A faithful record of channel mouth bifurcation angles in river delta stratigraphy on Earth and Mars

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ABSTRACT

Which geomorphologic features of sedimentary systems persist into the stratigraphic record? In modern river deltas, channel mouth bifurcation angles have been shown to be consistent with network growth in a Laplacian flow field proximal to the channel margins. This results in a characteristic bifurcation angle of 72°. However, the persistence of this formative angle through channel evolution and preservation into the stratigraphic record remains untested. Stratigraphic river delta channel mouth bifurcations were measured using stratal slices from 3D seismic as well as Mars HiRISE orbital imagery. We find that channel mouth bifurcations interpreted from terrestrial strata exhibit a mean angle of 72.8° ± 4.1° (95% confidence interval) and those from martian strata exhibit a mean angle of 73.9° ± 6.0°. This is both consistent with theory and with observations from modern river deltas, implying the persistence of this geometry throughout network evolution and preservation, and may therefore be used as a predictive tool. The consistency between terrestrial and martian bifurcation geometry shows the generality of process between planetary systems, independent of differences in gravitational acceleration.

Keywords

delta, stratigraphy, geomorphology, Mars, surface processes

INTRODUCTION

Prograding river deltas develop distributary channel networks exhibiting islands and bifurcating channels, and their associated deposits form one of the principle components of delta stratigraphy. Understanding morphologic properties of emergent channel networks has been the subject of significant recent work (e.g. Edmonds et al. 2011). It has been shown that the bifurcation angle in tributary river channels is predictable due to the Laplacian (diffusive) groundwater flow field in close proximity to the channels and centers about a mean angle of $2\pi/5$ or 72° (with significant variance) in environments with gaining groundwater fields (Devauchelle et al., 2012, Seybold et al., 2017). Recently, measurements of field data and experiments have also found that the same basic physics applies. In the distributary delta case, the theoretical angle applies when channels are hydraulically connected along their margins to shallow interdistributary bays where surface water flow is friction-dominated and well approximated by diffusion (the Laplace equation; Rinaldo et al., 1999; Coffey and Shaw, 2017). In experiments, the mean angle varies over time but remains consistent with the theoretical prediction of 72°. While the presence of this critical angle has been confirmed in modern deltas it is unknown whether it persists through network growth, evolution, abandonment, and ultimately preservation into the stratigraphic record.

The stratigraphic record is awash with deposits of distributary channel networks and provides a rich dataset spanning geologic timescales (e.g. Fisher and McGowan, 1967; Zeng et al., 2001; Payenberg et al., 2003; Zeng et al., 2015; see Figure 1a). Ancient deltaic deposits have also been interpreted on Mars (e.g. Ori et al., 2000; Mangold and Ansan, 2006; Wood, 2006; see Figure 1b). If predictable bifurcation angles are preserved in the stratigraphic record, they provide a potential tool for improving stratigraphic interpretation and prediction. However, it is unclear that channel mouth bifurcations have similar angles to their modern counterparts. Coffey and Shaw (2017) used experiments to show that bifurcation angles remained consistent with 72° for up to half the time required to fill the channel network with incoming sediment, but the timescales associated with network formation could be far longer. It has been noted that the Wax Lake Delta, in coastal Louisiana, has a network of channels that has changed slowly over 18 years (Shaw et al. 2013). However, it is also unclear what changes might occur to a network as it is abandoned due to an upstream avulsion.

Determination of bifurcation angles from stratigraphic archives may serve to inform the potential for long timescale persistence of this characteristic angle. In addition, measurement of bifurcation angles using stratigraphic archives of another planet (Mars) can yield insights into the universality of the proposed theory of Coffey and Shaw (2017) and further test the long timescale persistence of bifurcations in systems radically different from modern terrestrial river deltas (e.g. gravitational acceleration, sediment density and caliber, vegetation). Stratigraphic evaluation of theory regarding expected distributary channel mouth bifurcation angles similarly has potential to inform petroleum exploration and reservoir modeling. Prediction of downstream behavior of channel sand bodies can be better informed and reservoir models can be trained to this expected morphology.

METHODS

To test hypotheses of long timescale persistence of predicted delta channel mouth bifurcation geometries, we measured the angle of interpreted channel mouth bifurcations preserved in seismic volumes and imagery of Mars stratigraphy. The identification and interpretation of channel mouth bifurcations is a non-trivial task; the distinction between channel mouth bifurcations and channel avulsions is not easily made in the stratigraphic record (Olariu and Bhattacharya, 2006; Li and Bhattacharya, 2014). Channel avulsions do not form in an environment where channels are coupled to Laplacian, non-channelized flow outside the network itself, so we seek to consider only channel mouth bifurcations in this study. We relied on three criteria to interpret channel mouth bifurcations. First, we selected bifurcations which were at distal portions of the deltas. Second, we require that a branching node is strongly distributary, and the channels do not rejoin downstream. Third, at the node, channels must exist to be in the same story. This distinction was particularly apparent on Mars, where topographic changes were evident due to shadowing.

Data for distributary networks in terrestrial strata were compiled from published sources of 3D seismic data from distributary channel strata (data from Zeng et al., 2001; Hart, 2008; Zheng et al., 2012, 2013; Hao et al., 2014; Li et al., 2016; Dong et al., 2017). The strata analyzed are interpreted predominantly as shallow progradational river delta systems in both marine and lacustrine basins. The seismic attribute and method of data processing varied between individual sources and are described in the data repository (see Supplementary Materials[1]). 89 bifurcations were measured from 9 separate seismic data sets.

A sample set was also compiled of martian deltas using publically available imagery collected by the HiRISE camera on the Mars Reconnaissance Orbiter (NASA/JPL/University of

Arizona). Deltas with recognizable distributary networks previously identified at Eberswalde Crater (see Wood, 2006), in the Aeolis Dorsa region (see DiBiase et al., 2013), and a small delta at 8.53° N, 48.01° W (see Goudge et al., 2012) were used in our analysis. 37 individual bifurcations were measured from these three localities.

Angles were measured using the methods of Coffey and Shaw (2017): by selecting the apex and channel margins of the two daughter channels along the inside of the bifurcation (see Figure 2). The 72° bifurcation angle was only apparent in modern deltas when the bifurcation angle was measured over length-scales approximately equal to one upstream channel width. Upstream channel width was not typically apparent in stratigraphic data, and visible channel margins in the downstream were often incomplete, limiting our ability to measure at locations exactly 1 parent channel width downstream from the apex; however, we did our best to measure over an approximately similar scale to that of the channel widths wherever possible.

We seek to compare the mean of channel mouth bifurcation angle preserved in stratigraphy to the theoretically predicted angle of bifurcation (72°). Monte Carlo simulations were conducted to account for both a limited number of samples and uncertainty in each measurement (after Rubenstein and Kroese, 2016). At each bifurcation an envelope of possible angles was defined between a measured minimum and maximum value (see Figure 2). Sampled distributions were bootstrapped with replacement to produce 10^6 sets of n angle envelopes (n = 89 and 37 for terrestrial and martian strata, respectively). For each set, a simulated mean was calculated by randomly selecting angles from each envelope assuming a uniform distribution between the bounds. The distribution of 10^6 simulated means could then be compared to the theoretical angle (red dashed line in Figure 3). The output of these simulations allows the confidence interval on the mean stratigraphic bifurcation angles to account for both individual sample error and limited sample sizes. Code for the implementation of the Monte Carlo simulations is provided in the Supplemental Materials[1].

RESULTS

A mean angle of 72.8° ± 4.1° (95% confidence interval on mean) is calculated from bootstrapped Monte Carlo simulations of the terrestrial stratigraphic bifurcation data. Similar analysis yields a mean angle of 73.9° ± 6.0° for ancient channel mouth bifurcations on Mars observed in orbital imagery. Midpoint angles from each pair of minima and maxima are shown along with modern data (from Coffey and Shaw, 2017) in Figure 3a-c. The distributions of simulated means are shown in relation to the theoretical channel mouth bifurcation angle of 72° in Figure 3d-e.

We also tested the likelihood that the stratigraphic sample distributions were derived from a similar population as the modern sample distribution by performing two sample rank-sum U tests (after Wilcoxon, 1945; Mann and Whitney, 1947). The null hypotheses that distributions of the midpoint measured values of terrestrial and martian stratigraphic bifurcation angles were derived from the same population as modern samples were in no case rejected at the 95% confidence level (p-values = 0.22 and 0.33, respectively). Similarly, comparing the terrestrial strata to martian strata failed to reject the null (p-value = 0.90). Parametric descriptors were also similar between distributions, with the standard deviations of the measured samples being 17.7°, 17.4°, and 19.0° for terrestrial strata, martian strata, and modern deltas, respectively.

In summary, we find no significant difference between the channel mouth bifurcation angles on martian, ancient Earth, or modern Earth. In each case, the mean value is indistinguishable from the theoretical prediction of 72°. Likewise, there is no statistically significant difference between the distributions of any of the measured sets of channel mouth bifurcation angles.

DISCUSSION

Distributions of bifurcation angles measured from strata are found to be statistically similar to modern river delta channel mouth bifurcations with mean values consistent with proposed theory for bifurcation initiation in a diffusive flow field (Coffey and Shaw, 2017). This highlights the remarkable stability of channel mouth bifurcation angles after they are initiated, through network evolution, abandonment and stratigraphic preservation. These findings can be applied to modern deltas as evidence that distributary channel networks building from channel mouth bifurcations are unlikely to significantly rearrange their networks over centennial timescales associated with engineered diversions (Kim et al., 2009, Peyronnin et al., 2017).

Theory predicting bifurcation angles resulting from Laplacian flow over the distal delta channel margins (Devauchelle et al., 2012; Coffey and Shaw, 2017) yields the expectation that there is no dependence on gravitational acceleration. A key finding in this analysis of both terrestrial and martian stratigraphic data is consistency in bifurcation angle distributions between the two planets under factor 2.6 different gravitational accelerations. In this case, the martian stratigraphic record provides a unique archive to empirically test, and ultimately verify the independence of proposed theory on gravitational acceleration. Furthermore, the consistent angle distribution on Mars suggests that similar hydraulic conditions (laterally connected channels and shallow, friction-dominated flow) may have existed when these deltas formed. This may ultimately prove useful in reconstructing planetary paleohydrologic conditions. (e.g. Irwin et al., 2014).

Understanding of the persistence of this morphology through channel network evolution, abandonment, and preservation suggests it can be used to predict the stratigraphic architecture of sedimentary reservoirs. For example, a distribution of bifurcation angles may be a key variable in a training image (Scheidt et al. 2016), or in a process-mimicking statistical model (Pyrcz and

Deutsch, 2014). In light of new understanding of the persistence of bifurcation geometries geostatistical models may now be trained using distributions presented here, in conjunction with information about length-scales of bifurcations (e.g. Edmonds et al., 2011; Shaw et al., *in press*) to inform the locations and geometries of geobodies. Additionally, the persistence of this morphology is promising in its potential to be distinguished from other types of branching networks. It is possible that, upon further investigation, the distributions of channel mouth bifurcations may be found to be significantly different than those resulting from river avulsion in alluvial fan networks. Stratigraphic interpretation could ultimately be significantly improved by such a distinction in both terrestrial and planetary systems where other contextual evidence is lacking.

CONCLUSION

Our results indicate that the angles of river delta channel mouth bifurcations interpreted in the stratigraphic record are consistent with those observed on modern river deltas. This angle, with a mean of ~72°, is consistent with that predicted from theory of flow in a diffusive flow field around the channel during the growth of bifurcations. Persistence of this morphology is shown over geologic timescales indicating that once the bifurcation is established, the angle at the apex remains stable. As predicted from theory, bifurcations on Mars are also shown to be centered about 72° implying independence of this morphology on factors such as gravitational acceleration. Ultimately, these findings yield insight into the processes operating at river mouth bifurcations, as well as a predictive tool for stratigraphic modeling.

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FIGURE CAPTIONS

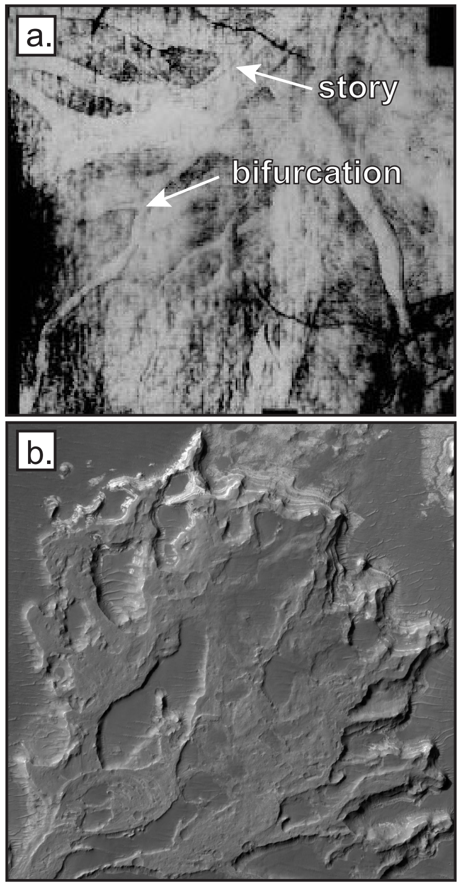

Figure 1: Stratigraphic distributary channel networks in (a) seismic coherence horizon slice from Pleistocene paleo-Mississippi delta deposits near South Marsh Island, Louisiana (non-copyrighted image, modified from Nissen, 2000); and (b) Martian inverted paleochannels preserved in Ebserwalde crater (MRO/HiRISE imagery courtesy of NASA/JPL/University of Arizona).

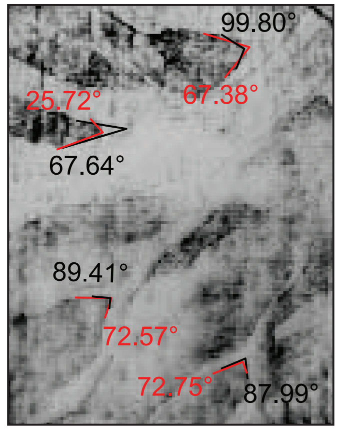

Figure 2: Example of determination of uncertainty in angle measurements (modified from Nissen, 2000). Black lines show wide angle and red lines show narrow angle approximations.

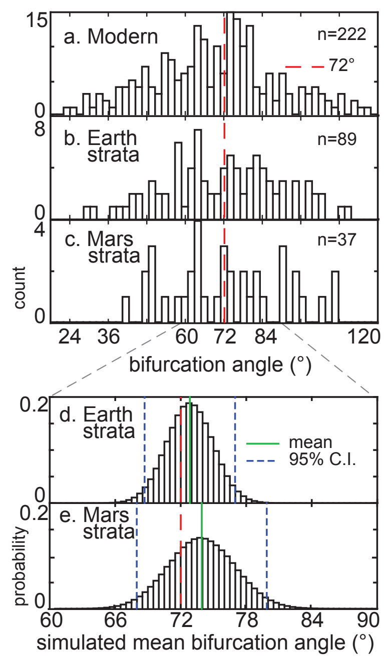

Figure 3: Histograms of bifurcation angles derived from (a) modern and experimental deltas (after Coffey and Shaw, 2017), and from midpoints of minimum and maximum interpreted bifurcation angles from stratigraphic sequences derived from (b) terrestrial seismic data and (c) Martian orbital imagery. (d) and (e) show distributions of sample means from bootstrapped, Monte Carlo simulations from Earth and Mars, respectively.

[1]GSA Data Repository item 2018xxx, [measured angles from Earth and Mars strata (S1) and Matlab code for simulation of mean values (S2)], is available online at www.geosociety.org/pubs/ft20XX.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.