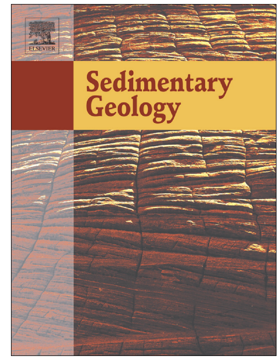

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Meandering rivers in modern desert basins: implications for channel planform controls and prevegetation rivers

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A B S T R A C T

The influence of biotic processes in controlling the development of meandering channels in fluvial systems is controversial. The majority of the depositional history of the Earth's continents was devoid of significant biogeomorphic interactions, particularly those between vegetation and sedimentation processes. The prevailing perspective has been that prevegetation meandering channels rarely developed and that rivers with braided planforms dominated. However, recently acquired data demonstrate that meandering channel planforms are more widely preserved in prevegetation fluvial successions than previously thought. Understanding the role of prevailing fluvial dynamics in non- and poorly vegetated environments must rely on actualistic models derived from presently active rivers developed in sedimentary basins subject to desert-climate settings, the sparsest vegetated regions experiencing active sedimentation on Earth. These systems have fluvial depositional settings that most closely resemble those present in prevegetation (and extra-terrestrial) environments. Here, we present an analysis based on satellite imagery which reveals that rivers with meandering channel planforms are common in modern sedimentary basins in desert settings. Morphometric analysis of meandering fluvial channel behaviour, where vegetation is absent or highly restricted, shows that modern sparsely and non-vegetated meandering rivers occur across a range of slope gradients and basin settings, and possess a broad range of channel and meander-belt dimensions. The importance of meandering rivers in modern desert settings suggests that their abundance is likely underestimated in the prevegetation rock record, and models for recognition of their deposits need to be improved.

Keywords: Meandering rivers; arid sedimentary basins; prevegetation fluvial deposits; remote sensing; modern analogues; dryland.

1. Introduction

Assessment of the biotic and abiotic controls on channel-planform development in alluvial rivers is a fundamental objective in fluvial sedimentology (Wolman and Brush, 1961; Leopold et al., 1965; Schumm, 1968; Peakall et al., 2007; Jansen and Nanson, 2010), and particularly in the geology of preserved fluvial deposits (Long, 1978, 2006, 2011; Sønderholm and Tirsgaard, 1998; Eriksson et al., 2006; Santos et al., 2014; Ielpi et al., 2017a; McMahon and Davies, 2017). A related research question is to what extent did the presence of vegetation in continental environments induce the development of single-channel, meandering planforms and the preservation of laterally-accreting strata (Davies and Gibling, 2010; Davies et al., 2017; Santos et al., 2017a,b)? Experimental studies of fluvial systems using laboratory-based flume apparatus have provided evidence which indicates that, although the presence of vegetation is believed to encourage fluvial systems to develop meandering planforms (Braudrick et al., 2009; Tal and Paola, 2010), vegetation is not a requirement for the growth and preservation of point-bar deposits associated with meandering river behaviour (Peakall et al., 2007; Van de Lageweg et al., 2014). Recent studies have highlighted the abundance of relict and potentially active flow-related features which were also apparently related to meander development in non-vegetated landscapes on other planetary bodies, including Mars and Titan (Schon et al., 2012; Burr et al., 2013; Matsubara et al., 2015). These observations contrast with the hypothesis that non-vegetated meandering rivers rarely developed in the pre-Silurian on Earth (Vogt, 1941; Cotter, 1978; Long, 1978; Davies and Gibling, 2010), and that most prevegetation river channels were typified by braided planform morphologies characterized by shallow and wide channels (Cotter, 1978; Long, 1978, 2011). Ideas that prevegetation systems were subject to lower river-bank stability and flashy runoff characterized by markedly peaked flood hydrographs (Schumm, 1968), lead to commonly observed biases on the interpretations of prevegetation river deposits in the literature (Ethridge, 2011).

Few environments in modern aggradational settings are entirely devoid of vegetation. Although the intrinsic association between life and water means that vegetation will inevitably develop where rivers are present, the density of vegetation cover can vary according to climatic conditions, with climatic deserts being the least vegetated continental environments in which rivers develop. The understanding of meandering rivers developed in subsiding desert sedimentary basins thus provides the best opportunity to assess not only how these rivers can develop with little to no vegetation, but also the plausibility of their occurrence on the prevegetated Earth.

Although braided channels are commonly considered to be the prevailing channel planform in drylands (Tooth, 2000), recent work has highlighted the geomorphology of ephemeral meandering rivers (Billi et al., 2018) and also meandering rivers developed in poorly vegetated environments such as those that host aeolian dunes fields, proglacial rivers (e.g. sandur plains in Iceland), and salt flats (Almasrahy and Mountney, 2015; Li and Bristow, 2015; Li et al., 2015; Ielpi, 2017b,c, 2019). However, there has hitherto been no systematic study of the worldwide distribution, prevalence, and characteristics of meandering rivers in modern arid sedimentary basins.

Here we identify and characterize the morphology of selected meandering rivers in a variety of desert basins with little to no vegetation. We seek to determine the ability of rivers to meander without vegetation present, and to assess what this means for prevegetation river behaviour. Specific research objectives are to understand the following: (i) the characteristics of major meandering fluvial systems developed with little to no vegetation; (ii) how restricted vegetation is in modern meandering river systems which are present in deserts on Earth; (iii) the controls that maintain meandering rivers with restricted vegetation; and (iv) if any of these meandering rivers are potential analogues for rivers in prevegetation systems.

2. Methods

2.1. Global identification of meandering rivers on modern desert basins

Modern depositional areas with the most limited vegetation on Earth have been analysed using Google Earth to identify representative meandering channel planforms; we selected rivers of basin-scale dimensions and with little or no anthropogenic influence. Sixteen meandering river systems developed in 12 modern sedimentary basins from different tectonic settings (Nyberg and Howell, 2015) developed under hot and cold desert climates (Kottek et al., 2006) from 5 continents have been studied (Fig. 1). Analysed river lengths varied between 10 and 400 km; laterally-amalgamated meander belts were between 1 and 60 km wide, and channels varied from 10 to 900 m in width (Table 1).

Selected rivers were analysed using GIS software to extract the following morphometric parameters: thalweg length, meander-belt length and width, channel sinuosity and planform pattern, main channel width, and stream gradient (Table 1; Supplementary Fig. S1). River gradient was calculated using Shuttle Radar Topography Mission (SRTM; http://www.jpl.nasa.gov/srtm) elevation data, version 4.1 (Jarvis et al., 2008) with 3 arc-seconds of spatial resolution (~90 m), with linear vertical relative height error less than 10 m for 90% of the data (Rodríguez et al., 2005); the reported error in these data is chiefly concentrated in mountainous regions (see Hirt, 2018).

Meander belts were identified as channel belts (thalweg and internal bars) and bends; meander-belt and channel width were measured at regular intervals (every 20 km for > 200 km-long rivers, and every 10 km for smaller rivers). River sinuosity was defined as the ratio of channel length (along channel centre path) to straight-line down-valley distance, in which rivers with sinuosity <1.1 were classified as straight, those with a sinuosity of 1.1-1.5 were classified as low sinuosity, and those with sinuosity ≥1.5 were classified as meandering (Leopold et al., 1965).

2.2. Vegetation cover classification

The presence of vegetation in the selected alluvial plains was identified through analysis of satellite images with high and medium spatial resolution. Vegetation classification was performed using different types of satellite imagery depending on the scale of the selected river reach. Large-scale reaches were analysed using Landsat 8 OLI (false colour composite bands RGB 753, 654 and 543) with 30 m spatial resolution. For smaller reaches, GeoEye (0.46 m spatial resolution) georeferenced snapshots acquired using the World Imagery plug-in were used (ESRI, 2013). Calculation of cover percentage of vegetation types (palustrine or grasses) was performed through supervised classification of medium- and high-resolution images using the "Maximum likelihood classification" method on ArcGIS 10.2.2 (ESRI, 2013). The images were usually segmented in three classes (vegetation, water and soil), but some areas required the use of additional subclasses (i.e.., vegetation 1 and 2, water 1 and 2, soil 1 and 2) to achieve a better image classification.

Vegetation cover percentage was computed for each active meander belt, where there is a clear segmentation between the latter and surrounding areas (Fig. 2); otherwise, vegetation cover across the entire alluvial plain was computed. Additionally, we have also separately calculated the vegetation cover on areas with no current fluvial sedimentation and also the total area of the analysed examples, which includes both the surrounding areas and the active meander belt (Table 1). These surrounding areas can be characterized by other ongoing sedimentation processes (e.g., non-confined runoff, aeolian re-working) or by exposed, older meander-belt and lacustrine deposits (e.g. flat valley-bottom topography).

Variations between dry and rainy seasons and morphological details were acquired from recently released Planet images (Planet Team, 2017), with 3 m spatial resolution. Dry and rainy periods were identified using CHIRPS (Climate Hazards Group InfraRed Precipitation with Station Data) (Funk et al., 2015) on the Google Earth Engine (GEE) environment. The Google Earth Engine was also used to create time-lapse imagery (see supplemental materials) of each area using the Landsat collection from 1984 to present.

3. Results

3.1. Meandering rivers in modern desert basins - overview

Sinuosity of the studied rivers ranges from 1.5 to 2.4, slope gradients from $9x10^{-6}$ to $2x10^{-3}$, and vegetation cover from 0 to 38% on the analysed meander belts (Table 1). Eleven of the studied systems developed laterally to, and were confined by, aeolian dunes. Scrolls, identified as crescent-shaped ridges and swales preserved along the inner channel banks, are recorded on a variety of scales (Fig. 3A, 3B), as are channel cut-offs (Fig. 3C) and oxbow lakes (Fig. 3A, 3D). Crevasses and crevasse splays are rare features in the studied examples, and develop in only two of the analysed systems: the Inner Niger Delta (Fig. 3B) and the Warburton River (Fig. 3C). Preserved scroll features are abundant in some examples (e.g. Senegal River) but are sparse in the other examples. In the Senegal River (Fig. 2A), which is fed by an equatorial climate in its source areas, vegetation follows scrolls and more recent deposits, particularly on river banks and on the inner parts of point bars. Small channels on the channel belt of the Senegal River shift laterally to erode the edge of vegetation-free aeolian dune fields and yet are able to develop meandering planforms (upper part of Fig. 3D).

Some of the studied examples are characterized by ephemeral flow (e.g., Amargosa River), others by perennial flow (e.g. Helmand River), and others are characterized by catchment areas with climatic regimes that differ from that of the depositional site (e.g., Senegal River). Yet, in all these different flow regimes, meandering rivers are able to develop with limited vegetation presence.

3.2 Geomorphology of meandering rivers in deserts

An abandoned contributory river to the Tarim River preserves multiple scrolls and abandoned-channel features (Fig. 4A). The example from Chad (Fig. 4B) is characterized by an abandoned or ephemeral system which flowed onto the exposed area of the extinct Lake Chad (Drake et al., 2011); it shows how fine-grained sediments can provide sufficient cohesion to stabilize river banks, even with very limited vegetation. Similarly, the Helmand River (Afghanistan) (Fig. 4C) meanders across a valley bottom composed of Neogene deposits of fluvial sand and silt, lacustrine silt and clay, and aeolian sand. These rivers develop in endorheic, intracratonic and foreland basin settings.

In rivers developed in siliciclastic environments, surrounding areas can either be largely devoid of aeolian dunes such as in the Bermejo River (Fig. 4D), or may be partly occupied by dune fields, such as in parts of the Senegal River. Areas with no currently active fluvial sedimentation are commonly dominated by aeolian processes, with the presence of aeolian dunes in 10 examples; vegetation presence in this setting ranges from 0 to 7%. Examples from Bolivia and Death Valley (USA) are exceptions whereby aeolian dunes did not develop on areas surrounding the active meander belt, with these rivers being developed in evaporitic settings: salt may have provided additional cohesion to induce meandering and scroll development (e.g., Matsubara et al., 2015).

The Inner Niger Delta is characterized by a single-channel trunk system (Fig. 5A) with multiple tributaries with varying sinuosities (Fig. 5B) and varying dimensions (Fig. 5 C, D);

abundant scroll bars and sparse crevasses are recorded. Such tributaries commonly flow into rectilinear interdune settings and yet develop highly sinuous single channels (Fig. 5E).

The Warburton River in Lake Eyre displays crevasse development (Fig. 3C, 6A, 6B) where flow overspills levées and develops floodplain lakes such as the Perra Mudla Yeppa Lake. The river is entrenched into, and surrounded by, areas with aeolian-dominated landforms (Fig. 6C), and also areas with developing channel-scrolls (Fig. 6D), abandoned channels and channel cut-offs (Fig. 6E).

3.3 Meandering as a function of tectono-climatic conditions and vegetation cover

The studied rivers develop in a variety of tectonic settings: foreland (Fig. 4A), intracratonic (Fig. 4B), pull-apart, and rift basins. They also develop in both cold (Fig. 4C) and hot (Fig. 4D) deserts. No significant differences between rivers developed in hot and cold desert climates is observable in terms of planform development and sinuosity (Table 1). The studied examples are stable at the scale of decades, as observed through time-lapse analysis using the Google Earth Engine (e.g., the Helmand River in Afghanistan: see multi-temporal links in Supplementary files). The meandering rivers we describe occupy large areas in the basin, tend to occur downstream of the point where the river enters a subsiding basin, and in an axial position in the basin, where surrounding sediment is largely distal alluvium or aeolian. In contrast to this, our observations show that, in most modern desert basins, braided systems form around the basin margins and have short-headed drainage catchments that supply fan-shaped bodies of sediment that are largely restricted in most cases to the basin flanks.

The presence of vegetation surface cover (Table 1) in the studied rivers varies from 0 to 39% in meander belts, from 0 to 7% in the laterally adjacent areas, and from 0 to 18% in the total studied area. Although potential time-lag effects may be present, there is no correlation in these rivers between channel sinuosity and vegetation cover (Fig. 7) in: (i) meander belt; (ii) surrounding areas of the meander belt; and (iii) total studied area (i + ii). Pearson's R ranges from -0.006 to 0.289.

The Inner Niger Delta (Mali) illustrates this lack of correlation: of the rivers considered in this study it has the second highest vegetation density on its meander belt (32%), the highest vegetation value for the total alluvial plain area (18%) and the adjacent area (7%), but it has the lowest sinuosity values of just 1.5. In contrast, the Zhanadarya River (Fig. 3A) has the second highest sinuosity value (1.8) and yet has extremely sparse vegetation cover on its meander belt (2%). The only system with a greater sinuosity is the Yobe river (Nigeria and Chad) with a sinuosity of 2.4; this has a far more densely vegetated meander belt (39%).

Importantly, many systems with no vegetation cover can develop meandering channels, and with different agents and mechanisms acting to provide cohesion other than vegetation. The studied example from the Bolivian Altiplano (Fig. 8A), is devoid of appreciable vegetation cover and yet develops features typical of meandering rivers, including oxbow lakes and preserved scrolls. The Amargosa River in the Death Valley (Fig. 8B) similarly is devoid of appreciable vegetation cover and develops highly sinuous single channels. These two systems are both characterized by evaporitic floodplain sediments, which give rise to cohesive properties that encourage channel-bank stabilization (e.g. Li et al., 2015; Ielpi, 2019). In addition, an ephemeral contributory of the Tarim River (Fig. 8C) is characterized by sandy and silty material (Li et al., 2017) and yet has been able to develop a similar channel sinuosity (1.7) to the aforementioned rivers developed in evaporitic settings. Additionally, no significant relationship between sinuosity and gradient (Fig. 7D) was identified (Pearson's R = -0.2201).

4. Discussion

4.1. Distribution of meandering rivers in modern sedimentary basins

Meandering channel systems are widespread features in modern desert basins, despite the absence or restriction of bank stabilization and runoff control by vegetation. Our data show no correlation between sinuosity and vegetation cover (Fig. 7). Furthermore, many such rivers flow through areas with varying vegetation-cover density, including vegetated areas and areas with no vegetation, with no observable changes on the overall appearance of channel organization (e.g., Senegal River). The studied meandering rivers show that the presence of vegetation is not mandatory for development of a meandering planform, in contrast to traditional models for pre-vegetation river deposits which assumed that meandering river channels were rarely able to develop prior to the Silurian (Schumm, 1968; Davies and Gibling, 2010; Long, 2011; McMahon and Davies, 2017, 2018; Went and McMahon, 2018), and which favour the ubiquitous presence of shallow and wide braided channels, i.e., the sheet-braided fluvial style (Cotter, 1978). However, our results are in accordance with more recent models for prevegetation fluvial deposits which propose that not only were meandering channels able to develop before land-plant colonization (Santos and Owen, 2016) but they were also able to develop more variable river dynamics (e.g. Santos et al., 2014; Ielpi and Rainbird, 2016; Ielpi et al., 2017; Ghinassi and Ielpi, 2018).

Our results are not intended to exhaustively document all existing examples of meandering rivers developed in modern desert sedimentary basins, but rather to demonstrate that they are common features in environments where vegetation cover is limited. Whilst we acknowledge that rivers are dynamic systems that are subject to local climate and geomorphology, this study is solely dedicated to understanding planform development within the realm of desert sedimentary basins.

4.2. Stabilization mechanisms in modern desert-basin rivers

Stabilization mechanisms for meander-belt development in the absence of vegetation include: (i) low-gradient alluvial plains, (ii) lateral confinement by aeolian dune-fields and dune forms, and (iii) cohesion provided by salt and fine-grained sediments. According to our results (Table 1), 87% of meandering channels studied develop in endorheic basin settings in non- and poorly vegetated environments. Endorheic basins preserve all sedimentary material supplied to the basin (Nichols, 2007), particularly fine-grained sediments, which would otherwise bypass the fluvial system and be transported downstream into a shoreline realm, chiefly as suspended load (e.g., Walsh and Nittrouer, 2009). Additionally, endorheic desert basins are prone to evaporite precipitation and accumulation (Schütt, 1998), which can provide a surface and channel banks that are highly stabilized, as illustrated by the examples from the Bolivian Altiplano and the Amargosa River in Death Valley (Ielpi, 2019). Here we also note that one of the most spectacular examples of an endorheic basin meandering systems is the currently inactive Uzboy Channel (Karakum Desert, Turkmenistan), which preserves channels formed under an arid palaeoclimate from the Upper Pliocene to Preglacial Quaternary (Fet and Atamuradov, 1994; Létolle et al., 2007). However, the Uzboy channel is excluded from analysis herein since it is not possible to estimate the vegetation content for when this system was active.

The only studied examples of desert meandering rivers developed in exorheic basins (i.e., Senegal River and the Inner Niger Delta; see discussions below) are characterized by fluvial-aeolian interactions. Wind-blown dust from the dune fields surrounding these meander-belts may also provide fine-grained sediments (e.g. Qiang et al., 2014) that serve to provide cohesion and stability to river channel banks in desert environments. Additionally, the Inner Niger Delta and Senegal River are two of the three lowest gradient systems in our studied examples. Importantly, the rivers in the present analysis are characterized by geomorphic features that are markedly different from most models of prevegetation rivers (e.g., the wide and shallow braided channels predicted by Cotter (1978). These examples are important in the construction of new models for prevegetation fluvial deposits.

The Senegal River meander belt (Fig. 2A) is restricted laterally by aeolian dune fields. Dune crests are oriented perpendicular to the trend of the meander belt, the transition being delineated by a sharp boundary typical of such fluvial-aeolian interaction (cf. Al-Masrahy and Mountney, 2015). This geomorphic style can commonly lead to mudstone and/or evaporitic sediment accumulation through floodwaters ponding against the edges of the adjoining aeolian dune fields (e.g. Stanistreet and Stollhofen, 2002). The reworking of such mudstone and evaporitic sediment could assist in promoting a cohesive lining to channel banks in desert meandering rivers. This is likely to be the case in the Senegal River; although fieldwork is needed to assess this hypothesis. The lateral relationship of the Senegal River to the non-vegetated dune fields to the north and south may promote meandering channel development through: (i) lateral confinement of the meander belt, and (ii) constant supply of sediment through dune-field erosion (Fig. 3D), both acting to restrict channel widening, and thus the change to a braided planform (e.g., Peakall et al., 2007).

The Senegal River also demonstrates that discharge variations, and related presence of vegetation, in desert environments do not necessarily impact river characteristics such as bankfull width and development of cutoff channels. Vegetation density increases significantly during the summer months (Fig. 9A); even during this period of relative drought relative to the wetter winter season (Fig. 9B); no changes in fluvial dynamics is observable between those periods. This increase in vegetation also hints at the opportunism of vegetation in occupying specific geomorphic niches. The described differences in water input during summer and winter likely result from the river being fed by areas external to the basin, providing perennial supply of water to the system.

Both the Senegal River and the Inner Niger Delta are characterized by more than one channel, each of which have individual meandering channel planforms. Whereas the Senegal River meander-belt is single and relatively rectilinear, the Inner Niger Delta is characterized by multiple meander belts (Fig. 3B). These belts are mostly oriented parallel to surrounding aeolian dune forms, a situation which would promote the winnowing of fine-grained sediment (cf. Al-Masrahy and Mountney, 2015). This river not only records the development of an anabranching system in a poorly-vegetated environment, but also shows that such anabranches can individually develop a sinuous channel planform even when laterally restricted by rectilinear dunes and with banks that are therefore likely composed of a substantial proportion of matrix-free cohesionless sand reworked from adjacent aeolian dunes (Fig. 5E).

4.3. Distribution of meandering rivers and vegetation in modern sedimentary basins

The presence of vegetation in the studied fluvial systems is concentrated in low-lying areas of the alluvial plain such as scroll bars and swales (e.g. Nanson, 1980; Mertes et al., 1995; Tooth et al., 2008), features resulting from point-bar deposition and which are prone to water stagnation and associated fine-grained sediment accumulation (e.g., Page et al., 2003). Muddy substrates typically encourage riverine plant growth (Prausová et al., 2015). This demonstrates the opportunism of vegetation in occupying specific geomorphic niches, as opposed to it acting as a geoengineer (cf. Corenblit et al., 2015). Vegetation requires sufficient humidity to prosper, but, as seen in the documented examples, the development of meandering channels can be achieved without vegetation.

It is likely that the meandering nature of the studied examples is the result of autogenic modulations that have an impact greater than that of vegetation (Erkens et al., 2011), particularly in tectonically active environments where an exogenic variable such as vegetation exerts less influence than a combination of processes related to dynamic equilibrium forms (Nanson and Huang, 2018). Those modulations include river self-organization through erosional and depositional processes (Stølum, 1996), which may have been influenced by river-bank cohesion (Peakall et al., 2007), induced by fine-grained deposition through small variations in flow depth (Howard, 2009). Such variations are supported by the analysis of multi-temporal imagery, which show little oscillation in river flow and slow channel lateral migration (see Supplementary information for details), likely to be linked with low water input.

4.4. Implications for rivers developed before land plant evolution

The majority (14 out of 16) of the examples documented here developed in endorheic basins (Table 1). This is a situation that likely increased the proportion of available fine-grained sediments compared to that in exorheic basins (e.g. Nichols, 2007). This may indicate that prevegetation river systems developed in such basin settings were more likely to develop meandering channel planforms than those developed on exorheic basins. The ability for prevegetation rivers to meander has also been credited to increased cohesion due to the presence of fine (Santos and Owen, 2016) and evaporitic sediments (Ielpi, 2019). Regarding the role of fine-grained sediment as an agent that promotes cohesion and strengthening of channel banks, the Helmand River (Afghanistan; this study) is currently incising Neogene deposits composed of, lacustrine silt and clay, and associated fluvial aeolian deposits. A similar situation occurs in the examples from Chad, which flow onto the exposed floor of the shrinking Lake Chad. These examples are similar to those described by Matsubara et al. (2015) as analogues to fluvial deposits on Mars.

Floodplain roughness is an additional variable which can induce sinuous channel development (Lazarus and Constantine, 2013); in desert basins this may result from the presence of aeolian bedforms. Non-vegetated, well-established aeolian dune fields commonly dominate the environments surrounding the studied meander belts (10 out of 16 examples). They are commonly topographically higher than the studied meander-belts and laterally constrain the fluvial systems (e.g., Senegal River), potentially countering lateral erosion through the near-continuous input of aeolian material, and hindering channel-widening and consequent evolution to a braided pattern (e.g., Schumm et al., 1987; Parker, 1998). Widespread aeolian dunes are also likely to have commonly occurred in barren, prevegetation fluvial systems (Long, 2011). Alluvial slope and sediment types alone (Peakall et al., 2007; Van Dijk et al., 2013) appear to be insufficient to induce channel meandering, and our observations show a weak correlation between alluvial gradient and sinuosity. These results differ from numerical models on the behaviour of prevegetation low-gradient areas, which predict that such rivers should be braided (Almeida et al., 2016).

In the majority of examples, meandering rivers form the dominant fluvial planform over much of the central parts of the studied basins. This suggests that prevegetation fluvial systems could develop meandering systems in the central parts of the basin. The sparseness of crevasse splays in our examples is likely an indication that avulsion frequency is lower in these systems, this being mostly the result of water sparseness in deserts; a characteristic not necessarily applicable to the prevegetation rock record.

Schemes that classify river morphology into end-members may be simplistic (Bridge, 1993; Ethridge, 2011) but they persist in the literature and are widely applied. Although interpretations of braided fluvial systems of all geological ages are dominant and far more abundant than those of meandering systems in the published literature (Gibling, 2006; Colombera et al., 2013), a large proportion (~46%) of distributive fluvial systems developed in modern sedimentary basins, including dryland areas, develop sinuous channel planforms (Hartley et al., 2015). Such an observation suggests that many sandy meander-belt deposits may not have been identified correctly in the fluvial rock record (e.g. Swan et al., 2019) and may also imply that amalgamated meandering sandy fluvial systems could be under-represented in pre-Devonian fluvial deposits. Our observations suggest that prevegetation meandering rivers may have been more common than previously envisaged, and the examples described here are potential analogues for prevegetation fluvial deposits (Santos and Owen, 2016).

5. Conclusions

Remotely sensed imagery shows that terrestrial meandering rivers can form where vegetation is restricted or absent. Crevasse splays are rare in non- and poorly-vegetated settings, and floodplain settings are commonly dominated by aeolian processes. Most examples of meandering rivers in desert basins are related to major drainage systems of their respective basins. By contrast, braided channels tend to be related to smaller-scale drainages and catchments. Stabilization mechanisms in the absence of vegetation include cohesion provided by fine-grained sediments and salt, and constant sediment input from adjacent aeolian dune fields. Endorheic basin settings are more likely to preserve meandering channel deposits in non- and poorly vegetated environments. These systems may make excellent analogues for prevegetation systems, yet are characterized by geomorphic features that are markedly different (i.e., narrow and single, meandering channels) from current models of prevegetation rivers.

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FIGURE AND TABLE CAPTIONS

Fig. 1. Global map featuring poorly to non-vegetated meandering rivers (circles) developed in modern desert basins (adapted from Nyberg and Howell, 2015): 1 – Algeria; 2 – Southern Altiplano Plateau, Bolivia; 3 – Amargosa River, Death Valley, USA; 4 – Batha River, Chad; 5 – Bermejo River, Argentina; 6 – Ephemeral river in Chad; 7 – Helmand River, Afghanistan; 8 – Inner Niger Delta, Mali; 9 – ephemeral river in Niger; 10 – Senegal River, Senegal/Mauritania; 11 – Taklamakan Desert river 1, China; 12 – Taklamakan Desert river 2, China; 13 – river in Ak-Altyn, Turkmenistan; 14 – Warburton River, Australia; 15 – Yobe River, Nigeria; 16 – Zhanadarya River, Kazakhstan.

Fig. 2. Examples of vegetation cover classification, highlighting (left), in yellow, the limits of selected meander belt areas and (right) resulting vegetation aerial identification. (A) Senegal River. (B) Zhanadarya River. (C) Unnamed ephemeral river in Chad. See supplementary data for all the classified examples. Black arrows at upper right of each image indicate river-flow direction.

Fig. 3. Selected examples of poorly and non-vegetated meandering rivers. (A) Oxbow lakes in the Zhanadarya River, Kazakhstan. (B) Aeolian linear dunes and scrolls in the Inner Niger Delta, Mali. (C) Crevasse-splay and channel cutoff in the Warburton River, Australia. (D) Laterally-eroding channels, scrolls and aeolian dunes in the Senegal River, Senegal/Mauritania. Black arrows at upper right of each image indicate river-flow direction.

Fig. 4. Detailed view of selected poorly- to non-vegetated meandering rivers. (A) Scrolls and abandoned channel form preserved of an ephemeral river in the Tarim Basin, China. (B) Scrolls

and abandoned channel form of an unnamed ephemeral river in the Sahara Desert in Chad. (C) Channel cutoff and valley limits of the Helmand River, Afghanistan. (D) Bermejo River, Argentina. Black arrows at upper right of each image indicates river-flow direction.

Fig. 5. Inner Niger Delta, Mali. (A) General view of the Inner Niger Delta as it crosses the southern Sahara Desert. (B) Detail of (A) showing the trunk system (arrow) and two anabranches with meandering planform. (C) Detail showing anabranches splitting into smaller channels (arrow). (D) Detail of much smaller channel (see location on C). (E) Small channel (arrow) flowing between linear aeolian dunes. Black bar (upper right) is 50 km.

Fig. 6. Warburton River in Simpson Desert (Lake Eyre, Australia). (A) General view of the Warburton River. (B) Crevasse development into floodplain lake. (C) Detail of the Warburton River channel entrenched into surrounding areas. (D) Development of scroll features. (E) Channel cut-off development. Black bar is 20 km long.

Fig. 7. Graph of sinuosity against (A) percentage of meander belt vegetation cover, (B) vegetation cover of areas surrounding studied meander belts, (C) total area of alluvial plain vegetation cover and (D) alluvial plain gradient for the studied rivers.

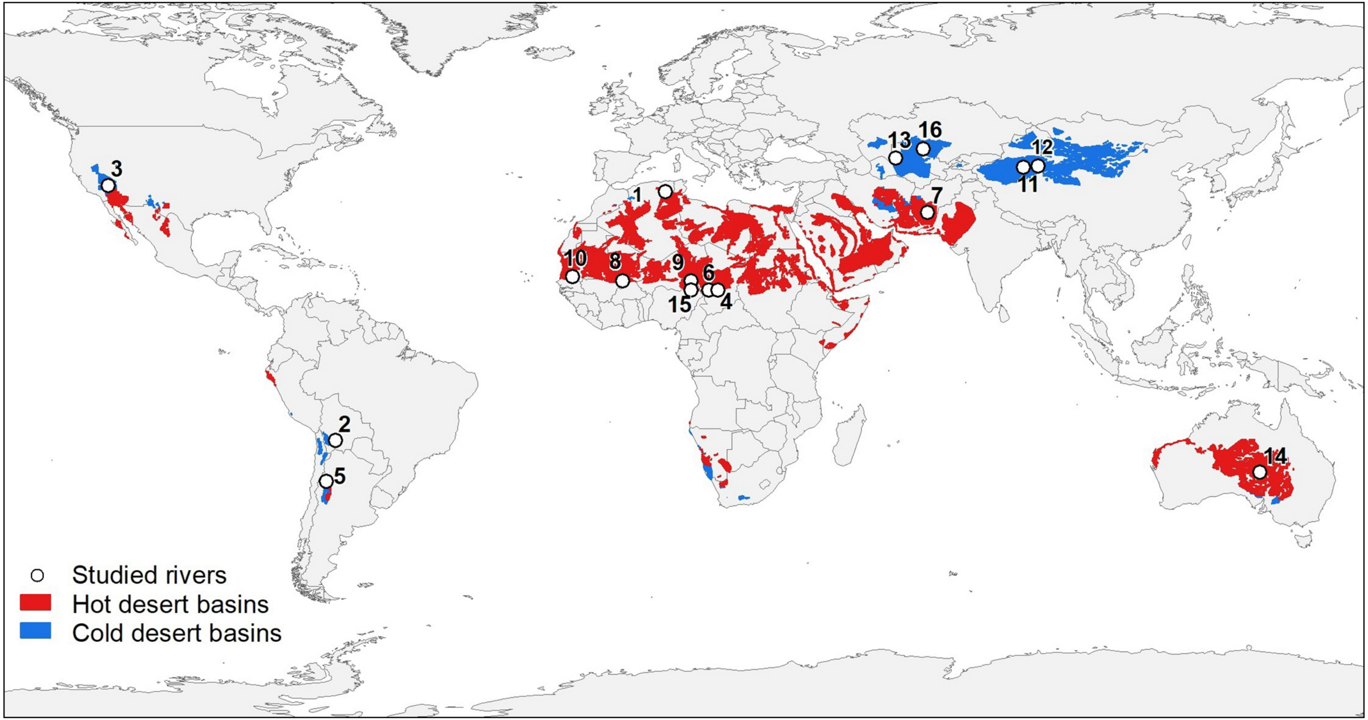
Fig. 8. Examples of agents and mechanisms acting to provide cohesion other than vegetation. Evaporitic floodplain sediments providing channel-bank cohesion (A) Uyuni Desert, Bolivia, and (B) Amargosa River, Death Valley. Fine-grained sandy and silty material: (C) ephemeral tributary of the Tarim River, China.

Fig. 9. Wet and dry seasons at the Senegal River (Senegal/Mauritania). One-month mosaic of Planet Images showing vegetation cover differences between (A) dry season and (B) wet season can be observed. Insert (lower right): CHIRPS climogram depicting temperature and rainfall at the region (average of last 30 years for rainfall and last 20 years for temperature).

Table 1 Morphometric data of the studied rivers.

River name	*Meander belt length (km)*	*Thalweg length (km)*	*Meander belt width average (km)*	*Meander width average (m)*	*Sinuosity*	*Gradient*	*Total area vegetation cover (%)*	*Meander belt vegetation cover (%)*	*Lateral area vegetation cover (%)*	*Aeolian dunes*	*Climate*	*Basin settings*	*Satellite image*
Algeria	44	77	1	37	1.8	0.001493	11.1	4.5	7.0	-	BWh	endorheic intracratonic	LS8 OLI
Altiplano	19	28	0.7	15	1.5	0.000256	0.0	0.0	0.0	-	BWk	endorheic foreland	Geo Cover
Amargosa	10	16	-	10	1.6	0.000384	0.0	0.0	0.0	-	BWh	endorheic pull-apart	Geo Cover
Batha	230	340	5	126	1.5	0.000362	6.4	7.1	6.1	-	BWh	endorheic intracratonic	Geo Cover
Bermejo	75	114	1	60	1.5	0.002773	6.0	6.9	5.8	-	BWk	endorheic intracratonic	Geo Cover
Chad 1	141	274	15	220	1.9	0.000029	5.0	6.2	0.7	x	BWh	endorheic intracratonic	Geo Cover
Helmand	333	485	4	105	1.5	0.000694	4.8	23.8	0.1	x	BWh	endorheic intracratonic	LS8 OLI
Inner Niger Delta	191	277	60	929	1.5	0.000009	18.2	32.2	7.2	x	BWh	exorheic intracratonic	LS8 OLI
Niger	-	-	4	-	-	0.000221	0.0	0.0	0.0	x	BWh	endorheic intracratonic	Geo Cover
Senegal	366	625	17	267	1.7	0.000030	10.9	14.7	0.1	x	BWh	exorheic intracratonic	LS8 OLI
Taklamakan 1	69	111	4	218	1.7	0.000243	1.3	1.7	1.2	x	BWk	endorheic foreland	LS8 OLI
Taklamakan 2	42	61	3	52	1.5	0.000213	5.9	10.6	3.8	x	BWk	endorheic foreland	Geo Cover
Turkmenistan 2	81	140	4	123	1.7	0.000457	9.7	28.7	5.1	-	BWk	endorheic intracratonic	Geo Cover

Warburton	142	206	2	30	1.5	0.000106	5.7	1.9	0.2	x	BWh	endorheic intracratonic	GeoCover
Yobe	295	630	6	31	2.4	0.000078	8.5	38.8	0.6	x	BWh	endorheic intracratonic	LS8 OLI
Zhanadarya	204	375	19	157	1.8	0.000199	6.1	2.3	3.8	x	BWk	endorheic intracratonic	GeoCover


1
2
3
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Studied rivers
Hot desert basins
Cold desert basins

Figure 1

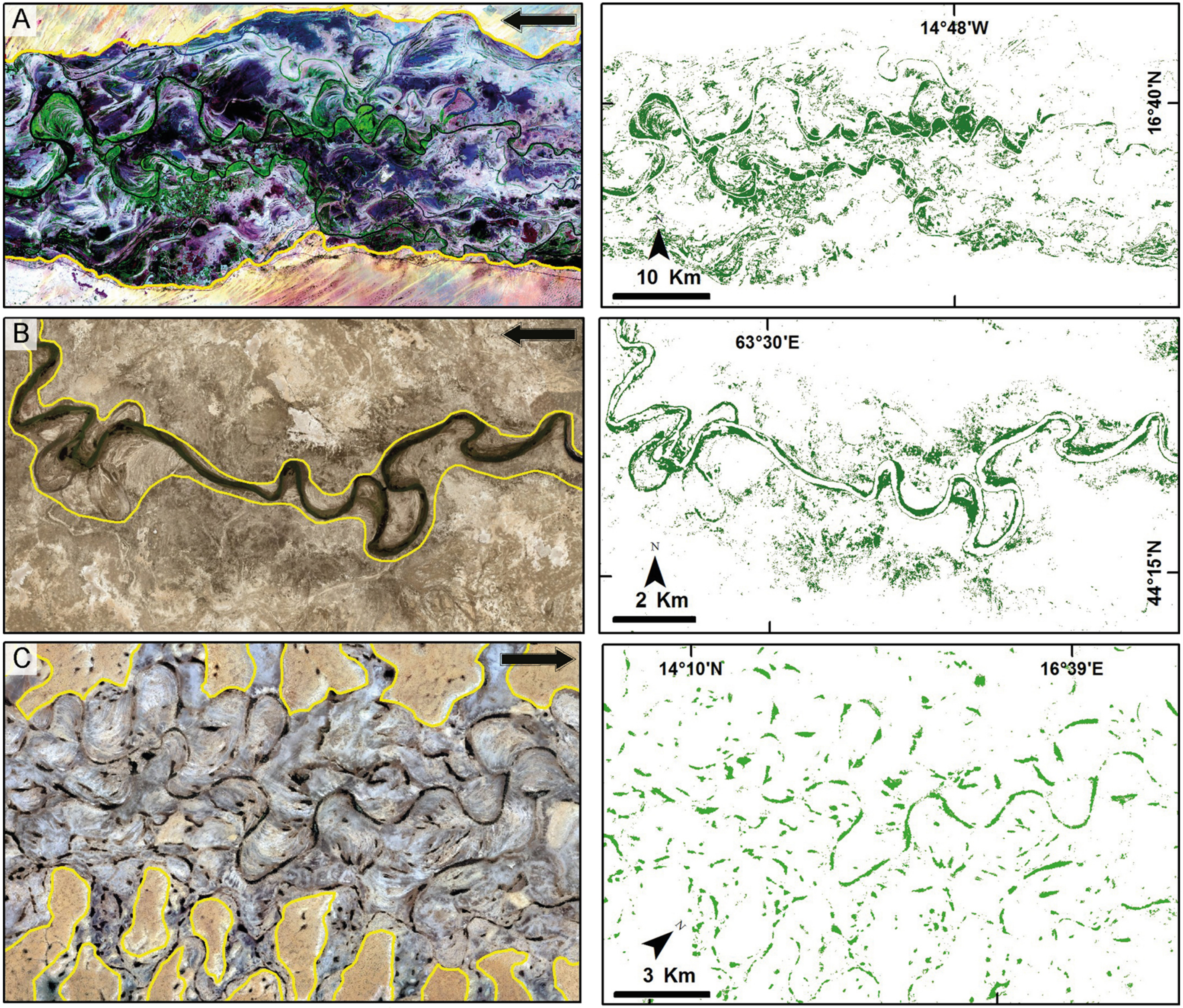


Figure 2

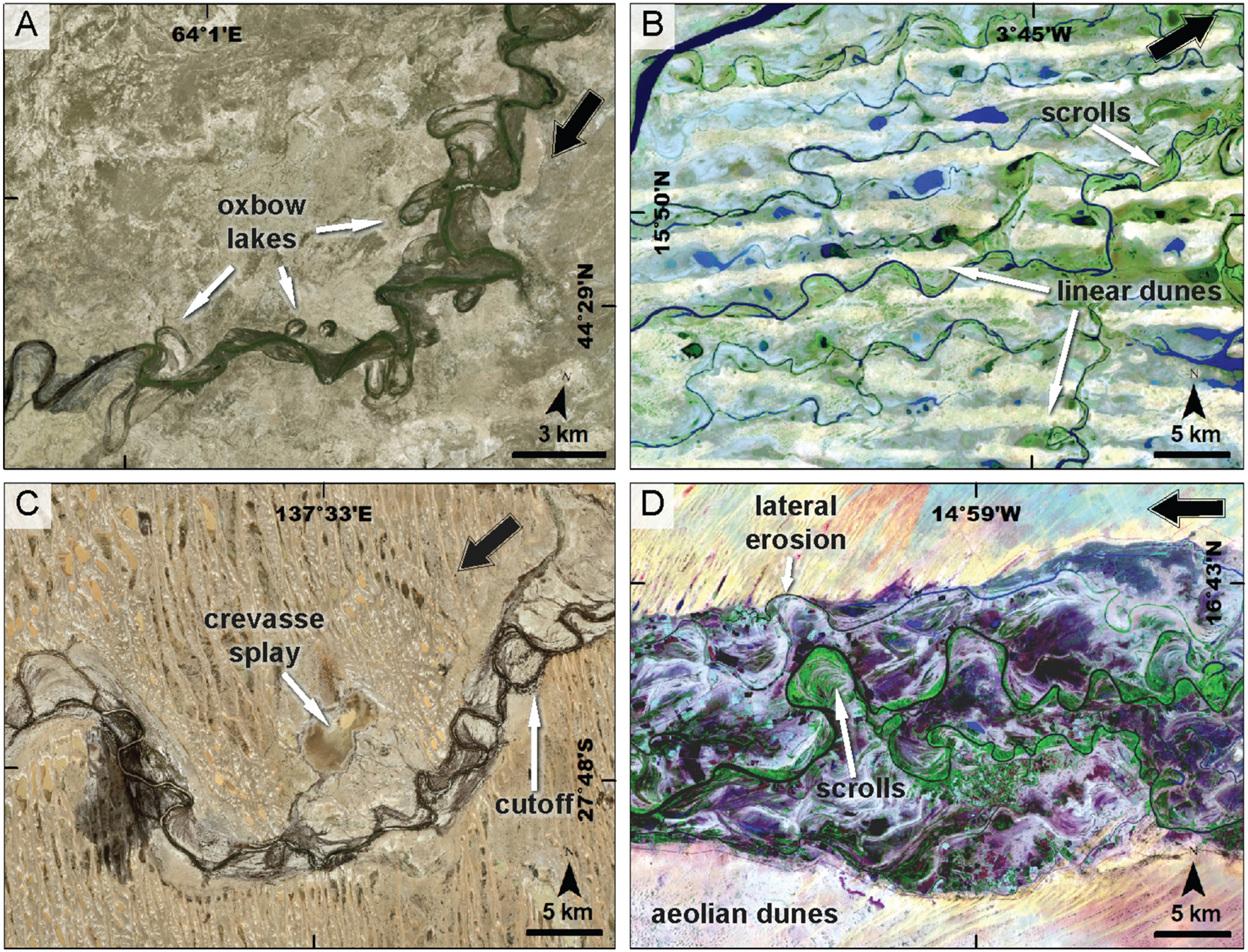

A
64°1'E
oxbow
lakes
44°29'N
3 km
B
3°45'W
scrolls
15°50'N
linear dunes
5 km
C
137°33'E
crevasse
splay
cutoff
27°48'S
5 km
D
lateral
erosion
14°59'W
16°43'N
scrolls
aeolian dunes
5 km

Figure 3

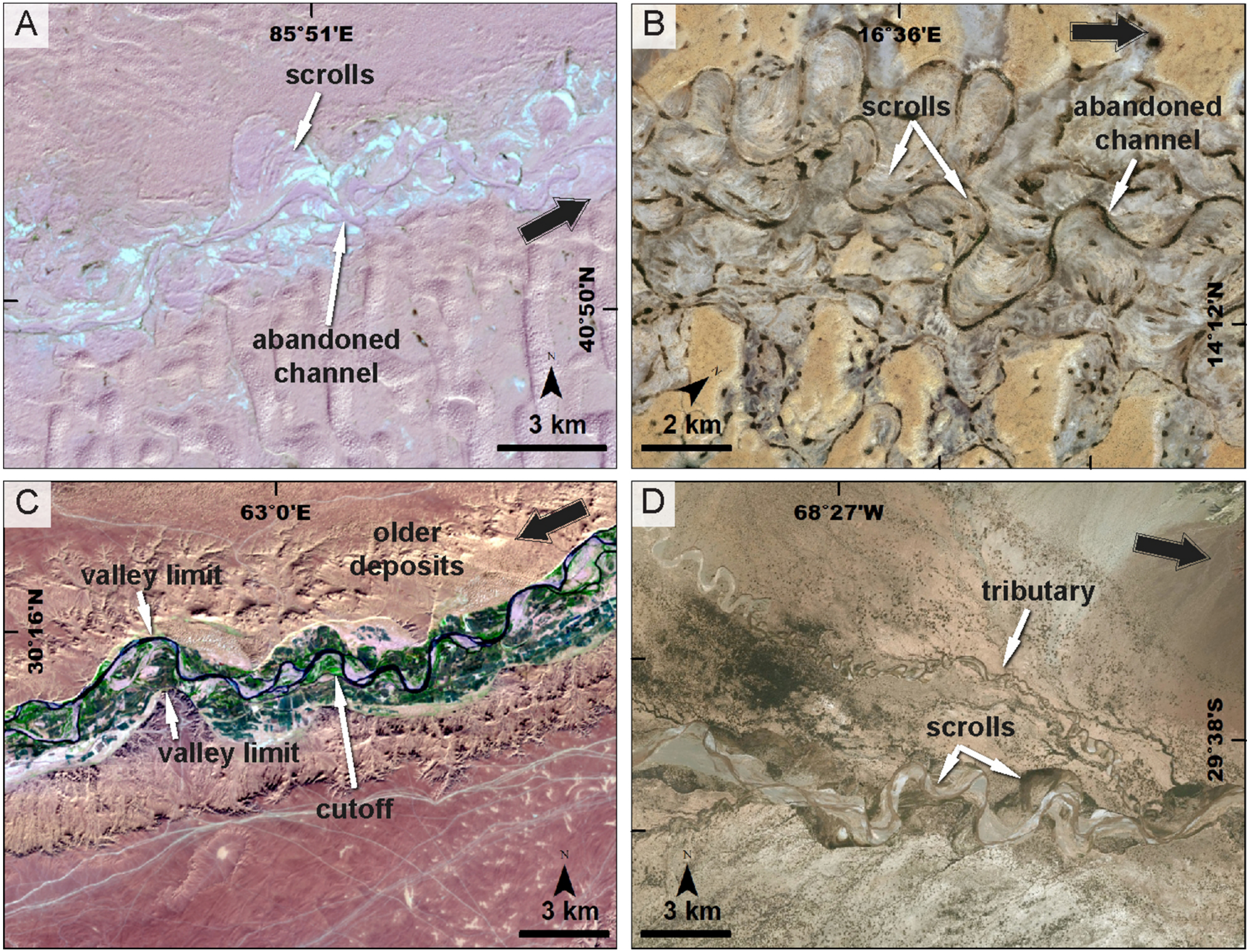

A
85°51'E
scrolls
abandoned
channel
40°50'N
3 km
B
16°36'E
scrolls
abandoned
channel
14°12'N
2 km
C
63°0'E
older
deposits
valley limit
30°16'N
valley limit
cutoff
3 km
D
68°27'W
tributary
scrolls
29°38'S
3 km

Figure 4

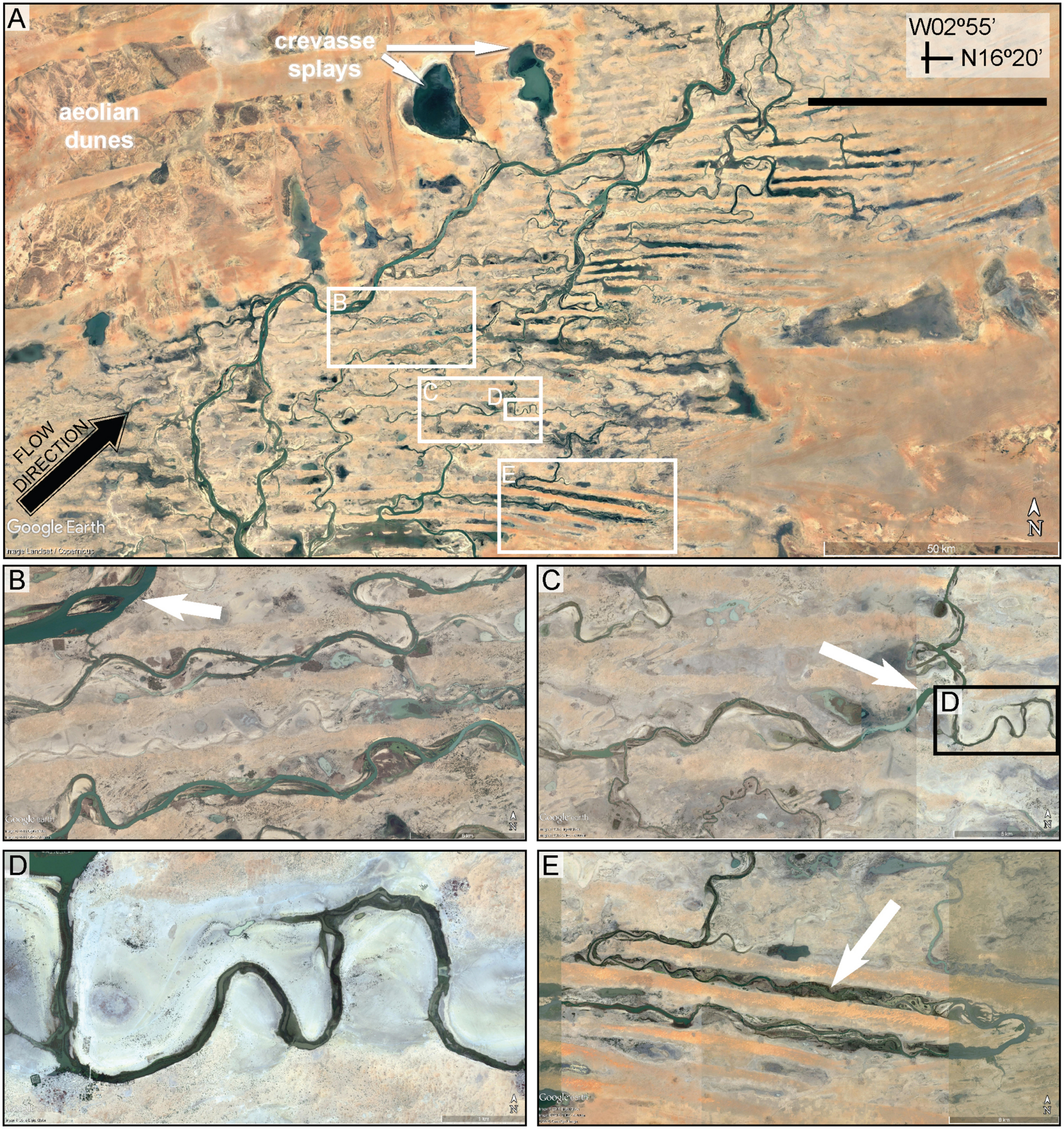

A
crevasse splays
aeolian dunes
W02º55'
N16º20'
B
C
D
E
FLOW DIRECTION
Google Earth
50 km
N
B
C
D
D
E

Figure 5

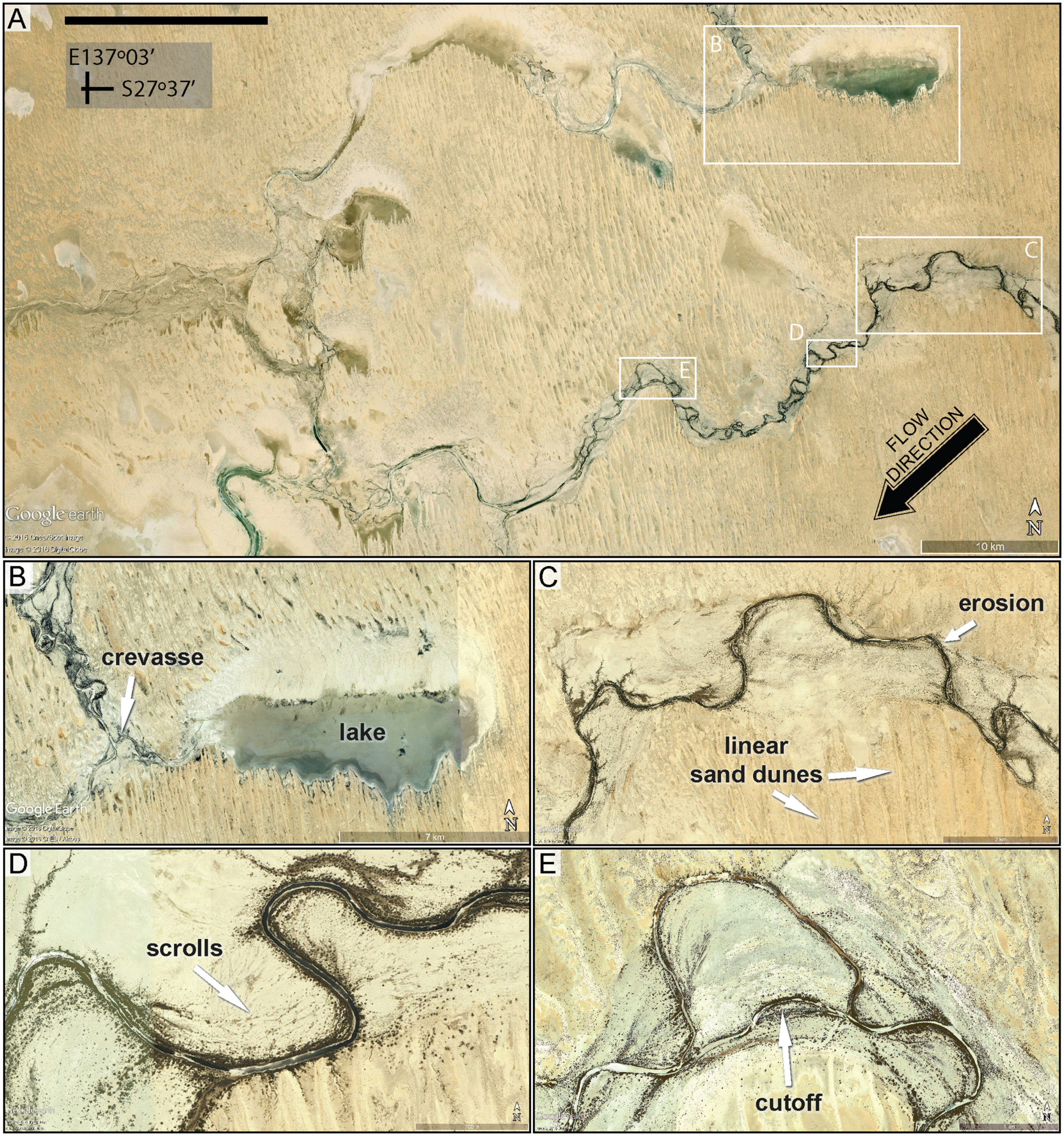

A
E137°03′
S27°37′
B
C
D
E
FLOW DIRECTION
Google earth
10 km
B
crevasse
lake
Google Earth
7 km
C
erosion
linear
sand dunes
D
scrolls
E
cutoff

Figure 6

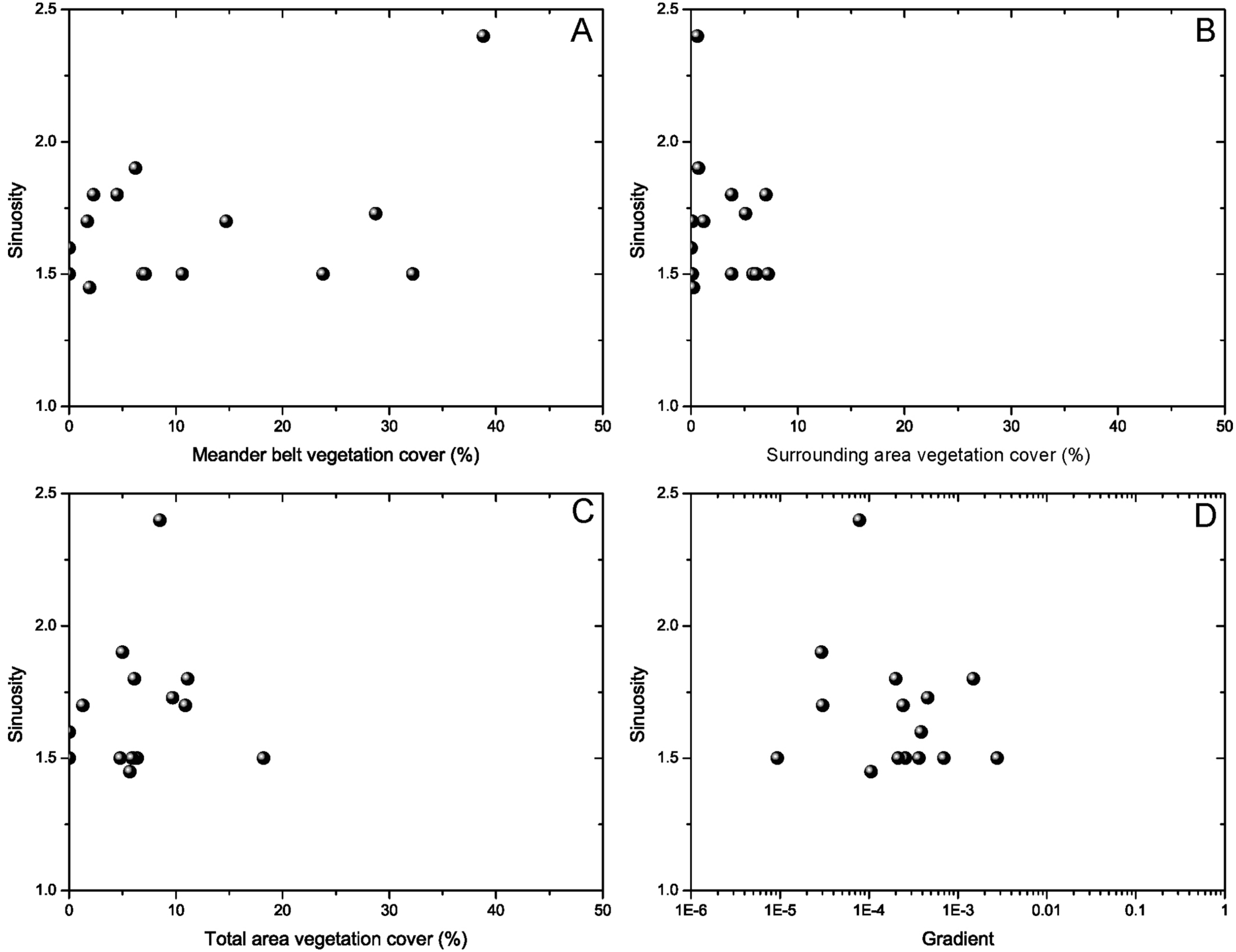
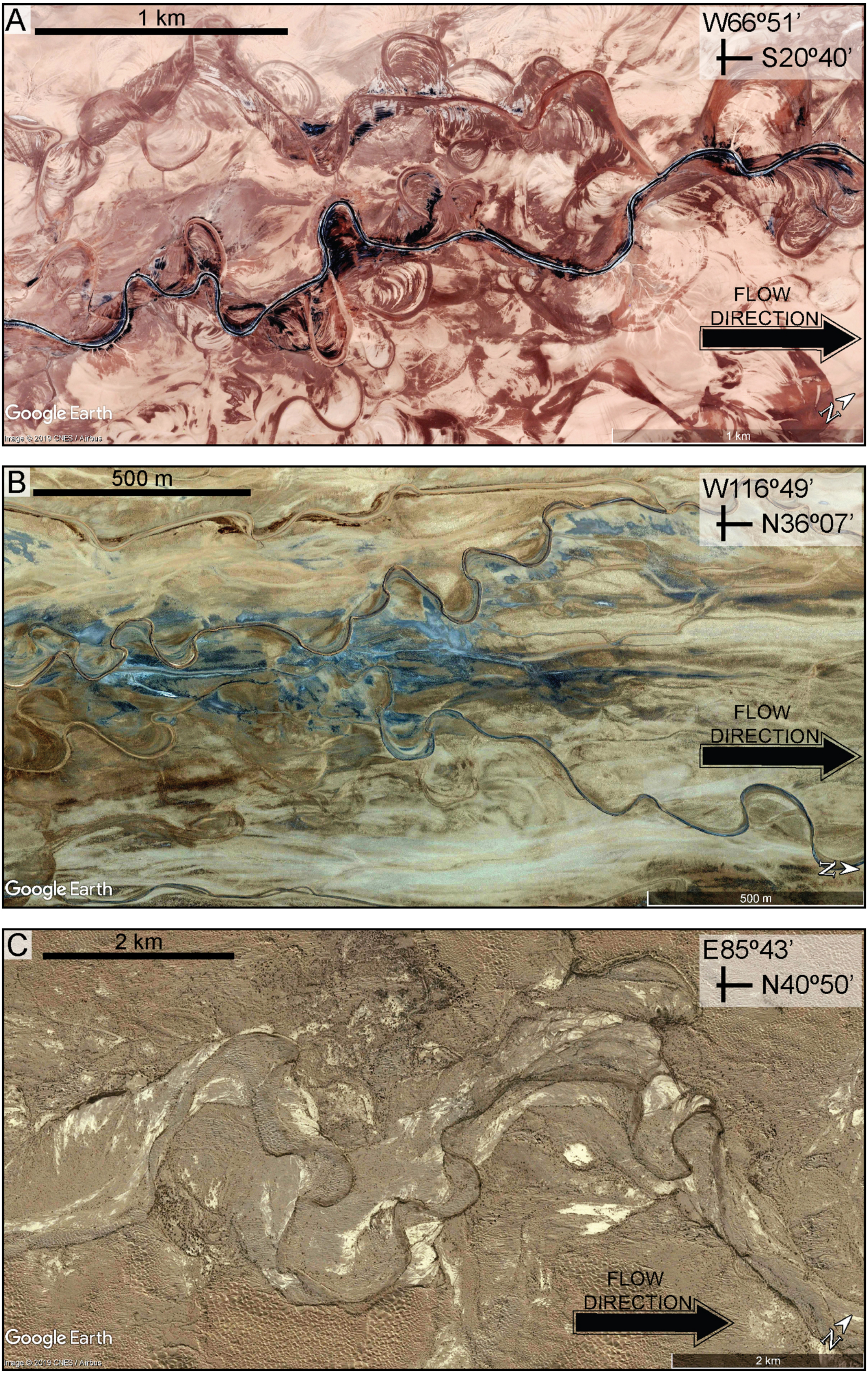

A
B
C
D
Sinuosity
Meander belt vegetation cover (%)
Surrounding area vegetation cover (%)
Total area vegetation cover (%)
Gradient
2.5
2.0
1.5
1.0
0
10
20
30
40
50
1E-6
1E-5
1E-4
1E-3
0.01
0.1
1

Figure 7



A
1 km
W66º51'
S20º40'
FLOW
DIRECTION
Google Earth
Image © 2019 CNES / Airbus
1 km
B
500 m
W116º49'
N36º07'
FLOW
DIRECTION
Google Earth
500 m
C
2 km
E85º43'
N40º50'
FLOW
DIRECTION
Google Earth
Image © 2019 CNES / Airbus
2 km

Figure 8

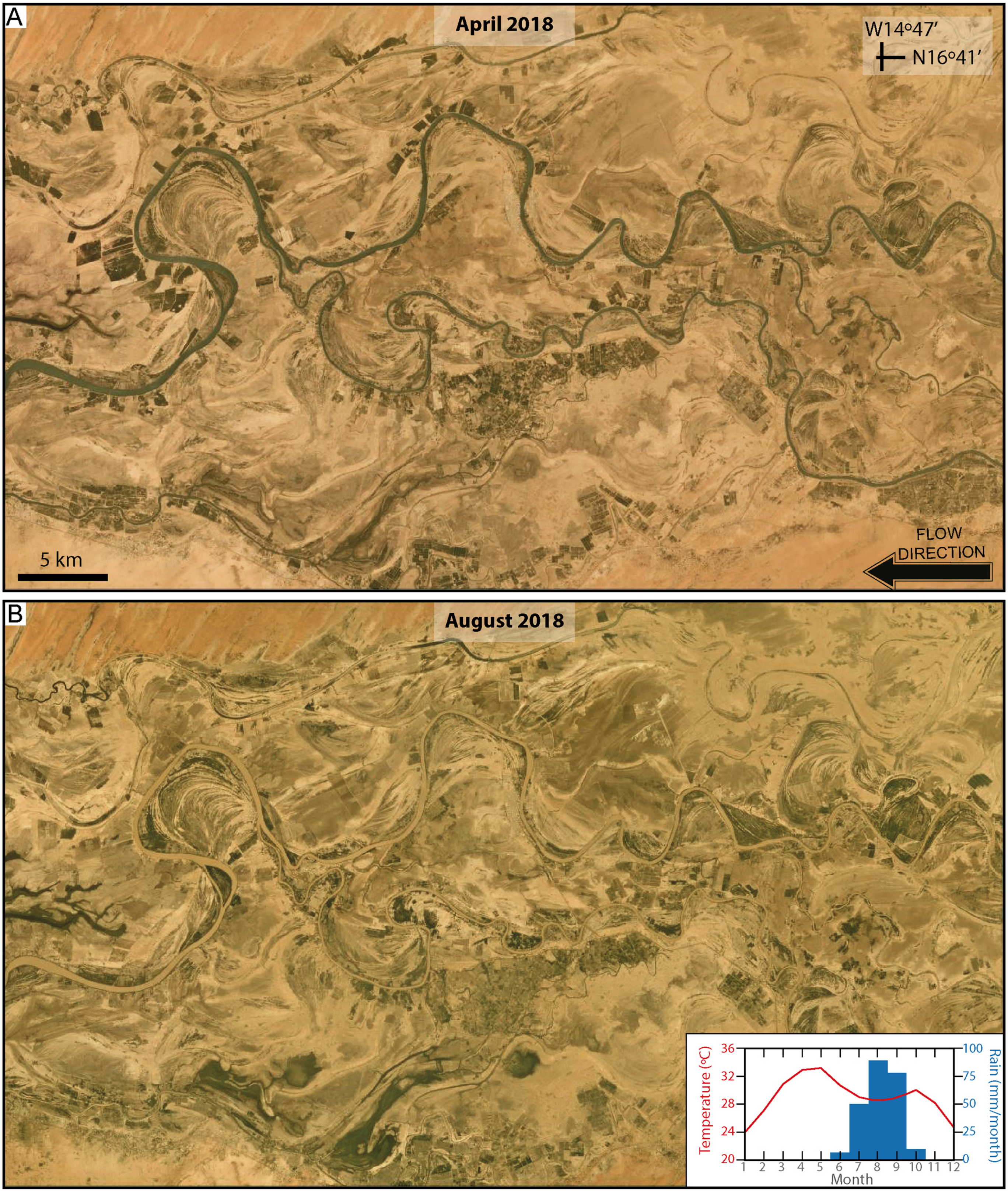

A
April 2018
W14°47′
N16°41′
5 km
FLOW
DIRECTION
B
August 2018
36
32
28
24
20
Temperature (°C)
100
75
50
25
0
Rain (mm/month)
1 2 3 4 5 6 7 8 9 10 11 12
Month

Figure 9