave evolution since their initiation. The sediment waves form an undulating stratified unit up to 50 m thick, and this thickness decreases irregularly downslope to <30 m (Fig. 4). The lower boundary of the sediment-wave unit is a distinct surface of high reflectivity, and it is present across all of the lower continental slope. This surface is irregular and displays numerous breaks of slope, the largest of which are directly overlain by the largest waves on the present-day sea floor (Fig. 4). The seismic-stratigraphic unit under the sediment-wave unit exhibits subparallel, hyperbolic and semi-transparent reflectors of high amplitude, which define lenticular bodies and channel-like features (Figs. 5 and 6A). The wavy stratified facies forming the sediment-wave unit is overlying and infilling (with an onlap configuration) the U-shaped channel-like features, destroying and/or modifying their original morphology (Fig. 7).

The acoustic character of the sediment waves is characterised by medium-high amplitude individual reflectors with high lateral continuity, showing a subparallel configuration (Figs. 4 to 6A). The acoustic character of this unit changes vertically. The basal section of the sediment-wave unit is composed of discontinuous and broken arched reflectors of medium amplitude that change upwards to well-bedded reflectors of high amplitude (Figs. 4 to 6A). Detailed analysis of the acoustic character indicates the occasional presence of layers with stronger reflectivity; these have a regional lateral continuity and seem to erode the underlying wave deposits (Fig. 4). The stratified reflectors within each sediment wave generally show an unconformable configuration, with onlapping and/or convergent reflectors approaching the wave crest, and higher reflectivity on the upslope flank (Figs. 4 to 6A). Sediment thickness also varies within each wave, with the sedimentary sequence on the upslope flank being about 30% thicker than that on the downslope flank. This indicates that the waves are migrating upslope, and the migration rate varies from 1:5 to 1:30 (1 m of vertical accumulation = 5 to 30 m of upslope migration).

The vertical distribution of individual sediment waves indicates that many waves observed at depth on seismic records mimic those observed on the present-day seafloor, although the dimensions vary (Figs. 4 to 6A). The WL and WH of individual waves generally increase upwards, and as a consequence the waves have higher WL and WH towards the top of the unit (Fig. 6B). In some cases, this increase in dimensions is related to the merging of two or more smaller waves into a single large wave (Figs. 5 and 6A).

## 6. Discussion

### *6.1. Genesis of the sediment waves*

There is good evidence to suggest that the recent sediment waves identified in the Magdalena Turbidite System have a sedimentary origin and represent primary depositional bedforms. They display a well-bedded internal structure, a homogeneous growth pattern, variations in sediment thickness across the wave crest, and an absence of deformational structures such as faults or diapirs that would disturb and displace the stratified layers. The troughs of the waves exhibit steep, downslope dipping, echosound bands that resemble fault-like features (Figs. 5 and 6A). However, they do not extend below the sediment-wave unit, and our interpretation is that the echosound bands do not represent faults, but instead represent areas of seismic reflection convergence. Although the Magdalena Turbidite System is developed in an active region of convergence between tectonic plates, the area of the continental slope covered by the sediment-wave field remains tectonically undeformed (Kolla et al., 1984; Ercilla et al., 2000). All of this information indicates that the sediment-wave unit is not folded or faulted, and its development is therefore unrelated to tectonism or gravitational mass-movements. Therefore, the waves must have been generated by the action of alongslope bottom currents or downslope turbidity currents.

There are few studies describing the bottom water circulation in this area of the Caribbean Sea (Wüst, 1957, 1964). Wüst (1964) describes the existence of a circulation system where bottom currents flow towards the north-west. This bottom current direction is oblique to the alignment of the wave crestlines, which are roughly parallel to the bathymetric contours (Fig. 3). This is not compatible with existing models of bottom-current-generated sediment waves developed on slopes, which suggest that wave crests are oblique to both the bottom current flow and the regional bathymetry (Blumsack, 1993). Therefore, the alignment of the wave crests indicates that the Magdalena sediment waves have probably not been generated by bottom currents.

There is good evidence to suggest that the Magdalena sediment waves are formed by turbidity currents, although these flows do not appear to be related to the activity of the adjacent channel-levee systems. In most turbidite systems, sediment waves are developed on the backslopes of levees bordering turbidite channels, but this is not the case in the Magdalena Turbidite System. The sediment waves are absent from levee backslopes, and it is therefore unlikely that their genesis is related to flow overspill from channels. The sediment waves actually occur across a broad area, and are locally filling some of the channels, destroying and/or modifying their morphologic expression (Fig. 7). It is therefore interpreted that the waves are generated by unconfined turbidity currents. There are several indicators that support this interpretation:

1) The Magdalena Turbidite System is presently active, and at least 18 submarine cable breaks have occurred in the turbidity current channels on the upper continental slope above the sediment waves since the 1950's (Heezen, 1956; Heezen and Muñoz, 1965). Several studies have demonstrated that submarine cable breaks are dominantly associated with turbidity current activity (e.g. Heezen and Ewing, 1952; Kuenen, 1952; Piper and Aksu, 1987). In addition, slumps and mass flows have also occurred frequently during the most recent sedimentary evolution of the Magdalena Turbidite System (Kolla et al., 1984; Ercilla et al., 2000). The sediment-wave field is developed immediately downslope

of the area cut by numerous slump scars and large-scale mass-flow deposits (Fig. 2). The location of the wave field, and its broad lateral extent, all indicate that the waves may have formed beneath unconfined turbidity currents related to the slumps and mass flows. The evolution of slumps and mass flows into unconfined turbidity currents has been well-documented (Heezen and Ewing, 1952; Parker, 1982; Cochonat and Piper, 1994; Mulder et al., 1997). It is therefore suggested that the Magdalena waves are generated by unconfined turbidity currents that are sourced from several points along the continental slope, leading to development of a laterally extensive wave field.

2) The thickness of the sediment-wave unit decreases downslope by at least 40%, although the exact decrease cannot be measured as the distal section of the wave field is not observed (Fig. 4). This downslope decrease has also been observed in other sediment-wave units developed beneath unconfined turbidity currents (Normark et al., 1980; Nakajima et al., 1998). These studies found that the sediment-wave units decrease by about 60% downslope. The downslope decrease of the sediment-wave unit indicates that the wave sediments are probably sourced from an area upslope of the waves, and are not derived from to the east or west.

3) The morphologic characteristics of the studied sediment waves are similar to those described from other turbidity current wave fields (e.g. Damuth, 1979; Normark et al., 1980; Carter et al., 1990; Wynn et al., 2000a, b). These characteristics include the wave crestlines being roughly parallel to the bathymetric contours (Fig. 3); the upslope wave migration; the asymmetry of the wave profile

with the steeper and larger flank generally facing downslope; and the variation in sediment thickness across the wave, with the upslope flank being about 30% thicker than the downslope flank (Figs. 4 to 6A).

*6.2. Turbidity current flow characteristics*

The flow characteristics of turbidity currents crossing the Magdalena sediment-wave field can be constrained using simple numerical modelling, as demonstrated by Wynn et al. (2000b). First, an attempt is made to calculate the internal Froude number, and this value combined with wavelength is then used to estimate flow thickness. Flow velocity is calculated using internal Froude number and sediment concentration as the key parameters.

6.2.1. Internal Froude number

It is possible to calculate the internal Froude number (*Fi*) for a turbidity current using a combination of slope gradient ($\sin\beta$), drag coefficient at the bed (*Cf*), and entrainment coefficient at the upper interface (*E*). The following calculations of *Fi* are based on Equation (1), from Bowen et al. (1984):

$$Fi^2 = \frac{\sin\beta}{Cf + E} \qquad (1)$$

Slope angles across the Magdalena sediment-wave field are highly variable. However, taking the average slope angle across several TOPAS profiles reveals that all values fall between 0.3°-0.6°. Previous research has shown that values for the drag coefficient in unconfined turbidity currents are in the range of 0.0035-0.004 (e.g. Bowen et al., 1984). The entrainment coefficient (*E*) for most turbidity currents varies between $5 \times 10^{-4}$ and $6 \times 10^{-3}$ (Bowen et al., 1984). Taking into account all of the available data, it is proposed that for the purposes of this study $Cf + E = 0.005$. Using these values in Equation (1) produces estimates of $Fi = 1.0$-1.4. These figures are in agreement with previous research of unconfined turbidity currents (Normark et al., 1980; Bowen et al., 1984; Piper and Savoye, 1993; Wynn et al., 2000b) and are within the calculated limits of antidune existence ($Fi = 0.8$-1.8, Allen, 1984). However, as discussed later, antidune conditions are not necessary for wave generation throughout the sequence.

6.2.2. Flow thickness

The relationship between wave length (*L*), flow thickness (*h*), and internal Froude number (*Fi*) is illustrated in Equation (2), and has been modified from Normark et al. (1980):

$$h = \frac{L}{2\pi Fi^2} \qquad (2)$$

Wavelengths of the Magdalena sediment waves generally fall between 500-1000 m. Using Equation (2), and accounting for variations in *Fi* as demonstrated in

Equation (1), we find that flow thicknesses across the entire wave field are in the range of 40-160 m.

6.2.3. Flow velocity based on internal Froude number and sediment concentration

Flow velocity can be estimated using the following equation (Piper and Savoye, 1993):

$$u^2 = \Delta\rho C g h Fi^2 \qquad (3)$$

where $\Delta\rho$ = grain density – density of fluid within TC/seawater density, $C$ = volume concentration, and $g$ = gravitational acceleration.

$C$ is a dimensionless number that represents sediment concentration. It should be noted that Equation (3) is very sensitive to changes in $C$, which is one of the most poorly constrained variables in turbidity current modelling. Existing data indicate that $C$ can vary by several orders of magnitude depending on the type of flow involved. However, for fine-grained, unconfined turbidity currents, previous research has shown that values of $C = 5 \times 10^{-5}$ to $5 \times 10^{-4}$ are suitable (e.g. Bowen et al., 1984; Piper and Savoye, 1993). When these variables are entered into Equation (3), combined with the values of $Fi$ and $h$ obtained above, it can be shown that flow velocities across the Magdalena sediment waves fall between 36-82 cm $s^{-1}$. These values are similar to those obtained from other turbidity current sediment-wave fields (Normark et al., 1980; Bowen et al., 1984; Piper and Savoye, 1993; Wynn et al., 2000b).

*6.3. Initiation and evolution of the sediment waves*

The TOPAS profiles investigated in this study have imaged the entire sediment-wave unit, from the basal boundary to the present-day seafloor (Figs. 4 to 6A). Therefore, we can analyse how the sediment waves were initiated, and how they have evolved through time. The base of the wave field rests upon an irregular bounding surface, which represents a regional unconformity that separates older channel-fill and overbank deposits, defined by subparallel, hyperbolic and semi-transparent reflectors, from the stratified sediment-wave unit (Ercilla et al., 2000) (Figs 4 to 6A). Therefore, the initiation of the sediment-wave field apparently occurred during a major change in the sedimentary regime of the Magdalena Turbidite System. This change is associated with the destruction of the channel-levee systems by large-scale mass-flow deposits, and also by numerous slumping events (Fig. 2). At this time, it is interpreted that a change from confined to unconfined flows occurred, with unconfined turbidity currents resulting from the downslope evolution of slumps and mass flows. The trigger for this change is unknown, but was possibly controlled by climate. Unfortunately there are no sediment cores recovered from the wave field that could provide definitive information about the timing of the processes and possible controlling factors.

The waves immediately above the basal boundary are typically small and irregular (Figs. 4 to 6A). Although the first waves to form were highly irregular, wave initiation appears to have occurred at roughly the same time across the wave field (Figs. 4 to 6A). The exact cause of wave initiation is still unknown, although the irregularities of the bounding surface may have initiated flow instabilities within passing turbidity currents, leading to development of internal waves and possible antidune formation. The irregularity of the lowermost waves suggests that wave development was affected by variations in the slope of the basal boundary, which in turn would affect the flow characteristics of passing turbidity currents (e.g. velocity, flow thickness). Carter et al. (1990) also noted that the morphology of the lowermost sediment waves on Bounty Channel levee appeared to be affected by the substrate morphology.

The largest waves are generally associated with breaks-of-slope in the lower bounding surface. Flows passing over these slope breaks may have undergone hydraulic jumps leading to a decrease in flow velocity and competency, which in turn leads to increased deposition and development of a large wave. A similar relationship between hydraulic jumps and enhanced sediment wave deposition has been discussed by Nakijama and Sato (2001). Areas of relatively smooth slope or smooth irregular sediment waves up to 400 m long are often developed immediately downslope of the largest waves (Figs. 4 and 5). These observations also allow us to speculate that hydraulic jumps may be occurring at slope breaks (associated with the largest waves), and consequently disrupting internal waves within the flow and hindering sediment wave development (Wynn et al., 2000b).

Once the sediment waves started growing they became ‘fixed’ in position, and began to display a vertical growth pattern characterised by higher WH and WL through time (Fig. 6). This vertical increase in wave dimensions through time was also noted by Carter et al. (1990). It is interpreted that this increase is related to the asymmetry of flow velocity across the wave. The small, early-formed waves did not display significant relief, therefore flow velocities across the wave would have been fairly uniform, but still with a slightly lower velocity on the upslope flank. Even this slight asymmetry in flow velocity would lead to asymmetrical sediment deposition across the wave, and would generate an increase in WH through increased deposition on the upslope flank. Once this process began it became self-perpetuating, with progressively larger waves leading to greater asymmetry of flow velocity across the wave, and greater asymmetry of deposition on either wave flank. This relationship between flow velocity and wave height is also evident where two or more smaller waves merge into a single larger wave. Generally, the highest wave to merge becomes dominant, and begins to form the crest of the final wave (Fig. 5). This is because the flow deposits more sediment on the largest wave, as this forms a larger obstacle. Consequently the highest wave begins to grow most rapidly and eventually becomes dominant. The merging of smaller waves into larger waves also explains why WL appears to have increased through time (Fig. 5), a feature also noted by Carter et al. (1990). The above process does not have to be related to supercritical flows or antidune generation. Previous studies (Hiscott, 1994; Nakijama and Sato, 2001) have demonstrated that enhanced deposition occurs on the upstream side of an obstacle regardless of the flow conditions within the turbidity current. Throughout wave evolution, preferential deposition on the upslope flank (in the manner of antidunes) led to upslope migration (Fig. 6A).

Studies of wave evolution on levee backslopes suggest that the lower limit of the wave field extends downslope through time (Carter et al., 1990, their Fig. 7; Nakajima et al., 1998, their Fig. 7A). This may be related to the increased influence of wave morphology in generating internal instabilities within the flow, or a change in flow velocity and/or sediment load. Unfortunately this feature cannot be investigated in this study as the lower limit of the wave field is not observed. Occasionally, during the formation of the Magdalena waves, larger turbidity currents occurred. These higher energy events resulted in the formation of layers with stronger reflectivity and regional lateral continuity, which eroded the underlying wave deposits on both flanks of the wave (Fig. 4).

Over time, the sediment waves appear to display more regular dimensions (Fig. 6B). This may be related to the fact that the irregularities of the basal boundary become less influential through time, and the waves begin to form more in equilibrium with passing turbidity currents. As the sediment waves become more regular, they will become more in-phase with the internal waves of passing turbidity currents, and consequently deposition across the waves will become even more regular. The bifurcation and clear sinuosity displayed by some of the wave crests may be associated with the interaction of different turbidity currents coming from different input points (Fig. 3). This feature was also noted by Wynn et al. (2000a).

## 7. Conclusions

This study has provided a unique insight into the evolution of a sediment-wave field, from its initiation through to the present-day. The Magdalena sediment waves are interpreted to have formed beneath unconfined turbidity currents, which may have evolved from slumps and mass flows occurring further upslope. These unconfined flows are probably sourced from several points along the slope, explaining the extensive lateral development of the wave field. Simple numerical modelling has revealed that the waves are generated beneath flows that are nearor super-critical, and are probably able to sustain antidune-type deposition. However, once the wave morphology is established, upslope migration can occur regardless of the flow conditions - antidune conditions are not necessary for wave migration to occur throughout the sediment-wave unit.

The base of the sediment-wave unit rests upon an irregular, unconformable surface. This surface represents a change in the sedimentary regime of the turbidite system, from dominantly confined to unconfined turbidity currents. As the waves began developing upon this surface, preferential deposition on the upslope flank led to upslope migration, in the manner of antidunes. The waves display a vertical growth pattern characterised by higher WL and WH through time. In addition, the waves appear to display more regular dimensions throughout their evolution. These features are related to both the inherited seafloor morphology and turbidity current flow characteristics.

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**Figure Captions**

Fig. 1. Location map of the study area in the southern Caribbean Sea. The boundary of the Magdalena Turbidite System is shown (after Kolla et al., 1984), together with the area covered by multibeam bathymetry and TOPAS profiles. The locations of Figs. 4-7 are indicated.

Fig. 2. Map illustrating the main morpho-sedimentary and morpho-structural features that characterise the present day Magdalena Turbidite System (modified from Ercilla et al., 2000). Note the apparent destruction of channel-levee systems by large-scale mass-flow deposits, and the presence of an extensive sediment-wave field downslope of the zone of erosional scarps. Box indicates location of Fig. 3.

Fig. 3. Shaded mean depth map obtained with the EM-12 multibeam system, and line drawing showing the distal Magdalena Turbidite System. Sediment waves are imaged as sinuous lineations that are aligned roughly parallel to the bathymetric contours (100 m interval). Location shown in Fig. 2.

Fig. 4. TOPAS profile illustrating well-developed sediment waves in the distal Magdalena Turbidite System. The overall downslope decrease in the thickness of the sediment wave unit is visible. Also, note the occasional presence of layers with stronger reflectivity and high lateral continuity, which apparently erode the underlying wave deposits. The lateral extent of one of these layers is indicated by a series of small arrows. Location of profile shown in Fig. 1.

Fig. 5. TOPAS profile illustrating the vertical evolution of the Magdalena sediment waves. Individual sediment waves show an upward increase in dimensions, often through the merging of two or more smaller sediment waves into a single large wave. The grey-shaded area refers to ancient leveed channels and related deposits. Location of profile shown in Fig. 1.

Fig. 6. A) TOPAS profile illustrating the internal seismic characteristics of the sediment waves. Note that individual layers display higher reflectivity on the upslope flank (yellow-orange colours) compared to the downslope flank (blue colour), indicating that sediments on the upslope flank are probably coarser-grained. In the line-drawing interpretation, the grey-shaded area refers to ancient channel-levees and related deposits. Location of profile shown in Fig. 1. B) Graphs showing how the wave height (WH) and wavelength (WL) of the sediment waves generally increases upwards through the unit. Note how wave dimensions become more regular through time. Numbers *1* to *6* refer to the different layers and letters *a* to *g* to the individual waves, both shown on Figure 6A.

Fig.7. TOPAS profiles showing two cross-sections of older turbidite channels (channel remnants in Fig. 2) that have been progressively filled by the stratified facies that form the sediment-wave unit. Location of profile shown in Fig. 1.