LATITUDINAL CHANGES IN THE MORPHOLOGY OF SUBMARINE CHANNELS: REEVALUATING THE EVIDENCE FOR THE INFLUENCE OF THE CORIOLIS FORCE

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Abstract: Using a script that automatically calculates sinuosity and radius of curvature for multiple bends on sinuous channel centerlines, we have assembled a new data set that allows us to reevaluate the relationship between latitude and submarine channel sinuosity. Sinuosity measurements on hundreds of channel bends from nine modern systems suggest that there is no statistically significant relationship between latitudinal position and channel sinuosity. In addition, for the vast majority of submarine channels on Earth, using flow velocities that are needed to transport the coarse-grained sediment found in channel thalwegs, estimates of the curvature-based Rossby number are significantly larger than unity. In contrast, low flow velocities that characterize the upper parts of turbidity currents in submarine channels located at high latitudes can easily result in Rossby numbers of less than one; this is the reason why levee deposits are often highly asymmetric in such channels. However, even in channels with asymmetric levees, the sinuosity of the thalweg is often obvious and must have developed as the result of an instability driven by the centrifugal force. Analysis of a simple centerline-evolution model shows that the increase in channel curvature precedes the increase in sinuosity and that low sinuosities are already associated with large curvatures. This suggests that the Coriolis effect is unlikely to be responsible for the low sinuosities observed in certain systems.

Key words: submarine channels, Coriolis force, sinuosity, curvature

INTRODUCTION

Submarine channels are common—and often beautifully sinuous—geomorphic features of the Earth's seafloor that serve as important conduits of sediment transport from rivers and shallow water to the continental slope and basin floor. In addition to their role in the large-scale redistribution of clastic sediment, they often correspond to locations of thick and relatively coarse-grained accumulations that can host commercially significant hydrocarbon reservoirs. Ever since it was recognized that these features exist (Menard 1955) and that their planform patterns can be remarkably similar to the meandering shapes familiar from rivers (Damuth et al. 1983, Clark et al. 1992) the assumption has been that the relevant physical processes are fundamentally the same across the globe and, therefore, there is no need for facies and architecture models of submarine channels that are specific for different latitudes.

This line of thinking has been challenged by Peakall et al. (2011), who have looked at the relationship between submarine channel sinuosity and latitude and suggested that channels closer to the poles had lower peak sinuosities. They concluded that this is largely due to the Coriolis force having a stronger influence at high latitudes. Experimental work relying on a rotating flume tank showed that at low Rossby numbers (that is, when the Coriolis force is larger than the centrifugal force) turbidity currents do behave differently from the conventional model (Cossu and Wells 2010, 2012; Cossu et al. 2010). Building on these and similar experimental results, Cossu et al. (2015) proposed that channel systems of the Cretaceous Cerro Toro Formation, exposed in southern Chile and deposited at high paleo-latitude, display low sinuosity and an asymmetric stratigraphic structure due to the Coriolis effect.

In a comment on the Peakall et al. (2011) study, we have presented evidence that the apparent pole-ward decrease in submarine channel sinuosity is unrelated to the Coriolis force (Sylvester et al. 2013). In the present article we expand on these ideas and present additional analysis (1) of an improved and more consistent set of channel sinuosity measurements and (2) of the magnitude of different forces as a function of channel size and flow behavior. In addition, we briefly discuss the impact of the Coriolis effect on overbank deposits, which is an important latitudinal effect in these systems.

METHODS: MEASURING SINUOSITY AND RADIUS OF CURVATURE

To analyze the relationship between latitude and sinuosity, a relatively precise and reproducible measure of sinuosity is needed. To estimate the importance of the Coriolis force, we also need to calculate a characteristic radius of curvature for each channel bend. Although it is possible to collect these measurements one by one by analyzing each channel bend separately, this manual approach would be fairly time consuming, and the results would be difficult to check and replicate. To avoid these issues, we have written a Python script that takes the "x" and "y" coordinates of a channel centerline as inputs and calculates both sinuosity and radius of curvature for each bend. This methodology also ensures that we are comparing sinuosity and radius of curvature values that were derived in the same way for all channels. To perform the analysis and generate the figures, we have

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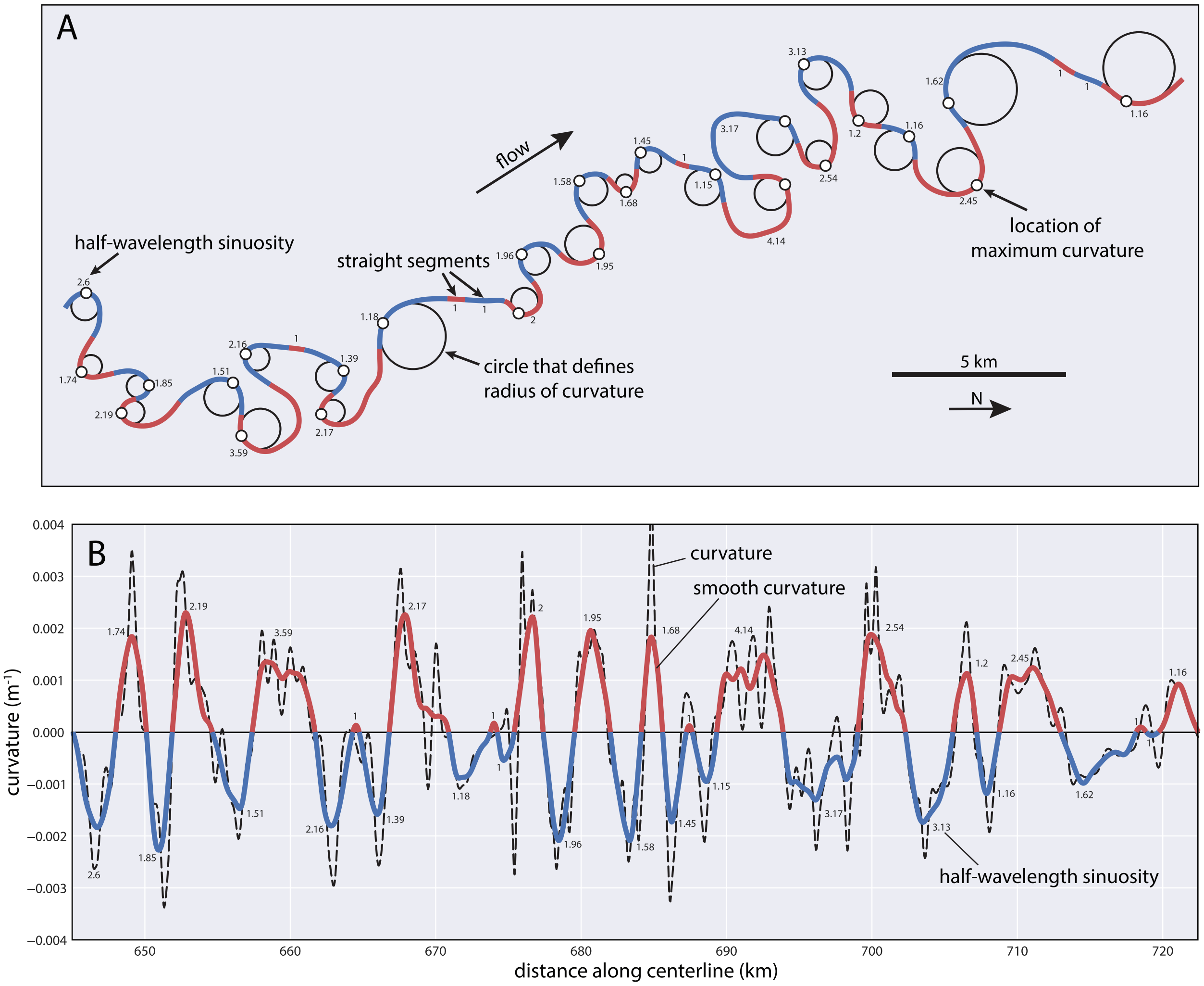

FIG. 1.—**A)** Example of a centerline segment from the Amazon Channel showing channel bends and fitted circles that define the radius of curvature. **B)** Raw and smoothed curvature calculated from the same centerline segment as in **A.** Red and blue segments correspond to channel bends with opposite signs of curvature.

used IPython (Jupyter) Notebook, an interactive notebook-like, open-source computing platform that is based on the Python programming language (Perez and Granger 2007).

The processing steps that are performed are as follows:

1. Resample the channel centerline so that its defining points are approximately equally spaced (50-m spacing). We used a parametric spline representation of the curve to do this.
2. Smooth the centerline using the Savitzky-Golay filter (Savitzky and Golay 1964). This filter is based on fitting successive sets of data points with a polynomial, using linear least squares. For our analysis, we used the *scipy* implementation of the algorithm and adopted a window length of 21 centerline points that were convolved with a third-order polynomial.
3. Calculate the curvature of the centerline and smooth it, using the same filter as in step 2. The number of points over which the smoothing is applied determines how many inflection points (points of zero curvature) will be found. To obtain consistent results, this window length has to scale with the channel, that is, the meander wavelength. We have used values between 11 and 201 points (550 to 10,050 m), depending on the scale of the channel, and a third-order polynomial.
4. Find inflection points and locations of maximum curvature. A strongly smoothed curvature function will result in fewer zero crossings of the function, fewer inflection points on the centerline, and a smaller number of channel bends.
5. Calculate half wavelengths, arc lengths, and sinuosity for each channel bend (= segment between two consecutive inflection points). Eliminate from further analysis straight channel segments with less than 1.01 sinuosity.
6. At each maximum curvature point, identify a centerline segment with a length of one-tenth of the average arc length. Using least-squares optimization, find a circle that matches these points best. One could also simply take the average curvature of the centerline at these locations to estimate the characteristic radius of curvature, but least-squares optimization allows us to quickly plot the corresponding circle and visually check the results (Fig. 1).

The methodology used here builds on the method developed by Pirmez (1994), which was in turn derived from Richards (1982), to

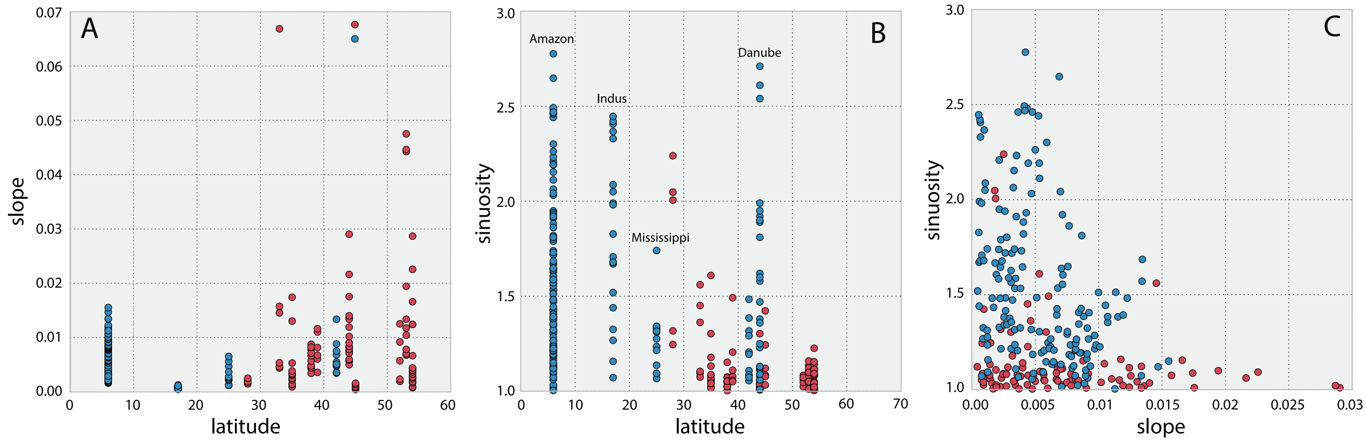

Fig. 2.—Plots of slope vs. latitude **(A),** sinuosity vs. latitude **(B),** and sinuosity vs. slope **(C).** Same data as in Sylvester et al. (2013); largely based on data in Clark and Pickering (1996), with the exception of data points for the Amazon and Danube systems. Blue dots correspond to channels that are directly related to large rivers; red dots represent channels that are not directly linked to large rivers.

quantify curvature and wavelength of the Amazon Channel. The minimum radius of curvature (which coincides with the location of maximum curvature) is not a representative value for calculating the centrifugal acceleration because it is sensitive to measurement errors and would give an underestimate of the radius (or an overestimate of curvature). On the other hand, using too many centerline points in this estimation results in a significant mismatch between the centerline and the fitted circles, plus an overestimation of the radius of curvature values. The radius of curvature (R) values obtained here are overall smaller than those calculated by Pirmez (1994) as a result of the fact that Pirmez (1994) used the entire segment between two inflection points in the calculation.

In contrast with Peakall et al. (2011), who have used only the peak sinuosity for each channel system, we have argued that all available measurements, not just the maximum values, should be used in such an analysis (Sylvester et al. 2013). This choice is justified by the fact that the forces we are interested in act on all channel bends, and a pole-ward decrease in sinuosity should be obvious not just in the extreme values of the sample distributions but in other measures of the upper range of the distributions as well.

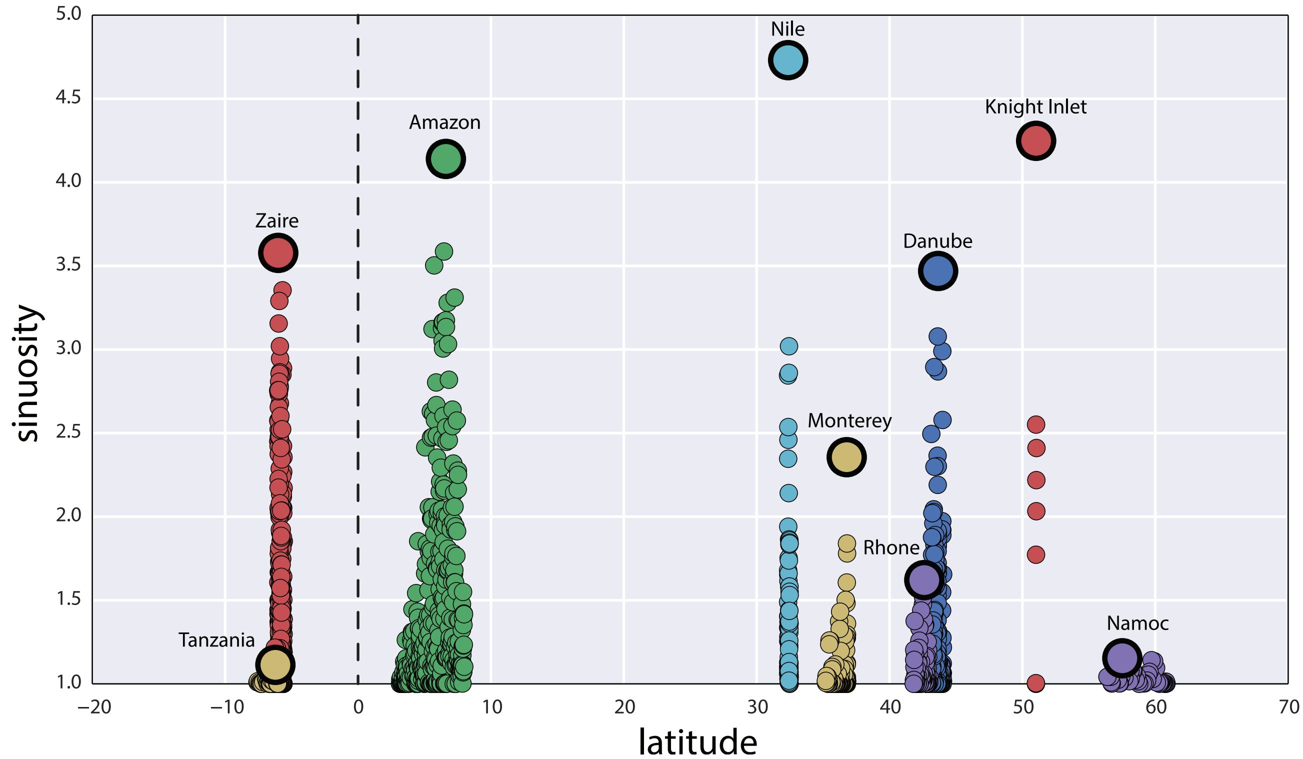

Fig. 3.—Plot of sinuosity vs. latitude, for all sinuosity values. Peak sinuosities are highlighted with larger circles.

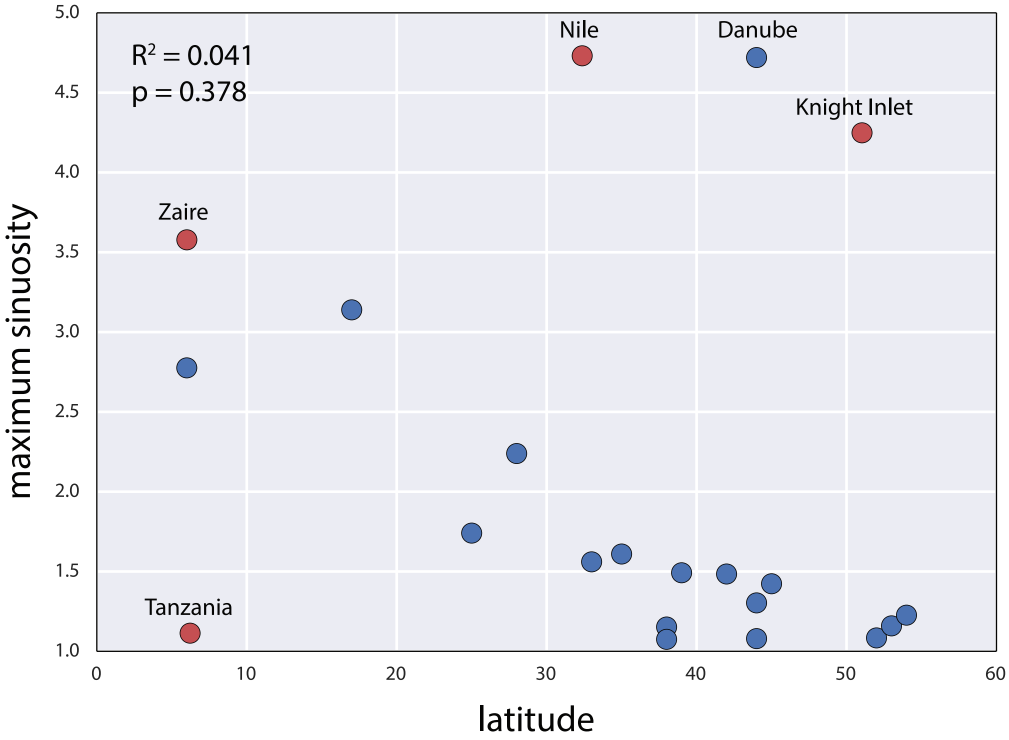

FIG. 4.—Scatterplot of peak sinuosities as a function of latitude. Red data points were added in this study (compared to Peakall et al. [2011] and Sylvester et al. [2013]).

The analysis shown in Sylvester et al. (2013) only includes new sinuosity measurements from the Danube Channel; the data for the rest of the systems come from Clark and Pickering (1996) and Pirmez (1994). The sinuosities were derived in three slightly different ways: for example, Pirmez (1994) used full wavelengths in the calculation, whereas Sylvester et al. (2013) worked with half wavelengths. Although the results should not be significantly different, for the present study we have made an effort to compare only sinuosities derived using the same scripted—and therefore fully reproducible—methodology, described above.

Using this methodology, we have digitized and analyzed channel centerlines from nine systems (Amazon—Pirmez 1994; Zaire—Babonneau et al. 2010; Danube—Popescu et al. 2001; Monterey—Fildani and Normark 2004, Paull et al. 2011; North-Atlantic Mid-Ocean Channel [NAMOC]—Klaucke et al. 1997; Knight Inlet—Conway et al. 2012; Rhone—Torres et al. 1997; Nile—Migeon et al. 2010; and Tanzania—Bourget et al. 2008). The sinuosity distributions are all strongly skewed, with lots of small values (close to 1.0), and much fewer values that are larger than 2.

Both the channel centerline data and the scripts used for analysis and plotting can be downloaded at the following data repository: https://github.com/zsylvester/channel_sinuosities.

ANALYSIS AND INTERPRETATION

Sinuosity–Latitude Relationship

For the sake of completeness, we reproduce here the results of our previous analysis of the sinuosity–latitude relationship (Fig. 2). Using sinuosity values for all channel bends, as opposed to relying on peak sinuosities, and after adding the Amazon and Danube channels to the Clark and Pickering (1996) data set, we have shown that—at least for those channels under consideration—both sinuosity and valley slope correlate with latitude (Sylvester et al. 2013). Thus, the impact of the Coriolis force is not the only possible explanation for the low sinuosities at high latitudes; it has been suggested before that, just like in the case of rivers, steeper valley gradients result in lower channel sinuosities (Clark et al. 1992, Pirmez 1994). Therefore, the pole-ward decrease in sinuosity in this data set is likely a reflection of the fact that many of the higher-latitude channels are steeper than the rest (Fig. 2A). We have suggested that this difference in gradient is primarily a reflection of the nature of the sediment source for the turbidite system (Sylvester et al. 2013): submarine channels that are fed by large rivers with high sediment discharge are located on extensive submarine fans or continental slopes with lower gradients, and these are the settings in which high-sinuosity channels tend to develop. Plotting only slope values for the bends with maximum sinuosities, Peakall et al. (2011) have essentially ruled out the possibility that slope might play a significant role in the sinuosity–latitude relationship that they have observed. Furthermore, relying only on the extreme values of the sample distributions reduces the robustness of the analysis, and our more inclusive approach does show an overall increase of valley slope with latitude, at least for the systems that were included in this initial, and still fairly limited, data set (Fig. 2A).

Additional insight about the latitude–sinuosity relationship can be gained if we look at the nine systems that we have analyzed for the present study. Plotting sinuosity against latitude (Fig. 3) shows no clear trend, not even for the peak sinuosities. High-sinuosity bends are present in the Nile, Danube, and Knight Inlet channels, despite the fact that these channels are all located at latitudes where the influence of the Coriolis force should be stronger. Similarly, low-sinuosity systems like the NAMOC are not restricted to high latitudes; the Tanzania Channel (Bourget et al. 2008) is located at latitudes similar to those of the highly sinuous Zaire Channel.

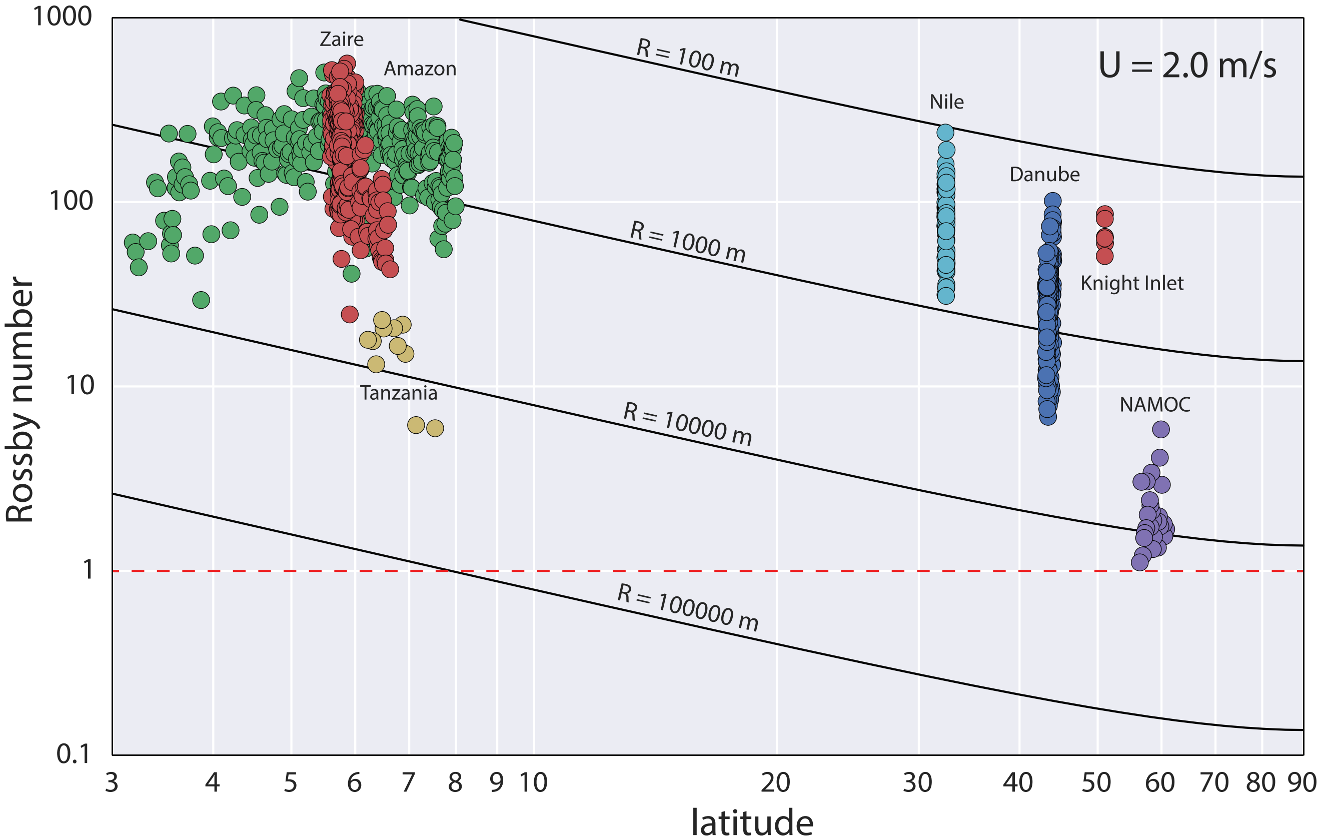

FIG. 5.—Estimates of the Rossby number for seven submarine channels, as a function of latitude, assuming a flow velocity of 2 m/s. Black lines are lines of equal radius of curvature.

This analysis does not include some of the systems that were looked at before; however, adding these systems would not change our conclusions about the lack of correlation between latitude and sinuosity. We have tested whether the combined data set of maximum sinuosities from the systems in Clark and Pickering (1996) plus the ones added in Sylvester et al. (2013) and in this study (Zaire, Danube, Knight Inlet, Nile, Tanzania) shows a robust latitude–sinuosity correlation. The resulting scatterplot suggests that there is no correlation (Fig. 4); the R^2 value for the linear regression is 0.041. In other words, only about 4% of the variance in the peak sinuosities might be caused by a latitudinal effect. More importantly, the large p-value (0.378) for the regression suggests that any apparent correlation is actually not statistically significant.

Estimation of the Impact of the Coriolis Force

The Coriolis force is an apparent force that affects objects or fluids moving within a rotating reference frame. In the case of planet Earth, particles moving on the northern hemisphere are pushed to the right, perpendicular to the direction of movement; the orientation of the force vector is to the left in the southern hemisphere. The magnitude of the Coriolis acceleration is given by

$$a_c = 2 \times \omega \times \sin(\phi) \times U, \tag{1}$$

where ω is Earth's angular rotation speed, ϕ is latitude, and U is the velocity of the particle. A particle that otherwise would move in a straight line is deflected and follows a circular trajectory, assuming that the effect of other forces is negligible.

In the case of a sinuous submarine channel, the particle in a channel bend is moving along a curved trajectory, characterized by a radius of curvature R. In a simplified view, we are interested in how the Coriolis force compares with the centrifugal force. The magnitude of the centrifugal acceleration is

$$a_{cf} = U^2/R. \tag{2}$$

The ratio between the centrifugal and Coriolis forces is the dimensionless Rossby number:

$$Ro_r = a_{cf}/a_c = U/(2 \times \omega \times \sin(\phi) \times R). \tag{3}$$

In this formulation of the Rossby number, we use radius of curvature as the length scale, as this is the parameter that determines the centrifugal force. A large value of the Rossby number means that the centrifugal force dominates; values of Ro_r below one describe situations in which the Coriolis force is larger than the centrifugal one. In theory, the Coriolis force would suppress the development of highly sinuous channel bends if it counteracted the centrifugal force, which is ultimately responsible for the instability leading to sinuosity development in submarine channels.

From a quick inspection of Eq. 3, it is clear that the Rossby number will tend to be smaller at higher latitudes, low flow velocities, and low curvature channel bends. In addition, taking into account that the angular rotation speed of the Earth is a relatively small number (7.29e-05 radians/s) and that flow velocities of turbidity currents are unlikely

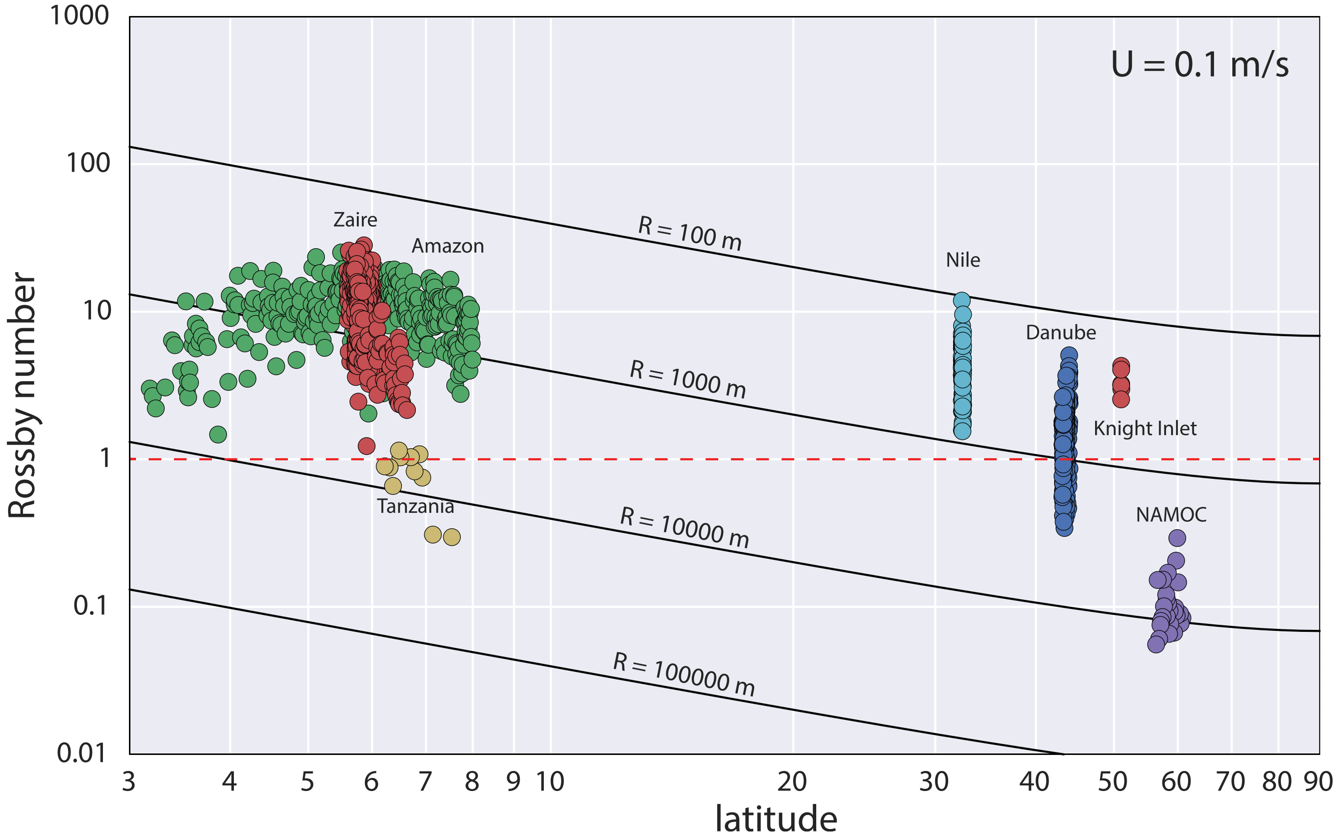

FIG. 6.—Estimates of the Rossby number for seven submarine channels, as a function of latitude, assuming a flow velocity of 0.1 m/s. Black lines are lines of equal radius of curvature.

to exceed ~20 m/s, the radius of curvature must be on the order of ~10 km in order to decrease the Rossby number enough so that the Coriolis force really matters.

To get a better idea of the typical ranges for Rossby numbers in submarine channels, we have estimated Ro_r for a large number of channel bends in seven channel systems: Amazon, Zaire, Tanzania, Nile, Danube, Knight Inlet, and NAMOC (Figs. 5, 6). To eliminate straight channel segments, we have only included channel bends with sinuosities larger than 1.01. Assuming a flow velocity of 2 m/s, a value that is likely to be characteristic of large channelized turbidity currents (Pirmez and Imran 2003), the results show that, with the exception of NAMOC, the Rossby numbers in these systems are all larger than 10 (Fig. 5). In the case of NAMOC, the Ro_r values are less than 10 but larger than 1. However, while a flow velocity of 2 m/s is a good estimate of turbidity current speeds in the Amazon Channel (Pirmez and Imran 2003), where sand-sized grains dominate the channel thalweg, it is likely an underestimate of the current velocities at the bottom of the NAMOC, where gravel is not uncommon (Klaucke et al. 1997). Assuming flow velocities of 6.5 to 8 m/s for the lower part of the flow, as suggested by Klaucke et al. (1997), the Rossby number increases about fourfold for the NAMOC bends as well.

An obvious way to reduce the Rossby numbers is to consider much lower flow velocities. At 0.1 m/s, most channel bends of the NAMOC and Tanzania channels, and a significant proportion of the Danube data points, fall below the $Ro_r = 1$ threshold (Fig. 6); for the Amazon and Zaire data points, the centrifugal force is still about an order of magnitude larger than the Coriolis force. Although flows with such low velocities would not be able to transport most of the sediment that characterizes the active channel thalwegs in virtually all systems, current speeds of a few centimeters per second are probably common in the upper, more dilute, much finer-grained parts of the flows (Cooper et al. 2013). The below-unity Rossby numbers for the Danube and NAMOC channels are consistent with the observation that levees are strongly asymmetric in both systems (Klaucke et al. 1998, Popescu et al. 2001). The asymmetry of submarine levees at higher latitudes has long been recognized in other systems as well (Komar 1969, Carter and Carter 1988).

In summary, for the bottom-hugging parts of turbidity currents flowing in submarine channels that cover a wide range of latitudes and channel dimensions, the centrifugal force is at least an order of magnitude larger than the Coriolis force. Therefore, it is unlikely that the latter is responsible for the low sinuosity of some high-latitude channels.

DISCUSSION

If we revisit Eq. 3, the expression of the Rossby number, we can see that the radius of curvature has a much larger impact on the value of Ro_r than latitude. Going from a latitude of 20° to the pole results in only a threefold decrease in the Rossby number, but radius of curvature in submarine channels can cover several orders of magnitude (from ~100 m to tens of kilometers), and Ro_r is a hundred times smaller in the case of a channel bend with $R = 10$ km compared to one with $R = 100$ m.

In other words, for channels at high latitudes, the overall size of the channel is more important for determining the impact of the

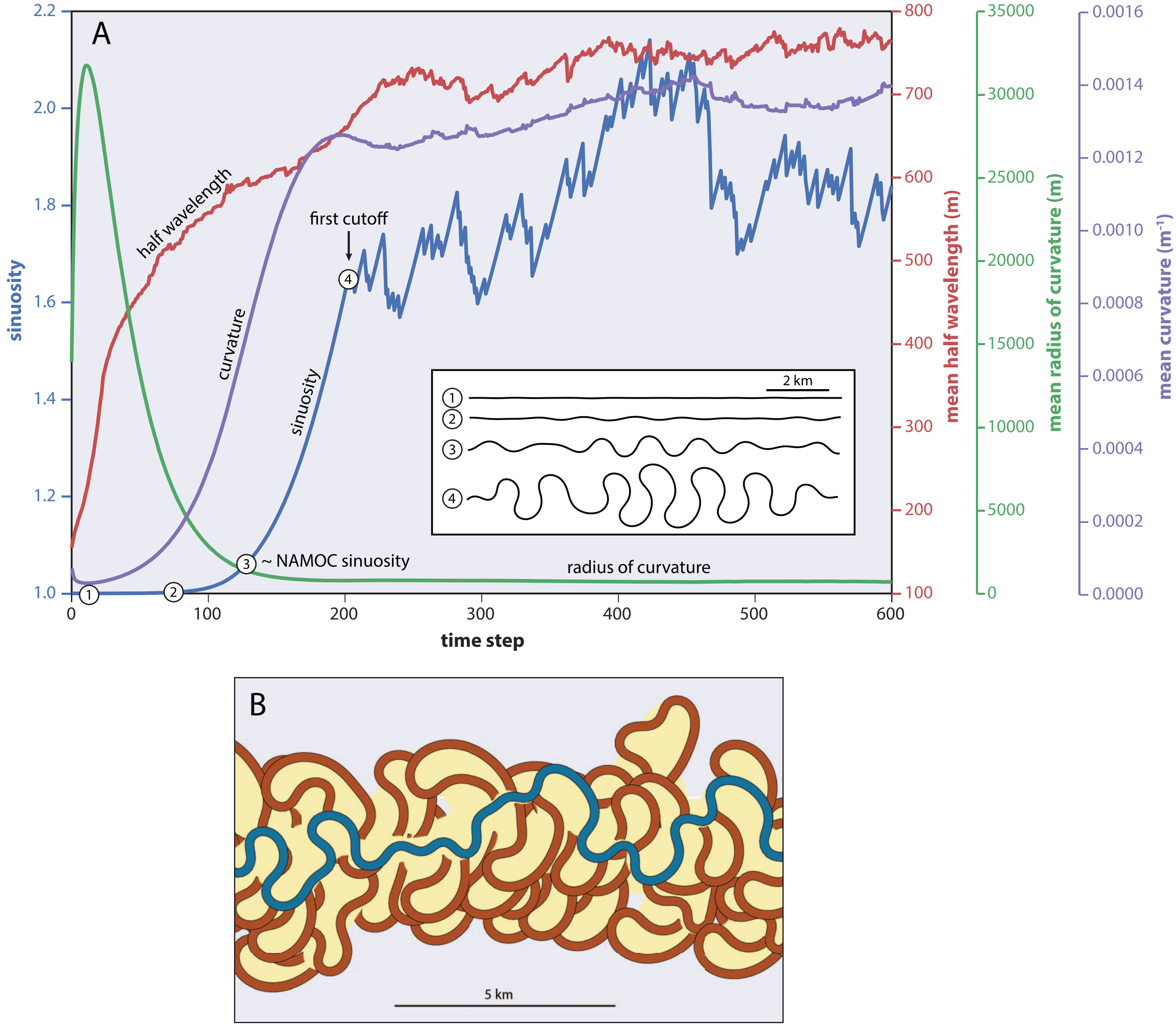

FIG. 7.—**A)** Sinuosity, half wavelength, mean radius of curvature, and mean curvature through time in an implementation of the Howard and Knutson (1984) model. Inset shows how the centerline looks at four different stages of the early evolution of the channel. **B)** Detail of the simulation output that was used to derive the data in **A.**

Coriolis force than the precise latitudinal position. As is the case for rivers, both radiuses of curvature and meander wavelengths of sinuous submarine channels correlate with channel widths (Pirmez and Imran 2003); the average radius of curvature is a measure of the scale of the channel system and of the typical flows that have carved and built the channel. Peakall et al. (2013) have suggested that "as bend sinuosity decreases with latitude, radius of curvature increases." However, low sinuosity does not necessarily imply a large radius of curvature. To better understand the relationship between sinuosity development and changes in radius of curvature, we have used an implementation of the Howard and Knutson (1984) curvature-based centerline model and briefly discuss the results here.

As in all centerline evolution models, the first centerline is a straight line, with some noise added. Initial curvature values of the noisy centerline are large (and, therefore, the mean radius of curvature is small), but they decrease as the centerline gets smoother and a characteristic wavelength is being established. A peak value of R is reached early on and then the radius of curvature declines rapidly (Fig. 7). The increase in sinuosity lags behind the increase in curvature, so that there is barely any departure from a straight line during the early phase of high values of R (Fig. 7A). If the Coriolis effect was suppressing the development of sinuosity, this phase of large radiuses of curvature would represent the time period during which the Coriolis force could and should limit the development of the instability that leads to meandering. However, our numerical simulations suggest that

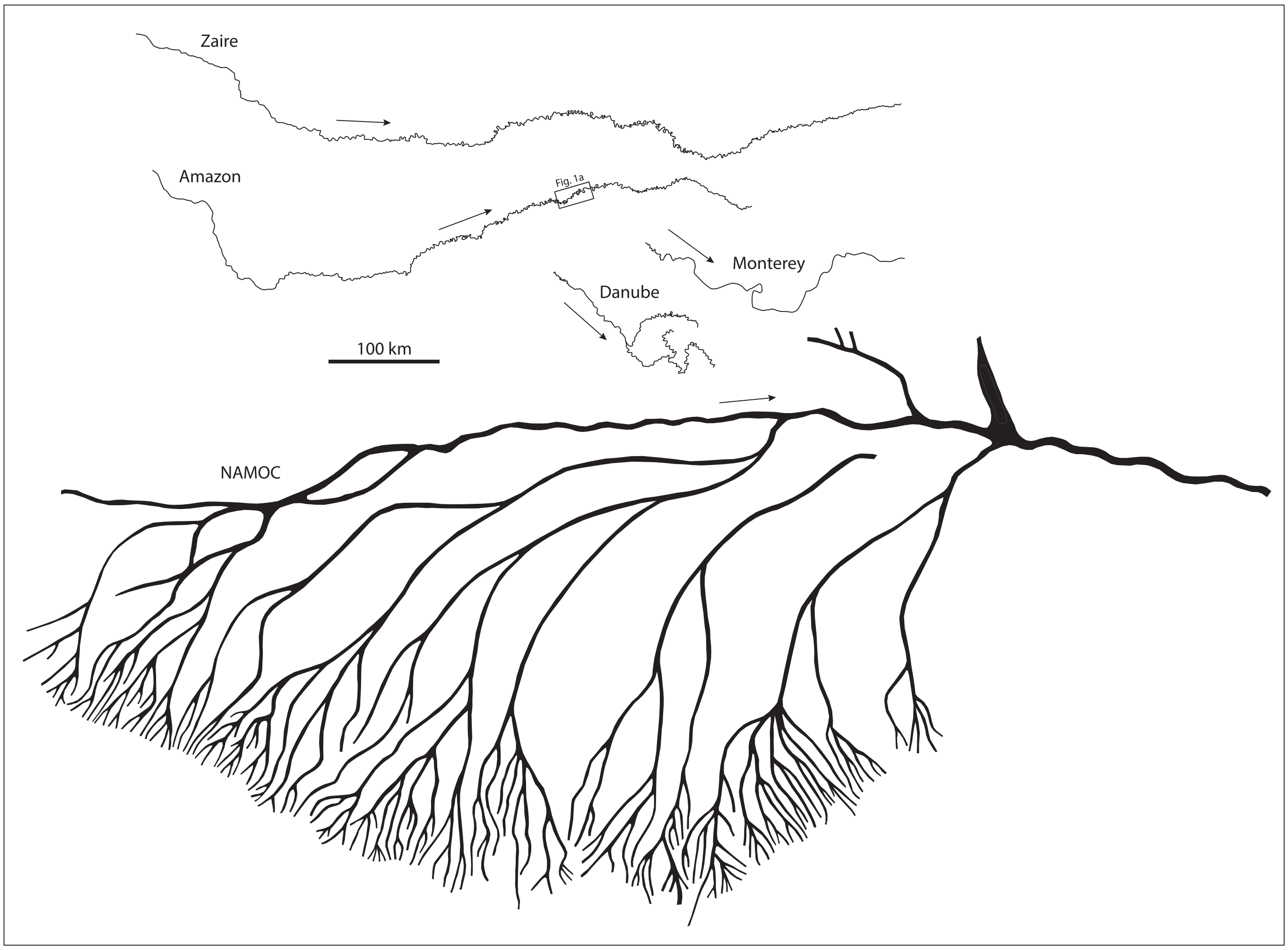

FIG. 8.—Plotting a selection of submarine channels at the same scale shows how much larger the NAMOC system is than any of the other systems.

by the time the centerline has a visually noticeable sinuosity, curvature values have increased significantly and the radius of curvature has dropped to a value that remains characteristic for the system for the rest of its evolution (Fig. 7A). A similar early phase of low curvature values that rapidly transitions to larger curvatures characteristic of the sinuous channel has been documented using other, more sophisticated numerical models as well (Camporeale et al. 2005).

The implication of this analysis is that channels with low but clearly visible sinuosity are likely to have already established a characteristic radius of curvature that is not going to significantly decrease any further. More sinuous stretches of the NAMOC have an overall sinuosity of $\sim$1.06, a value high enough to suggest that this system is past its early phase, characterized by small curvatures (Fig. 7A). In other words, the NAMOC has large values of R because it is a large system, not because of its low sinuosity. The presence of an obvious sinuosity is evidence for an inertial instability in the first place; as Klaucke et al. (1997) have stated in their study of the NAMOC, "in general, the thalweg appears to be located on the outside of meander bends, which demonstrates the predominant effect of the centrifugal force on the lowest and fastest parts of the flows."

Thus, the low sinuosity of very large channels like the NAMOC and Tanzania is unlikely to be caused by the Coriolis effect. Both of these systems reflect important differences compared to the highly sinuous channels that are more or less directly linked to their feeding rivers/deltas: (1) they are about an order of magnitude larger than even the largest "typical" submarine channel (Fig. 8); and (2) they are fed by a tributary channel system, as opposed to the typical avulsion-related distributary channel pattern characteristic of channels on submarine fans.

Instead of comparing low-latitude channels fed by large rivers to high-latitude, often steeper systems that are not directly linked to rivers and their deltas, it is more insightful to compare systems that have many characteristics in common but are situated at different latitudes. The best candidate in this regard is the Danube Channel, located at 43 to 44°N, fed by the Danube River, and sharing many similarities with large submarine channels close to the Equator. The most interesting feature of the Danube submarine fan is that the channels are highly sinuous, yet the levees display a strong asymmetry that is clearly driven by the Coriolis effect (Popescu et al. 2001). This suggests that a turbidity current can be strongly influenced by the centrifugal force in its lower, faster, coarser-grained part while the upper, slower, and finer-grained layer is pushed preferentially to one side by the Coriolis force. In addition to the velocity differences, the geomorphology of many leveed submarine channels is likely to further

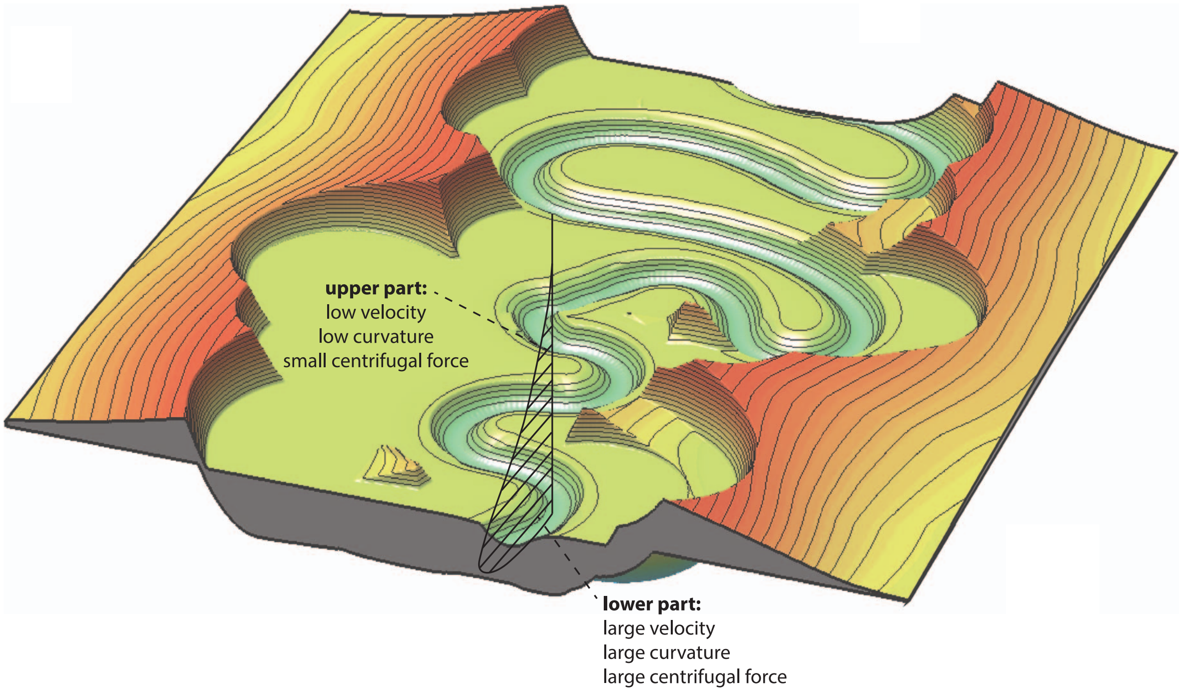

FIG. 9.—Three-dimensional model of typical leveed submarine channel morphology. The lower part of the flow is faster and following a more sinuous path than the upper part. Modified from Sylvester et al. (2011).

contribute to this effect: the lower part of the flow goes through channel bends with large curvatures, while the upper part follows a much straighter path, often only partly confined by the levees, with lower sinuosity and large values of R (Fig. 9).

The levee asymmetry of the channels on the Danube Fan also influences the large-scale stratigraphic architecture of the system. As a result of the taller and wider right-side levees, avulsions preferentially occur on the left side (Popescu et al. 2001); this results in the asymmetric overall structure of the Danube Fan, as most of the deposition—and certainly most of the sand deposition—takes place on the northern side of the initial channel levee system.

Peakall et al. (2013) have suggested that there was a cutoff for high-sinuosity channels at 50° latitude; according to this view, this cutoff would explain why some high-sinuosity channels like the Danube and Knight Inlet still occur at latitudes less than or close to 50°. We see no particular reason for a step change in the Coriolis effect at 50° latitude. For the same velocity and radius of curvature, the Rossby number decreases rapidly at low latitudes and then stays almost constant at latitudes higher than $\sim$50° (Fig. 10).

One of the potential reasons why sinuous submarine channels are uncommon on the modern seafloor at higher latitudes is the lack of large sources of significant sediment input into the deep sea. The low gradient systems with the highest-sinuosity channels (e.g., Amazon, Zaire, Indus, Bengal, Danube) are all directly linked to a large fluvial sediment source. Most of the larger rivers that drain Asia and North America into the Arctic Ocean (e.g., Kolyma, Indigirka, Lena, Yenisei, Ob) have relatively low sediment discharges (Milliman and Farnsworth 2011), and, under the present-day conditions with high sea level, most of the limited amount of sediment that reaches the sea never gets to the shelf edge. An exception is the Mackenzie Delta, where thick accumulations of deep-water clastic sediments are known from the subsurface (e.g., Bergquist et al. 2004). The analysis and arguments presented here suggest that such settings, with their high sediment supply, low gradients, and relatively long continental slopes, are favorable for the development of highly sinuous submarine channels, regardless of their latitude.

CONCLUSIONS

A new look at a number of submarine channels, using an automated workflow for calculating sinuosity and curvature, suggests that there is no robust relationship between submarine channel sinuosity and latitude. The apparent correlation between peak sinuosity and latitude for a certain set of channels (Peakall et al. 2011, Wells and Cossu 2013) becomes statistically insignificant if more data points are added.

The Coriolis force is a weak force that becomes important only at large scales: assuming a flow velocity of 2 m/s, the Coriolis force exceeds the centrifugal force in the lower, channel-shaping parts of the flow only in very large channel bends, those with a radius of curvature larger than $\sim$10,000 m. The vast majority of submarine channels on Earth do not reach these dimensions. Decreasing velocities tilt the force balance in favor of Coriolis, even in smaller systems, and, as a result, the upper, more dilute and slower layers of turbidity currents are more likely to be affected by the Coriolis effect, even at relatively low latitudes.

Analysis of sinuosity development using a simple centerline-evolution model shows that the initial low-curvature phase—during which the curvature-based Rossby number must be small—corresponds to extremely low sinuosities, and by the time there is a visible undulation in the centerline, the mean radius of curvature has dropped significantly (Fig. 7). Channels with low but clearly visible sinuosity are likely to have established a characteristic radius of curvature early on, which is not going to significantly decrease any further.

The Coriolis-driven asymmetry in levee height is well documented in large systems located at higher latitudes. Unequal levee heights can occur in systems with high overall sinuosities, suggesting that strong

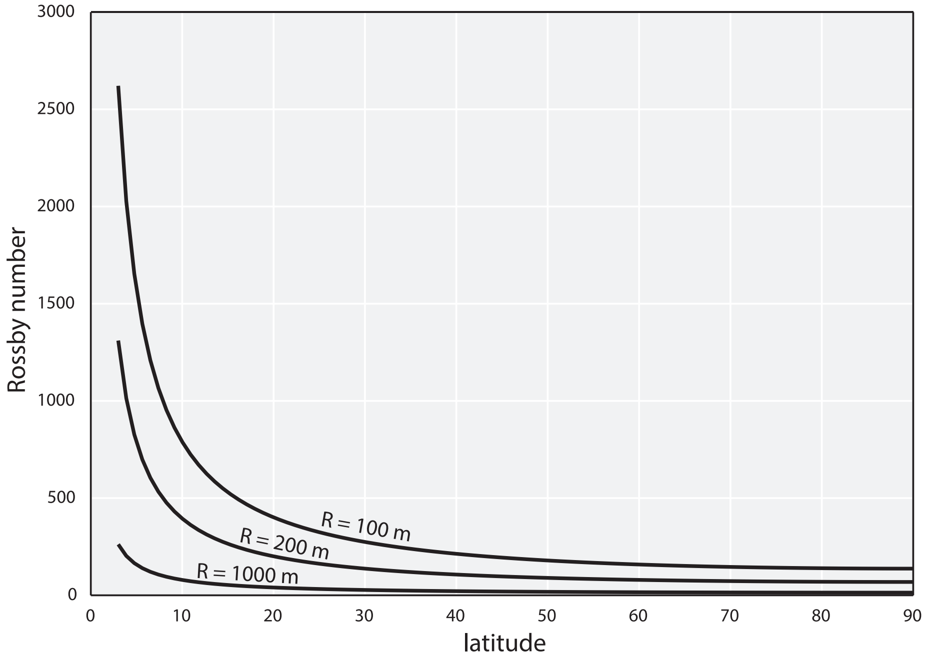

FIG. 10.—The variation of Rossby number as a function of latitude, for a flow velocity of 2 m/s and three values of the radius of curvature.

Coriolis effects in the upper part of the flow can accompany a faster lower part that is dominated by centrifugal forces. This phenomenon is enhanced by differences in flow behavior: large curvatures associated with the sinuous thalweg characterize the lower part, whereas centrifugal accelerations are small in the upper part that tends not to strictly follow the underlying sinuous pattern. Channels of the Danube Fan are good examples of such systems: they are highly sinuous yet show a strong levee asymmetry. The increased levee height on the right channel banks of the Danube Channel results in preferential avulsion on the low-levee side to the left; in the long term, this leads to a characteristic large-scale channel pattern that might be possible to recognize in ancient systems.

Even in large high-latitude systems, patterns of erosion and deposition and the direction of channel migration alternate from one channel bend to the other and are consistent with an instability-driven channel evolution model. Although it is possible that the Coriolis force plays a role in limiting bend growth in a few very large systems, in the majority of submarine channels this force is unlikely to strongly affect the higher-density, faster-moving lower parts of gravity flows, which are driving the development of sinuosity.

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