Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G38158.1

Comparing submarine and fluvial channel kinematics: Implications for stratigraphic architecture

Zane R. Jobe[1*], Nick C. Howes[1], and Neal C. Auchter[2]

[1]*Shell International Exploration and Production Inc., Houston, Texas 77079, USA*

[2]*Department of Geosciences, Virginia Polytechnic Institute, Blacksburg, Virginia 24060, USA*

*Current Address: Colorado School of Mines, Golden, Colorado 80401, USA; E-mail: zanejobe@mines.edu.

ABSTRACT

Submarine and fluvial channels exhibit qualitatively similar geomorphic patterns, yet produce very different stratigraphic records. We reconcile these seemingly contradictory observations by focusing on the channel-belt scale and quantifying the time-integrated stratigraphic record of the belt as a function of (1) the geometric scale and (2) the trajectory of the geomorphic channel, applying the concept of stratigraphic mobility. By comparing 297 submarine and fluvial channel belts from a range of tectonic settings and time intervals, we identify channel kinematics (trajectory) rather than channel morphology (scale) as the first order control on stratigraphic architecture and show that seemingly similar channel forms (in terms of scaling) have the potential to produce markedly different stratigraphy. Submarine channel-belt architecture is dominated by vertical accretion (aggradational channel fill deposits), in contrast to fluvial systems that are dominated by lateral accretion (point bar deposits). This difference is best described with the channel-belt aspect ratio, which is 9 for submarine systems and

72 for fluvial systems. Differences in channel kinematics and thus stratigraphic architecture between the two environments appear to result from markedly different coupling between channel aggradation and overbank deposition. The methodology and results presented here are also applicable to interpreting channelized stratigraphy on other planets and moons.

INTRODUCTION

Sinuous submarine and fluvial channels have qualitatively similar planform morphologies, but very different preserved stratigraphic records (Flood and Damuth, 1987; Kolla et al., 2007). Sinuous fluvial channel belts are dominated by lateral migration deposits, including point bars and oxbow cutoffs (Allen, 1965; Sun et al., 1996) and undergo only minor aggradation (>1 channel depth of super-elevation) prior to avulsion (Mohrig et al., 2000). Submarine channels, while displaying lateral migration (Abreu et al., 2003; Kolla et al., 2012), tend to have a more significant component of vertical aggradation (Peakall et al., 2000; Deptuck et al., 2007; Sylvester et al., 2011). Submarine channel-belt deposits are commonly offset to vertically stacked, sand-rich channel fill deposits (Macauley and Hubbard, 2013). This study quantifies the similarities and differences between submarine and fluvial channel belts and explores the formative processes that result in vastly different kinematics and stratigraphic architecture.

CHANNEL KINEMATICS: TRAJECTORY AND MOBILITY

Definitions and Methodology

Jerolmack and Mohrig (2007) introduced the channel mobility number (Equation 1) as a metric to characterize and understand channel deposits. The mobility number is defined as the ratio of avulsion and lateral migration time scales. In a more general sense, channel mobility describes a channel trajectory scaled by the dimensions of the geomorphic channel form. For applications to modern rivers, channel trajectory can be expressed as the ratio of temporal rates of lateral (V_c) and vertical (V_a) migration (Jerolmack and Mohrig, 2007). Because we are interested in characterizing the preserved stratigraphic record of channel trajectory where rate data (i.e., V_a, V_c) are uncommon, we propose a stratigraphic mobility number, M_s.

We recast the mobility equation, by substituting the temporal rates (V_c/V_a) with the relative spatial displacements (L_c/L_a) of the channel as measured in a strike-oriented cross section (Fig. 1; Equation 2). The two formulations (M and M_s) are conceptually identical if considered over the same time-period. The ‘local’ stratigraphic trajectory (L_c/L_a) can be thought of as spatially separated points that denote the spatial path of the channel thalweg/centerline through time, where each point along the path represents an easily identifiable location of the channel thalweg (Fig. 1C; cf. ‘discrete migration events’ of Deptuck et al., 2007; Kolla et al., 2007). We also define an aggregate or belt averaged stratigraphic mobility number, M_{sb}, using the channel belt dimensions (Equation 3). Channel belt width (B_{cb}) and thickness (H_{cb}) are defined as the maximum lateral and vertical extent of the belt (including the youngest channel form), respectively (Fig. 1). Channel width (B) and thickness (H) were estimated from the final channel form (Fig. 1). Note that B_{cb} and H_{cb} are minimum estimates because we do not include any coeval overbank or levee deposits.

$$M = \frac{V_{\mathrm{c}}}{V_{\mathrm{a}}}\frac{\overline{h}}{B}, \qquad (1)$$

$$M_{\mathrm{sl}} = \frac{L_{\mathrm{c}}}{L_{\mathrm{a}}}\frac{H}{B}, \qquad (2)$$

DOI:10.1130/G38158.1

$$M_{\mathrm{sb}} = \frac{(B_{\mathrm{cb}} - B)}{(H_{\mathrm{cb}} - H)} \frac{H}{B} . \quad (3)$$

The local (M_{sl}) and belt-averaged (M_{sb}) methods calculate the stratigraphic mobility number at the scale of individual channel migration events and the entire channel belt scale, respectively (Fig. 1). While the stratigraphic record is biased toward the preservation of net-aggradational channel belts that produce $M_s > 0$, negative values of M_s describe degradational phases of channel belt evolution or net-degradational fluvial and submarine channel belt deposits. Because M_{sl} is calculated using each L_c/L_a point pair of the channel trajectory, it has a broader distribution of values than M_{sb}. In both definitions, large values of M_s result from channels with abundant lateral migration but little aggradation relative to the size of the geomorphic channel form.

Data Sources and Interpretation

This study compiles 297 channel trajectory and channel-form geometry measurements from a global sampling of 21 submarine systems and 13 fluvial systems (Fig. 1B; Table DR1 in the GSA Data Repository[1]). Data sources include seismic-reflection cross-sections and outcrop exposures. In order to standardize measurements, we utilized a simple set of guidelines based on observable seismic/outcrop facies and geometries (Fig. 1C; see the Data Repository). We define a channel belt as a coherent package of channel-related deposits that does not contain significant erosion (i.e., >1 channel depth). Thus, channel belts are separated by avulsion or significant erosion events that reset the geomorphic channel surface. This definition of channel belt does not imply an absolute temporal duration, only the relative time of channel belt formation, which may vary by system.

Trajectory data (L_c, L_a) were collected for each channel belt at the basal terminations of inclined reflectors/surfaces from selected cross sections, with the assumption that these points closely approximate the coeval channel thalweg (Fig. 1). The spacing of recorded trajectory points was dictated by observable reflectors/surfaces (Fig. 1C). Channel forms were interpreted based on concave up geometries, internal lap-out geometries, and vertical transition to horizontal, parallel, laterally continuous reflectors (Fig. 1C). Some channel forms were truncated by subsequent erosion and thus form minimum values of B and H. We acknowledge that the measurement of channel form within the stratigraphic record can be difficult and at times may differ from the geomorphic channel form. However, our measurements of B, H, and B/H (aspect ratio) generally agree with measurements from modern topographic and bathymetric data (Fig. DR1), indicating that better preservation and/or decompaction of the channel form would not significantly alter the results of this study. Interestingly, the B/H data from Jerolmack and Mohrig (2007) is quite different from all other sources, likely due to their focus on anastomosing and distributary systems (see the Data Repository; Fig. DR1).

COMPARISONS OF SUBMARINE AND FLUVIAL DATA

Channel and Channel Belt Dimensions

Channel and channel-belt width (B, B_{cb}) are broadly similar for submarine channels and rivers, with submarine channels tending to be somewhat wider than rivers (Fig. 2; Fig. DR1). However, submarine channel and channel-belt thickness (H, H_{cb}) are 4–5× thicker than their fluvial counterparts (Fig. 2). While the absolute dimensions (Figs. 2A–D) display differences in width and thickness, normalized dimensions (Figs. 2E–G) are more useful to evaluate differences in lateral and vertical channel migration at the channel-belt scale. Our data indicates that the median value of normalized channel belt width (B_{cb}/B) for fluvial systems is 4.7, much greater than 2.1 for submarine systems (Fig. 2E). Normalized channel belt thickness (H_{cb}/H) values have the opposite relationship, with median values for submarine systems (2.9) being almost twice that of fluvial systems (1.6; Fig. 2F). These results are summarized with the channel belt aspect ratio (B_{cb}/H_{cb}) that describes the shape of the channel belt (Fig. 2G). Due to high aggradation (i.e., low values of L_c/L_a), submarine channel belts tend to be thick and narrow, with a median value of $B_{cb}/H_{cb} = 9$, whereas fluvial channel belts are thin and wide, with a median value of 72 (Fig. 2G).

Channel Kinematics: Trajectory and Stratigraphic Mobility

Trajectory describes the shape of the path of a channel as it migrates in time and space to form a channel belt. A plot of L_c versus L_a presents the shape of the trajectories collected from seismic and outcrop channel belts (Fig. 3A). Fluvial and submarine trajectories have broadly similar ranges of L_c but submarine channels have ~10× larger values of L_a (Fig. 3). Submarine channel trajectories clearly demonstrate a two-phase evolution that results in a hockey-stick trajectory shape: (1) a phase of lateral migration (sometimes with degradation), followed by (2) a phase of increasing L_a (i.e., increasing aggradation).

When calculating M_{sl}, the height above the base of the channel belt (z in Fig. 1A) can be normalized to H, allowing us to plot M_{sl} against the number of ‘aggraded channel depths’ (Fig. 3B). A temporal trend of lateral migration ($M_{sl} >> 0$) followed by increasing vertical aggradation ($M_{sl} \geq 0$) is very robust for submarine channel belts (Fig. 3B).

Interestingly, the same trend is present for fluvial channel belts, albeit with 10× lower values of aggraded channel depths.

At the belt scale, submarine systems have much smaller values of M_{sb} than fluvial systems (Fig. 3C), with median values of 0.6 and 5.5, respectively. This order-of-magnitude difference indicates that during channel belt formation, submarine channels aggrade ~10x more than fluvial channels, resulting in a thicker, narrower channel belt (Fig. 2G) and thus lower M_{sb} values (Fig. 3C). If a submarine channel belt is evolving within larger-scale (i.e., canyon) confinement, this trend would be further exaggerated.

CONTROLS ON CHANNEL KINEMATICS

Why Do Submarine Channels Evolve from Lateral Migration to Aggradation?

The hockey-stick shape of channel trajectory (i.e., decreasing M_{sl} through time in Fig. 3B) is consistent with conceptual models of submarine channel evolution (e.g., Peakall et al., 2000; Deptuck et al., 2007; McHargue et al., 2011). However, this study is the first to quantify the trend with a global data set. Various mechanisms have been proposed to explain this evolution, including turbidity current flow properties (Kolla et al., 2007), progressive levee growth (Peakall et al., 2000), sediment supply versus accommodation (Kneller, 2003), and changes in equilibrium profile (Hodgson et al., 2011). Many studies invoke complex interactions between the above mechanisms. While we cannot exclude allogenic mechanisms, our data were collected over a range of tectonic settings, geologic-time intervals, and sediment supply regimes. Thus, we limit the present discussion to autogenic variables that must be present in every submarine channel system, regardless of tectonic setting or other allogenic controls.

We interpret that the flow properties unique to submarine channels are responsible for enhanced levee growth and the resultant aggradation. Flows in submarine channels have ~50× less density contrast between flow and ambient fluid than rivers (Imran et al., 1999), enhancing super-elevation of the flow around bends. This increases the potential for overspill and flow stripping, which result in overbank deposition and levee growth (Piper and Normark, 1983; Straub et al., 2008). In addition, the velocity maximum in the vertical profile of a characteristic submarine flow is located much closer to the bed relative to its fluvial counterpart (Sequeiros et al., 2010), such that overbanking has a lower potential shear stress. Combined, these factors promote levee growth and discourage avulsion.

For a submarine channel to maintain a constant cross-sectional area locally, there must be coupling such that the thalweg aggrades as the levees grow or vice versa (e.g., Imran et al., 1999). If either levee deposition (or thalweg deposition) occurs in isolation, the cross sectional area of the channel is perturbed, causing either flow expansion (or acceleration) (Exner equation, see Paola and Voller, 2005). This results in local deposition (or erosion) in the channel thalweg to return the cross sectional area to its original, equilibrium state. This depositional feedback results in aggradation of the entire channel belt. These processes are reflected in the high aggradational potential of submarine systems, which results in systematically thicker channel belts compared to fluvial systems and is reflected in larger values of H_{cb}/H (Fig. 2F). Dorrell et al. (2015) suggest that aggradational submarine channels are inherently unstable; we do not disagree, but argue that instability is a relative term and that submarine channels are much more stable under aggradational conditions than fluvial channels.

DOI:10.1130/G38158.1

Resultant Stratigraphic Architecture

Normalized channel belt dimensions allow us to plot channel belts of differing scale to assess their 'shape' and spatiotemporal evolution (Fig. 4A). The threshold separating the dominance of lateral accretion versus 'vertical accretion' (i.e., aggradation) can be described by the equation

$$\frac{B_{cb}}{H_{cb}} = \frac{\mathrm{B}}{H}. \qquad (4)$$

In cases where $B_{cb}/H_{cb} << B/H$, vertical accretion is the dominant form of stratigraphic preservation, and where $B_{cb}/H_{cb} >> B/H$, lateral accretion is dominant. Equation 4 is plotted as a line in Figure 4A. All fluvial systems plot below the threshold line (Fig. 4A), indicating that lateral accretion is the dominant kinematic form. 73% of submarine systems plot above the threshold, indicating that vertical accretion (i.e., aggradation) is dominant for the majority of submarine channel belts.

A schematic of the key differences in the evolution and channel belt dimensions of submarine and fluvial systems is presented in Figure 4B. Values of B_{cb}/B are variable for both submarine and fluvial systems, likely because B_{cb}/B is proportional to the belt maturity and floodplain erodability (cf. Sun et al., 1996). However, values of H_{cb}/H for submarine systems are commonly 2× and sometimes 10× larger than fluvial systems. The low stratigraphic mobility (M_s) and high aggradational potential of submarine channel belts promotes the preservation of sandy channel fills and muddy levee and overbank deposits (e.g., Jobe et al., 2015), while high M_s and low aggradational potential of fluvial channel belts results in the preservation of sandy point bars and muddy oxbow deposits (Fig. 1).

CONCLUSIONS

Fluvial and submarine channels have qualitatively similar planform patterns, but very different stratigraphic records. Fluvial channel belts are relatively thin and dominated by lateral migration deposits, while submarine channel belts are very thick and contain more vertical accretion (i.e., aggradational channel-fill) deposits. Using a global data set, this study describes the dimensions, kinematics, and stratigraphic mobility of submarine and fluvial channel belts. Both submarine and fluvial systems exhibit a two-phase evolution of the channel trajectory, a phase of lateral migration (sometimes with degradation) and a phase of increasing aggradation while lateral migration decreases. However, submarine channel belts are 2× thicker and have 10× smaller stratigraphic mobility numbers than their fluvial counterparts. The channel belt aspect ratio best describes this relationship, with median values for submarine and fluvial systems of 9 and 72, respectively. These results can be used to help interpret channelized stratigraphy on other planets and moons, where the distinction between fluvial and submarine deposition is often difficult. These data are collected from a range of tectonic settings and time intervals, suggesting that differences in channel kinematics and thus stratigraphic architecture in submarine channel systems are caused by flow properties of turbidity currents. We interpret that higher quantities of suspended sediment in upper portions of the flow and the position of the velocity maximum close to the bed cause enhanced levee development and thus aggradation of the channel belt.

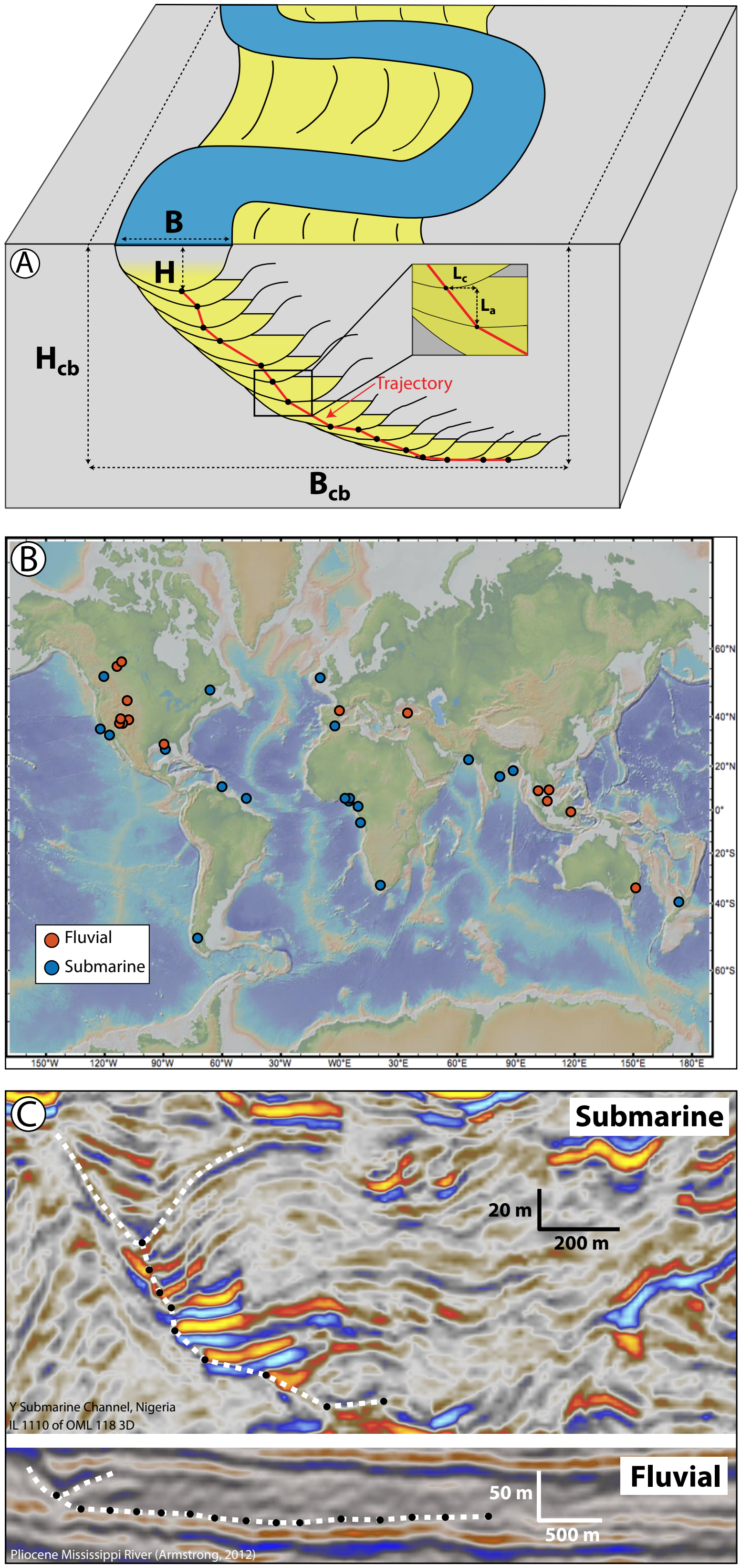
ACKNOWLEDGMENTS

The authors would like to thank Shell International Exploration and Production for permission to publish. David Mohrig, Kyle Straub, and Tim Demko provided

DOI:10.1130/G38158.1
insightful reviews that greatly improved the paper. Finally, this paper benefitted from discussions with Jake Covault, Steve Hubbard, and Brian Romans.

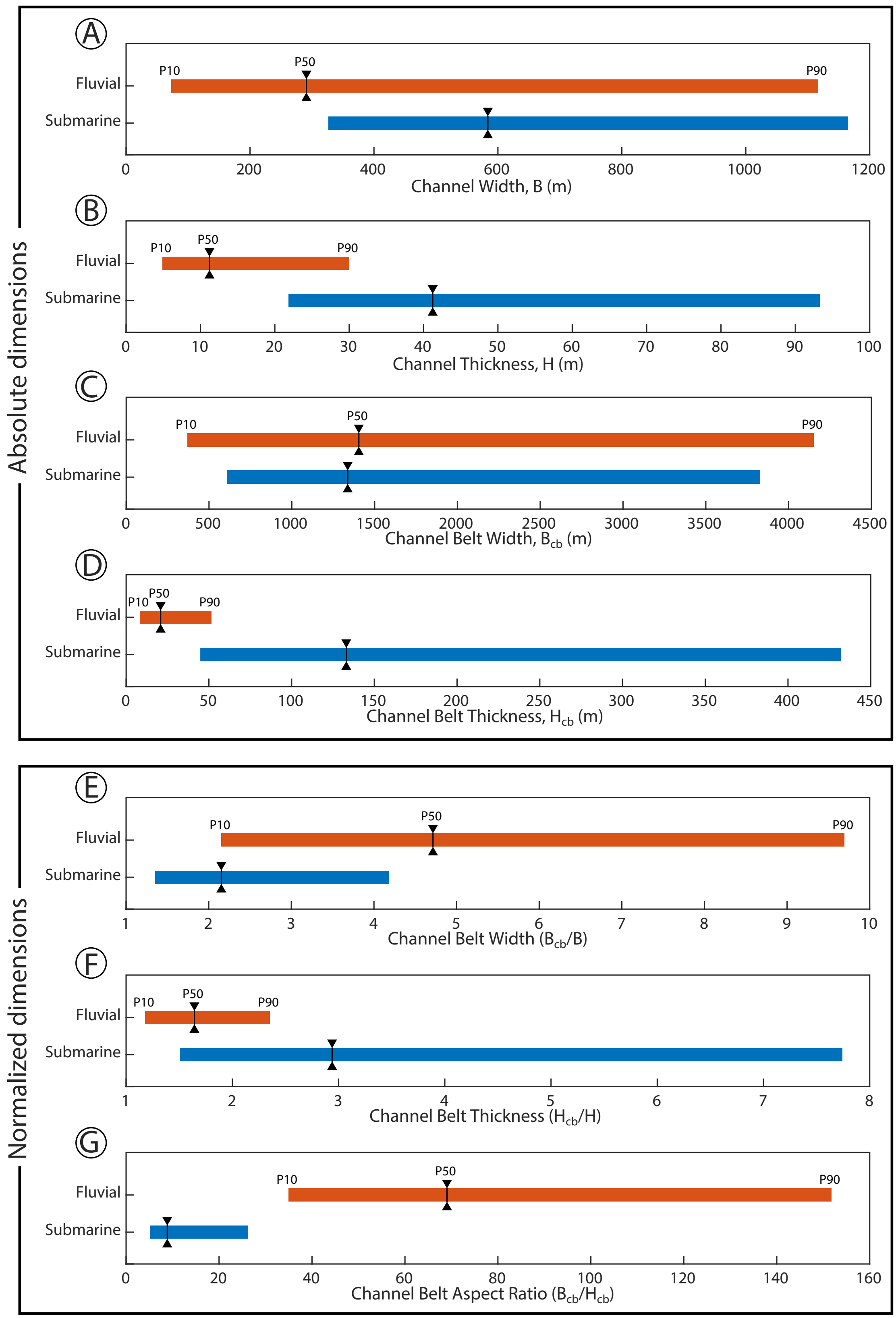
Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G38158.1

Figure 1. Kinematics of submarine and fluvial channels. A: Channel belt schematic. Local stratigraphic mobility M_{sl} is calculated using relative spatial displacements (L_c/L_a), while belt-averaged M_s (M_{sb}) is calculated using channel belt width and thickness aspect ratio B_{cb}/H_{cb}. B: Map of the data set utilized in this study, including 21 submarine and 13 fluvial systems. C: Typical submarine and fluvial channel belts with interpretation overlain. Submarine channels are more aggradational and thus have lower M_s values.



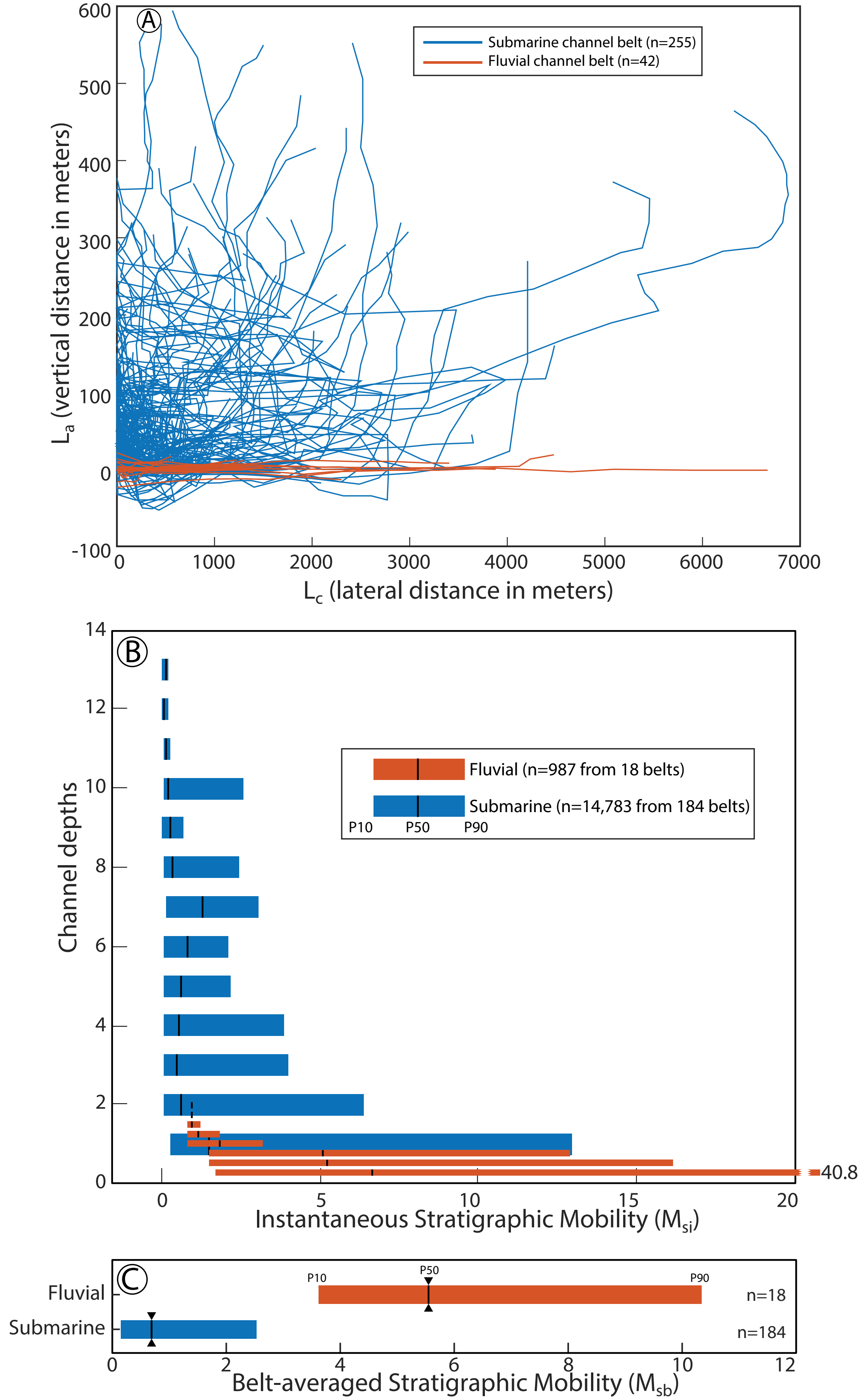
A
B
H
L_c
L_a
H_{cb}
Trajectory
B_{cb}
B
Fluvial
Submarine
C
Submarine
20 m
200 m
Y Submarine Channel, Nigeria
IL 1110 of OML 118 3D
Fluvial
50 m
500 m
Pliocene Mississippi River (Armstrong, 2012)

Figure 2. Absolute (A–D) and normalized (E–G) channel and channel belt dimensions. These data are summarized in the channel belt aspect ratio (G), where submarine channel belts are ~10× lower aspect (i.e., thick and narrow) as compared to fluvial channel belts.



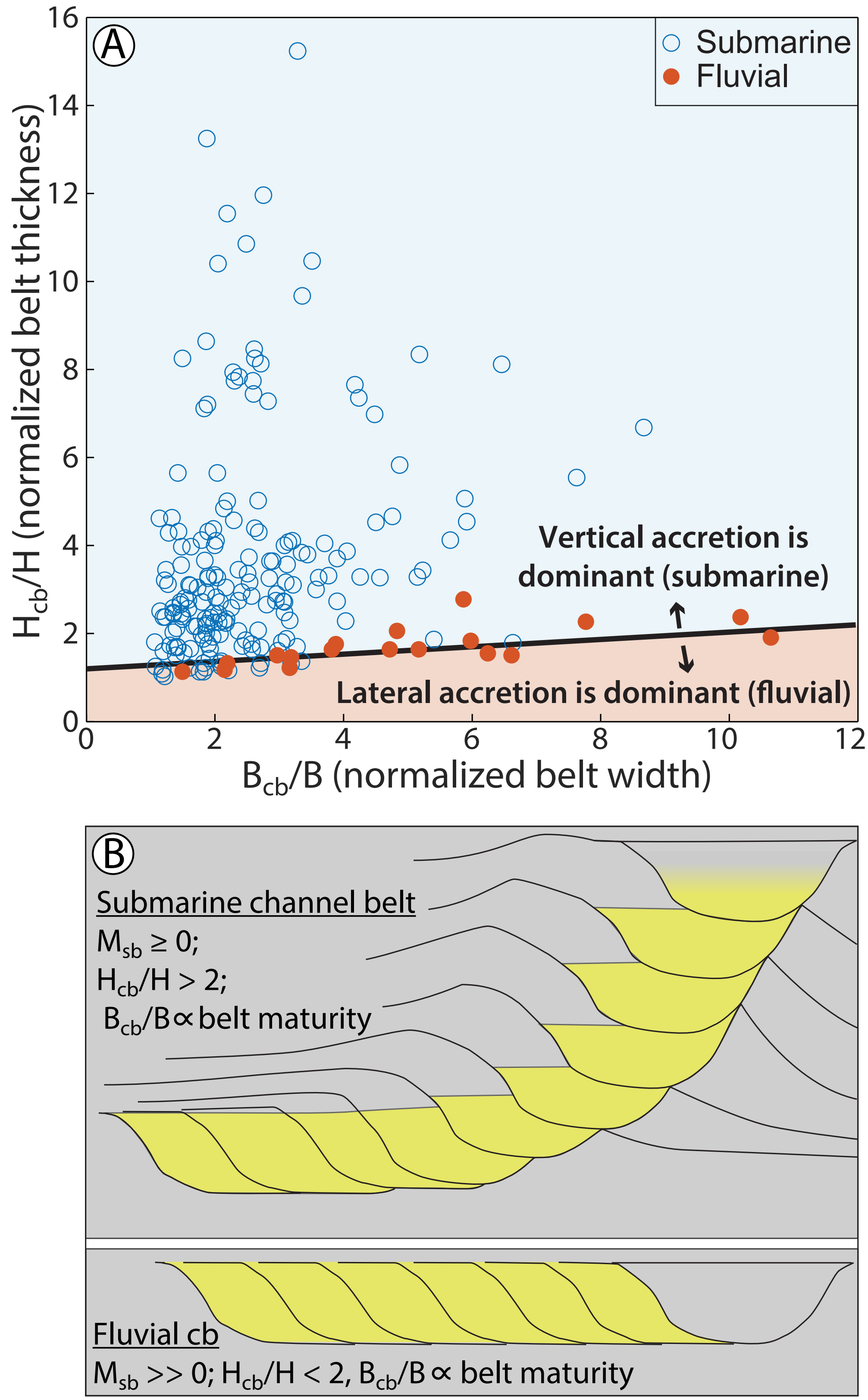
Absolute dimensions
A
Fluvial
Submarine
P10
P50
P90
0
200
400
600
800
1000
1200
Channel Width, B (m)
B
P10
P50
P90
0
10
20
30
40
50
60
70
80
90
100
Channel Thickness, H (m)
C
P10
P50
P90
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Channel Belt Width, B_{cb} (m)
D
P10
P50
P90
0
50
100
150
200
250
300
350
400
450
Channel Belt Thickness, H_{cb} (m)
Normalized dimensions
E
P10
P50
P90
1
2
3
4
5
6
7
8
9
10
Channel Belt Width (B_{cb}/B)
F
P10
P50
P90
1
2
3
4
5
6
7
8
Channel Belt Thickness (H_{cb}/H)
G
P10
P50
P90
0
20
40
60
80
100
120
140
160
Channel Belt Aspect Ratio (B_{cb}/H_{cb})

Figure 3. Stratigraphic trajectory and mobility measurements. A: Trajectories (i.e., kinematic paths) of submarine and fluvial channel belts. B: Plot of Local stratigraphic mobility M_{sl} versus the height above the channel-belt base (z) normalized by the channel thickness H. Submarine and fluvial channel belts have similar kinematic pathways, but submarine channels have ~10× more aggradation. C: Distribution of belt-averaged M_s (M_{sb}), with submarine systems displaying 10× lower values (i.e., less lateral migration and more aggradation) than fluvial systems.



A
Submarine channel belt (n=255)
Fluvial channel belt (n=42)
L_a (vertical distance in meters)
L_c (lateral distance in meters)
B
Fluvial (n=987 from 18 belts)
Submarine (n=14,783 from 184 belts)
P10
P50
P90
Channel depths
40.8
Instantaneous Stratigraphic Mobility (M_{si})
C
Fluvial
Submarine
P10
P50
P90
n=18
n=184
Belt-averaged Stratigraphic Mobility (M_{sb})

Figure 4. A: Normalized channel belt dimension cross-plot. Dashed line separates the dominance of lateral and vertical accretion deposits. Submarine channel belts are dominated by ‘vertical accretion’ rather than lateral accretion. B: Summary diagram of the stratigraphic architecture of submarine and fluvial channel belts.

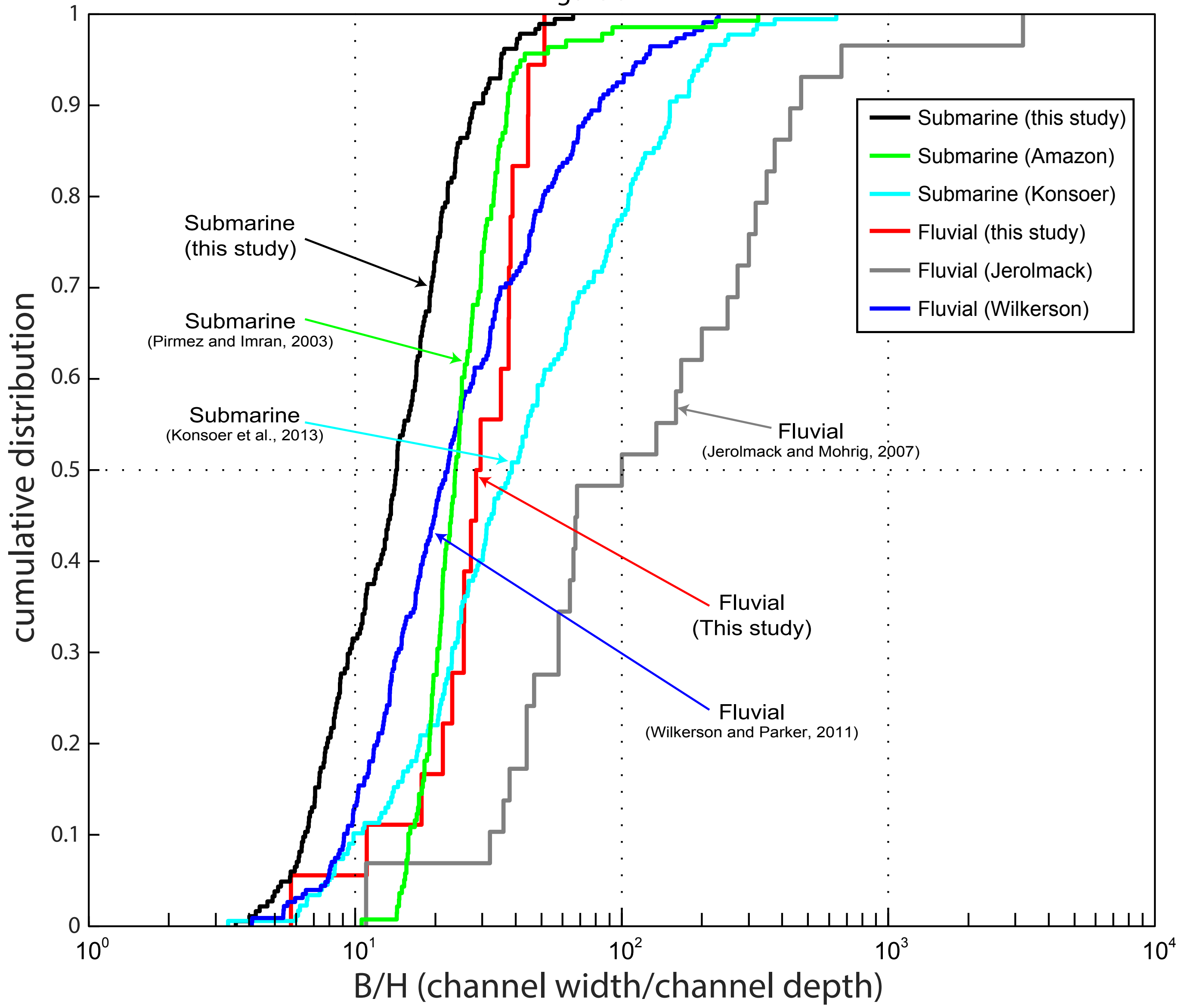


A
16
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12
Submarine
Fluvial
H_{cb}/H (normalized belt thickness)
B_{cb}/B (normalized belt width)
Vertical accretion is dominant (submarine)
Lateral accretion is dominant (fluvial)
B
Submarine channel belt
$M_{sb} \geq 0$;
$H_{cb}/H > 2$;
$B_{cb}/B \propto$ belt maturity
Fluvial cb
$M_{sb} >> 0$; $H_{cb}/H < 2$, $B_{cb}/B \propto$ belt maturity

DOI:10.1130/G38158.1

[1]GSA Data Repository item 2016xxx, data collection methodology and channel dimension data, is available online at http://www.geosociety.org/pubs/ft2016.htm or on request from editing@geosociety.org.

Figure S1


Submarine (this study)
Submarine (Amazon)
Submarine (Konsoer)
Fluvial (this study)
Fluvial (Jerolmack)
Fluvial (Wilkerson)
Submarine
(this study)
Submarine
(Pirmez and Imran, 2003)
Submarine
(Konsoer et al., 2013)
Fluvial
(Jerolmack and Mohrig, 2007)
Fluvial
(This study)
Fluvial
(Wilkerson and Parker, 2011)
cumulative distribution
B/H (channel width/channel depth)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10^0
10^1
10^2
10^3
10^4

REFERENCES CITED

Abreu, V., Sullivan, M., Pirmez, C., and Mohrig, D., 2003, Lateral accretion packages (LAPs): An important reservoir element in deep water sinuous channels: Marine and Petroleum Geology, v. 20, p. 631–648, doi:10.1016/j.marpetgeo.2003.08.003.

Allen, J.R.L., 1965, A Review of the Origin and Characteristics of Recent Alluvial Sediments: Sedimentology, v. 5, p. 89–191, doi:10.1111/j.1365-3091.1965.tb01561.x.

Deptuck, M.E., Sylvester, Z., Pirmez, C., and O'Byrne, C., 2007, Migration-aggradation history and 3-D seismic geomorphology of submarine channels in the Pleistocene Benin-major Canyon, western Niger Delta slope: Marine and Petroleum Geology, v. 24, p. 406–433, doi:10.1016/j.marpetgeo.2007.01.005.

Dorrell, R.M., Burns, A.D., and McCaffrey, W.D., 2015, The inherent instability of leveed seafloor channels: Geophysical Research Letters, v. 42, p. 4023–4031, doi:10.1002/2015GL063809.

Hodgson, D.M., Di Celma, C.N., Brunt, R.L., and Flint, S.S., 2011, Submarine slope degradation and aggradation and the stratigraphic evolution of channel-levee systems: Journal of the Geological Society, v. 168, p. 625–628, doi: 10.1144/0016-76492010-177.

Imran, J., Parker, G., and Pirmez, C., 1999, A nonlinear model of flow in meandering submarine and subaerial channels: Journal of Fluid Mechanics, v. 400, p. 295–331, doi:10.1017/S0022112099006515.

Jerolmack, D.J., and Mohrig, D., 2007, Conditions for branching in depositional rivers: Geology, v. 35, p. 463–466, doi:10.1130/G23308A.1.

Jobe, Z.R., Sylvester, Z., Parker, A.O., Howes, N., Slowey, N., and Pirmez, C., 2015, Rapid Adjustment of Submarine Channel Architecture to Changes in Sediment Supply: Journal of Sedimentary Research, v. 85, p. 729–753, doi:10.2110/jsr.2015.30.

Kneller, B., 2003, The influence of flow parameters on turbidite slope channel architecture: Marine and Petroleum Geology, v. 20, p. 901–910, doi:10.1016/j.marpetgeo.2003.03.001.

Kolla, V., Posamentier, H.W., and Wood, L.J., 2007, Deep-water and fluvial sinuous channels—Characteristics, similarities and dissimilarities, and modes of formation: Marine and Petroleum Geology, v. 24, p. 388–405, doi:10.1016/j.marpetgeo.2007.01.007.

Kolla, V., Bandyopadhyay, A., Gupta, P., Mukherjee, B., and Ramana, D.V., 2012, Morphology and internal structure of a recent upper Bengal fan-valley complex, *in* Prather, B.E., et al., eds., Application of the Principles of Seismic Geomorphology to Continental-Slope and Base-of-Slope Systems: Case Studies from Seafloor and Near-Seafloor Analogues: Society for Sedimentary Geology Special Publication 99, p. 347–369, doi:10.2110/pec.12.99.0347.

Macauley, R.V., and Hubbard, S.M., 2013, Slope channel sedimentary processes and stratigraphic stacking, Cretaceous Tres Pasos Formation slope system, Chilean Patagonia: Marine and Petroleum Geology, v. 41, p. 146–162, doi:10.1016/j.marpetgeo.2012.02.004.

McHargue, T., Pyrcz, M.J., Sullivan, M.D., Clark, J.D., Fildani, A., Romans, B.W., Covault, J.A., Levy, M., Posamentier, H.W., and Drinkwater, N.J., 2011, Architecture of turbidite channel systems on the continental slope: Patterns and predictions: Marine and Petroleum Geology, v. 28, p. 728–743, doi:10.1016/j.marpetgeo.2010.07.008.

Mohrig, D., Heller, P.L., and Paola, C., 2000, Interpreting avulsion process from ancient alluvial sequences: Guadalope-Matarranya system (northern Spain) and Wasatch Formation (western Colorado): Geological Society of America Bulletin, v. 112, p. 1787–1803, doi:10.1130/0016-7606(2000)112<1787:IAPFAA>2.0.CO;2.

Paola, C., and Voller, V.R., 2005, A generalized Exner equation for sediment mass balance: Journal of Geophysical Research, v. 110, F04014, 8 p.

Peakall, J., McCaffrey, B., and Kneller, B., 2000, A Process Model for the Evolution, Morphology, and Architecture of Sinuous Submarine Channels: Journal of Sedimentary Research, v. 70, p. 434–448, doi:10.1306/2DC4091C-0E47-11D7-8643000102C1865D.

Piper, D.J.W., and Normark, W.R., 1983, Turbidite depositional patterns and flow characteristics, Navy Submarine Fan, California Borderland: Sedimentology, v. 30, p. 681–694, doi:10.1111/j.1365-3091.1983.tb00702.x.

Sequeiros, O.E., Spinewine, B., Beaubouef, R.T., Sun, T., Garcia, M., and Parker, G., 2010, Characteristics of velocity and excess density profiles of saline underflows and turbidity currents flowing over a mobile bed: Journal of Hydraulic Engineering, v. 136, p. 412–433, doi:10.1061/(ASCE)HY.1943-7900.0000200.

Straub, K.M., Mohrig, D., McElroy, B., Buttles, J., and Pirmez, C., 2008, Interactions between turbidity currents and topography in aggrading sinuous submarine channels: A laboratory study: Geological Society of America Bulletin, v. 120, p. 368–385, doi:10.1130/B25983.1.

Sun, T., Meakin, P., Jøssang, T., and Schwarz, K., 1996, A Simulation Model for Meandering Rivers: Water Resources Research, v. 32, p. 2937–2954, doi:10.1029/96WR00998.

Sylvester, Z., Pirmez, C., and Cantelli, A., 2011, A model of submarine channel-levee evolution based on channel trajectories: Implications for stratigraphic architecture: Marine and Petroleum Geology, v. 28, p. 716–727, doi:10.1016/j.marpetgeo.2010.05.012.