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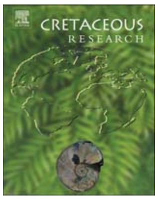

Fluvial styles, palaeohydrology and modern analogues of an exhumed, Cretaceous fluvial system: Cerro Barcino Formation, Cañadón Asfalto Basin, Argentina

Nicolás Foix[a,b,*], José Oscar Allard[a], José Matildo Paredes[a], Raúl Eduardo Giacosa[a,c]

[a] Dpto. de Geología (F.C.N.), Universidad Nacional de la Patagonia San Juan Bosco, Ruta Prov. N° 1 S/N Km 4, 9005 Comodoro Rivadavia, Argentina
[b] CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas), Argentina
[c] Servicio Geológico Minero Argentino, Delegación Regional Comahue, CC 228 (8332), General Roca, Río Negro, Argentina

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ABSTRACT

Superb surface exposures of a fluvial palaeochannel-belt 2–5 km wide and 13 km long occur in Cretaceous sedimentary rocks of the Cerro Barcino Formation (Las Plumas Member), Chubut Group, Cañadón Asfalto Basin, Argentina. The exceptional plan-view exposures of fluvial sandbodies allowed identification of a large number of WNW–ESE sinuous ridges that represent high-sinuosity, braided and low-sinuosity fluvial palaeochannels, crevasse and chute palaeochannels, and crevasse-splay deposits. Predominance of low-sinuosity palaeochannels and low values of the width/thickness ratio of most them suggest high stability of their margins, probably controlled by the cohesiveness of tuffaceous floodplain deposits. Morphological and sedimentological observations provide evidence of abrupt lithofacies changes in palaeochannel fills, fine-grained intercalations in multi-storey palaeochannels and occurrence of different fluvial styles, implying temporal/spatial variations in palaeodischarge and/or slope conditions. Comparison of the near-identical plan view morphology of the Cretaceous palaeochannel belt with the nearby Chubut River, plus the comparison of palaeohydrological data of the exhumed palaeochannels with hydrological data from this modern analogue, gives evidence of a very similar fluvial behaviour. This provides an integrative tool to be employed in the study of other ancient fluvial successions, including the reconstruction of palaeofluvial hydrological parameters in planetary geology.

1. Introduction

Most ancient fluvial systems are analyzed by detailed measurements of outcrop on cliffs that intersect palaeochannel and floodplain deposits. Only in exceptional conditions is the plan view of palaeochannel belts coincident with the current land surface to allow detailed reconstructions of downstream changes in the fluvial pattern. Several terms have been used to describe palaeochannels preserved in inverted relief including “suspendritic drainage lines” (Miller, 1937), “gravel-capped ridges” (King, 1942), “perched wadis” or “wadi ridges” (Butzer and Hansen, 1968), “suspenparallel drainage” (Reeves, 1983), “raised channel systems” (Maizels, 1990), “inverted channels” (Williams et al., 2007, 2009) and “exhumed channels” (Edwards et al., 1983; Smith, 1987; Brookes, 2003; Cuevas Martínez et al., 2010). Examples of such exceptional conditions have been described in Carboniferous (Padgett and Ehrlich, 1976; Gardner, 1983), Permian (Edwards et al., 1983; Smith, 1987), Cretaceous (Brookes, 2003; Williams et al., 2007, 2009) and Cenozoic successions (Maizels, 1990; Cuevas Martínez et al., 2010).

Most fluvial facies models have been described from examining the depositional environments of modern fluvial systems (Walker and Cant, 1979; Miall, 1996). Comparison between ancient and modern fluvial systems represents a common method of interpreting the geologic record (e.g., Schumm, 1985; Bridge, 1993; Miall, 1996). This can be especially useful in exhumed fluvial systems where the plan view is preserved.

The Cerro Barcino Formation (Chubut Group, Cañadón Asfalto Basin) is a Cretaceous mainly fluvial, pyroclastic-rich unit (e.g., Figari and Courtade, 1993; Manassero et al., 1998, 2000; Cladera et al., 2004) deposited in the central part of Chubut Province, Argentina. Exhumation of palaeochannels by relief inversion allows description of exposures in three dimensions, with retention of many attributes of the original channel form. This paper focuses on the interpretation of ribbon-shaped fluvial sandstone bodies of the Las Plumas Member of the Cerro Barcino Formation. Plan view

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[*] Corresponding author. Dpto. de Geología (F.C.N.), Universidad Nacional de la Patagonia San Juan Bosco, Ruta Prov. N° 1 S/N Km 4, 9005 Comodoro Rivadavia, Argentina.

E-mail address: nicofoix@unpata.edu.ar (N. Foix).

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morphology, palaeochannel dimensions and discharge values from the exhumed fluvial system were compared with a modern fluvial system, the nearby Chubut River.

2. Geological setting

The sedimentary record of the Cañadón Asfalto Basin has been divided into megasequences bounded by regional unconformities in order to describe sedimentary units related with rift evolution (Figari and Courtade, 1993; Figari, 2011) (Fig. 1). The Cretaceous Cerro Barcino Formation (Chubut Group) of the Cañadón Asfalto Basin accumulated during a regional subsidence stage (Figari and Courtade, 1993; Figari, 2011), as evidenced by layer-cake successions with gradual variations in thickness on a regional scale. The unit is characterized by isolated sandstone bodies that represent the infill of palaeochannels encased in ash-dominated, floodplain fines. The occurrence of charophyes and ostracods in fine-grained deposits indicates the occasional development of standing water bodies (Musacchio, 1972; Musacchio and Chebli, 1975; Chebli et al., 1976).

The Cerro Barcino Formation has been divided by Codignotto et al. (1978) into five members: Puesto La Paloma, Cerro Castaño, Las Plumas and Puesto Manuel Arce/Bayo Overo. The Puesto La Paloma Member is characterized by well-developed pyroclastic floodplain sediments where primary ash-fall deposits were reworked on wide floodplains characterized by very shallow water bodies and palaeochannels (Allard et al., 2010; De la Fuente et al., 2011), which contain dinosaur (Rauhut et al., 2003) and turtle (De la Fuente et al., 2011) remains.

The Cerro Castaño Member was strongly conditioned by volcanic ash fall-out (Manassero et al., 1998, 2000; Cladera et al., 2004) and contains vertebrate fossil remains (Rich et al., 2000; Cladera et al., 2004). Three types of fluvial systems have been interpreted in this member, developing during syn-eruptive, early post-eruptive and late post-eruptive stages (Cladera et al., 2004).

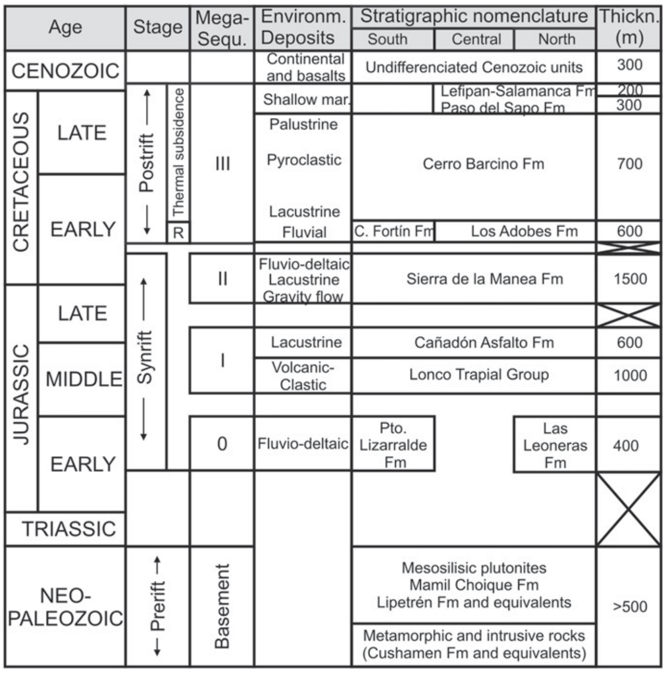

Fig. 1. Synthetic lithostratigraphy and palaeoenvironments of the Cañadón Asfalto Basin (modified from Figari, 2011). The Cerro Barcino Formation was deposited during the post-rift stages, controlled by thermal subsidence and pyroclastic input. R, reactivation.

The Las Plumas Member is mainly composed of reddish tuffs and tuffaceous sandstones, but contains abundant pebbly sandstones and conglomerates; lithological similarity of the Cerro Castaño and Las Plumas members makes differentiation difficult (Anselmi et al., 2005).

The Puesto Manuel Arce Member is mainly composed of grey mudstones, tuffaceous siltstones and sandstones (Codignotto et al., 1978); this unit has been considered as a separate formation by several authors (Chebli et al., 1976; Cortés, 1987; Anselmi et al., 2005).

The Bayo Overo Member is composed of yellowish and greenish tuffs and subordinated sandstones (Codignotto et al., 1978), which contain tuffaceous paleosols (Genise et al., 2010).

Recently, palynological data from the underlying Los Adobes Formation indicates an Albian age for this unit (Marveggio and Llorens, 2011), hence supporting a younger age for the Cerro Barcino Formation (Cenomanian?).

3. Study area

The study area is located 50 km southwest of Las Plumas locality in Chubut Province (Argentina; Fig. 2A) and a few kilometres to the east of Guanaco Hill (44°04′00″S, 67°50′00″W; Fig. 2B). In the area, the Cerro Barcino Formation mostly crops out as a near-horizontal succession consisting of ribbon-shaped sandstone bodies and red-coloured tuffaceous fines. Intense winds that currently occur in central Patagonia, in combination with minor surface runoff, have eroded most of the floodplain fines, highlighting the shapes of the palaeochannels by inversion of relief. The present-day arid climate

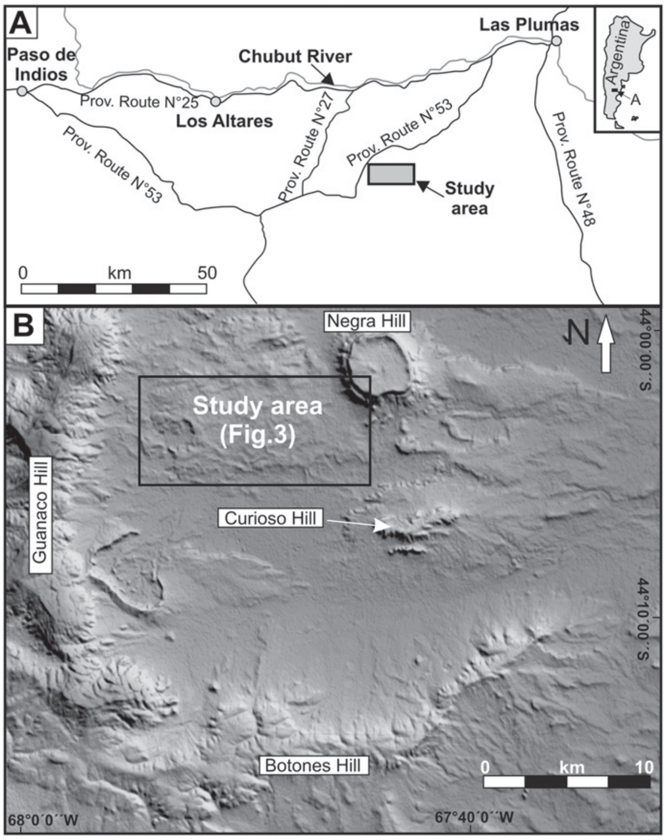

Fig. 2. A, the study area is located 50 km southwest of the Las Plumas locality in Chubut Province, Patagonia, Argentina. B, location map of the study area. The outcrops studied are located between the Guanaco and Negra hills, in a low-relief area of about 100 km^2. The box shows the location of Fig. 3.

in Patagonia has inhibited the development of thick soil profiles and pervasive vegetative cover, leaving these fluvial palaeochannels clearly exposed.

The most complete sections of the analyzed succession are exposed in cliffs up to 30 m high, which are located in the western part of the study area, most of them formed by vertical incision of high-energy, ephemeral modern fluvial systems (arroyos) and gravitational collapse of the flanks of the palaeochannels.

4. Material and methods

The outcrops are characterized by elongated sandstone ridges that correspond to palaeochannels, and occur over an area up to 100 km^2 (Fig. 2B). The study has been carried out by means of two techniques: (1) the analysis and interpretation of available satellite images, which were used to recognize the trace of palaeochannels and to measure morphometric parameters, including length, width, radius of curvature and wavelength; and (2) fieldwork to obtain data on the thickness of the palaeochannels, lithology and sedimentary structures, and to undertake palaeoflow measurements.

The external shape of the fluvial sandbodies were described following the width/thickness (W/Th) criteria of Gibling (2006) as broad sheets ($W/Th > 100$), narrow sheets ($W/Th > 15$), broad ribbons ($W/Th > 5$) and narrow ribbons ($W/Th < 5$).

5. Results

5.1. Satellite observations

Exceptional plan-view exposures of the fluvial sandbodies allowed characterization of a number of WNW–ESE sinuous ridges that collectively define a palaeochannel belt 2–5 km wide and 13 km long (Fig. 3). Most of the palaeochannel-fill sandstones are low sinuosity, but some well-preserved high-sinuosity palaeochannels are also recognized (Fig. 4). Individual channels can be traced downslope over distances from hundreds of metres up to 5 km (Fig. 3).

In the study area, low-sinuosity sandbodies ($S < 1.5$; Friend et al., 1979) represent up to 85% of the identified palaeochannels in the Las Plumas Member of the Cerro Barcino Formation and are up to 120 m wide (Fig. 4E, F).

Meandering sandbodies are wider at bends than at inflection points and are characterized by the occurrence of point bars that reflect several episodes of lateral migration (Fig. 4A, B). Palaeochannel plan-form features determined from high-sinuosity sandbodies include meander belt width, channel width, radius of curvature, meander wavelength, length of palaeochannel for one wavelength and sinuosity (length of palaeochannels/meander wavelength) (see Fig. 4B). A crevasse channel 200 m long was identified in the external margin of a meandering channel, feeding

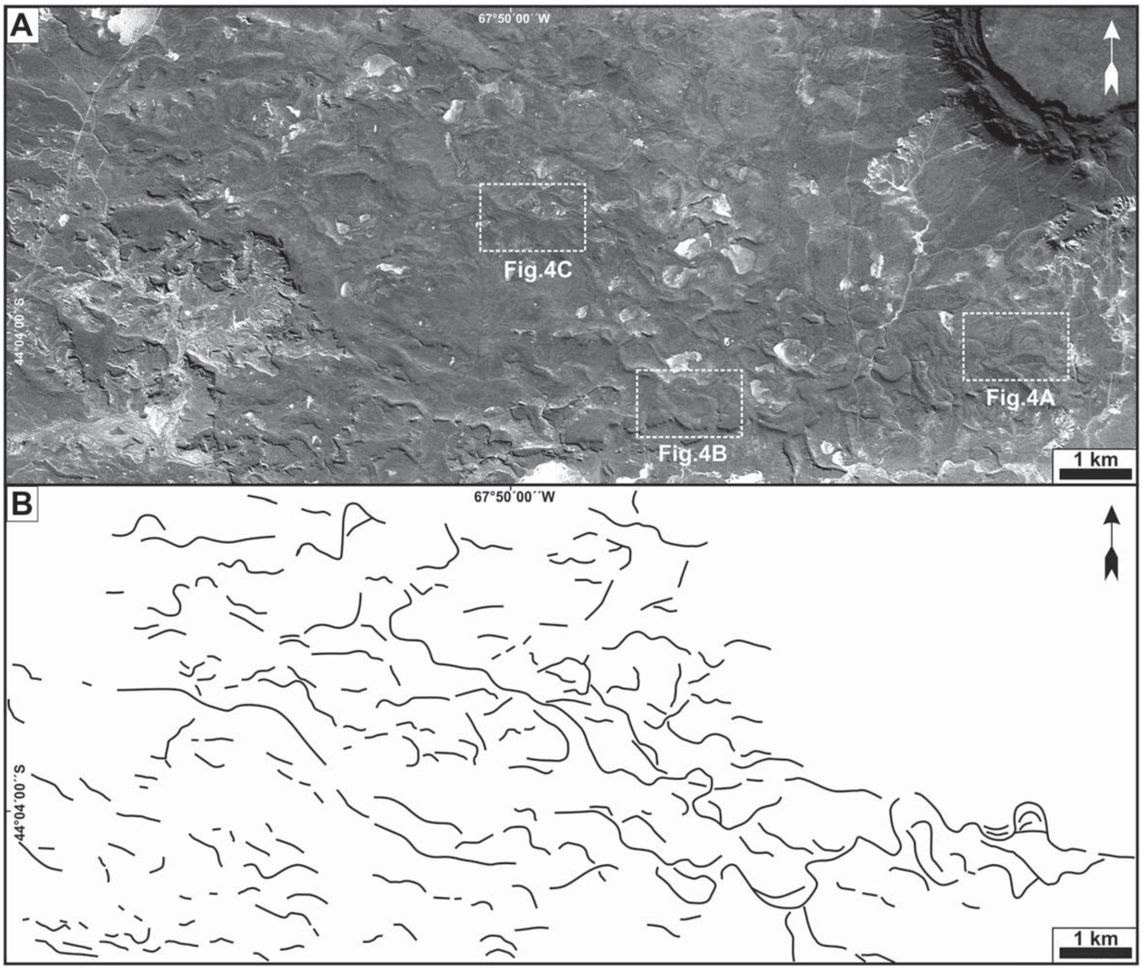

Fig. 3. A, satellite image of the study area (obtained from Google Earth). The boxes show the location of Fig. 4A–C. B, map of the channel-fill sandstone ridges (Cerro Barcino Formation, Las Plumas Member) covering about 100 km^2, showing the predominance of WNW–ESE palaeochannels. Most palaeochannels are low-sinuosity sandbodies, with some well-preserved meandering palaeochannels.

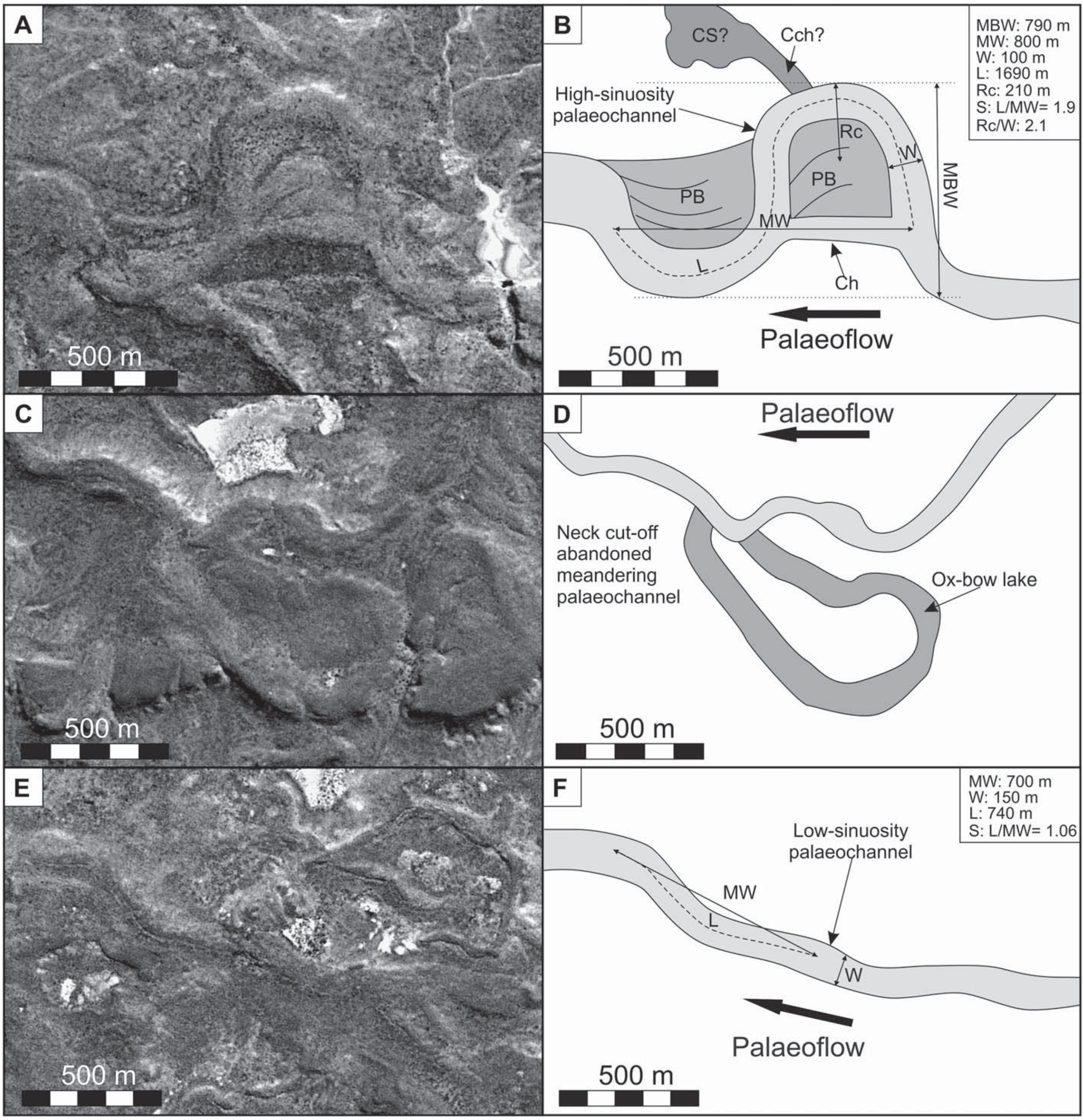

Fig. 4. A, satellite image of a meandering palaeochannel. B, interpretation of Fig. 4A. C, satellite image of an abandoned meandering palaeochannel. D, interpretation of Fig. 4C. E, satellite image of a low-sinuosity palaeochannel. F, interpretation of Fig. 4E. PB, point bar; Cch, crevasse palaeochannel; CS, crevasse splay deposits. Ch, chute palaeochannel; MBW, meander belt width; MW, meander wavelength; Rc, radius of curvature; W, palaeochannel width; L, length of palaeochannel for one wavelength; S, Sinuosity. In Fig. 4B Rc/W has a value of near 2 (210/100 = 2.1), as indicated by Williams (1986) for meandering rivers.

a crevasse-splay lobe in the proximal floodplain (Fig. 4A, B). High-sinuosity sandbodies are up to 500 m wide and the observed chute palaeochannel is up to 70 m wide and 350 m long. Some abandoned meandering palaeochannels associated with a “neck cut-off” mechanism apparently developed shallow water bodies (oxbow lakes) (Fig. 4C, D).

The exceptional preservation of some meandering palaeochannels allowed analysis of the spatial (downstream) and temporal (lateral) evolution of channel sinuosity. The sequence of successive circle centres from lateral migration surfaces (see dashed line in Fig. 5) is considered to be the axis of accretion (sensu Rabelo et al., 2007) and suggests translation during down-channel migration. As a consequence of this migration, the radius of the meander bends also increases owing to bend expansion (i.e., there is a change in meander amplitude; 1–3 in Fig. 5). Supposing a near-constant meander wavelength during the temporal evolution of the meander bends, this increase in the radius of curvature implies an increase of sinuosity (Williams, 1986). Conversely, the downstream

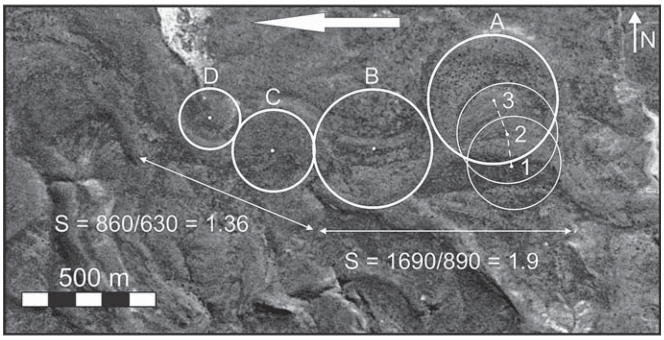

Fig. 5. Spatio-temporal changes in palaeochannel sinuosity (S), showing translation and expansion of meanders during the cross-channel and down-channel migration. A–D, meander loops; 1–3, circle centres; dashed line, axis of accretion; single-headed arrow, palaeoflow direction.

decrease in the radius of curvature from 210 to 150 m over approximately 1 km of distance (A–D in Fig. 5) is accompanied by a correlative decrease in the sinuosity from 1.9 to 1.36.

5.2. *Palaeochannel fills*

Palaeochannels are single (0.3–1.5 m thick) or multi-storey (up to 5.5–6.0 m thick) (Fig. 6A), with abrupt margins (Fig. 6B) and common hollows in their bases (Fig. 6C); their infill is dominated by conglomerates and sandstones with general fining-upward trends. Conglomerates are composed of moderately well-sorted, well-rounded, acidic to intermediate volcanic and tuffaceous clasts up to 5 cm in diameter; reactivation surfaces are common (Fig. 6D). Low-sinuosity palaeochannels can contain either braid bars that separate channel-fill deposits (braided palaeochannels) (Fig. 6E) or alternate bars that migrate oblique to the palaeochannel axis (Fig. 6F); both styles were only recognized during fieldwork after detailed measurement of architectural data, and cannot be differentiated in satellite images alone. Fieldwork has also demonstrated that some multi-storey sandbodies consist of the stacking of braided and low-sinuosity storeys.

Sandbodies in the Las Plumas Member have an average thickness of 3.3 m ($n = 26$, SD = 1.18 m) and an average width of 87.6 m (range 15–490 m). Measurements of palaeochannel W/Th ratios show an average of 18 (range 7–120, SD = 33), including broad ribbons (W/Th > 5), narrow sheets (W/Th > 15) and broad sheets (W/Th > 100).

Multistorey palaeochannel fills often contain lenses of burrowed siltstones, ranging from 0.05 to 0.5 m in thickness (Fig. 6G) that separate storeys. Lens-shaped and lobate sandbodies up to 0.5 m thick and a few metres wide that are encased in tuffaceous fine-grained rocks represent proximal floodplain deposits, and are interpreted as floodplain channels and crevasse-splay respectively (Fig. 6H). Distal floodplain deposits are composed of massive or laminated, reddish tuffaceous siltstones that are frequently bioturbated (Fig. 6I).

5.3. *Palaeoflow directions*

The palaeochannel orientations were determined from satellite images following the methodology of Cuevas Martínez et al. (2010), dividing the axes of each mapped palaeochannel in straight segments 100 m long. A total of 1282 oriented segments were measured that are up to 128 km long. The mapped palaeochannels display a 285–105° orientation (SD = 35.7°) (Fig. 7A), but the palaeocurrent data obtained from cross-bedding strata show a WNW mean vector (mean = 287°; SD = 52.6°; $n = 543$) (Fig. 7B).

The obtained palaeoflow direction of the palaeochannel belt allows the inference that the main depocentre of the Las Plumas Member was located WNW of the study area; the lithological composition of the gravel fraction suggests that Jurassic volcanic rocks located 80 km to the ESE of the outcrops studied probably represent the source rocks.

5.4. *Palaeohydrology*

The palaeohydrology of fluvial systems in the Las Plumas Member (Cerro Barcino Formation) were estimated from empirical relationships. Considering a hypothetical cross-sectional channel area, discharge can be calculated from the following equation:

$$Q = v \times A$$

where Q is the discharge in cumecs (m^3/s), and A is the cross-sectional area of the channel (approximated by $d_m \times W$) in m^2, where d_m is the mean depth of the channel measured in metres, and W is the width of the channel in metres (Costa, 1983). The width-depth ratio (F) is closely related to channel silt-clay content (M) as follows:

$$F = 225\ M^{-1.08}$$ (Schumm, 1968a, 1968b, 1972)

Applying these relationships to the exhumed palaeochannels of the Cerro Barcino Formation and supposing $M = 10$ (corresponding to mixed-load palaeochannels with sinuosity $S < 2$), the following results were obtained (see Table 1). The width of the palaeochannels was measured from satellite images and GPS point data. Their depths were estimated from channel width and F ratio. Simplifying the calculation of palaeohydrological parameters, the velocity of water discharge can be assumed as an intermediate value (ranging between 0.5 and 1 m/s) for subaqueous trough cross-bedded bedforms (Leopold et al., 1964), which is 0.75 m/s (e.g., Eriksson et al., 2006; Köykkä, 2011a, b). Water discharges for 16 selected palaeochannels of the Cerro Barcino Formation range from 8 to 353.6 m^3/s (mean = 70.3 m^3/s, SD = 99 m^3/s) (see Table 1).

If the virtual wavelength of a meander is known, it is possible to verify the estimated palaeodischarge by using the empirical relation for meander wavelength and discharge proposed by Carlston (1965):

$$L = 24.5\ Q^{0.62}$$

where L is the bend wavelength and Q the bank-full river discharge. Applying this empirical relation to the meander shown in Fig. 4A, gives:

$$L = 24.5 \times 353^{0.62} = 930\ \text{m}$$

The similarity between the measured meander wavelength (890 m) and that calculated from the palaeodischarge estimation (930 m) suggests only a slight overestimation (4.3%).

6. Discussion

6.1. *Fluvial styles*

Geomorphological and sedimentological observations have allowed definition of meandering, braided and low-sinuosity fluvial patterns in the Las Plumas Member of the Cerro Barcino Formation. Two unrelated lines of evidence suggest important variations in the palaeodischarge of the fluvial system: (1) common fine-grained

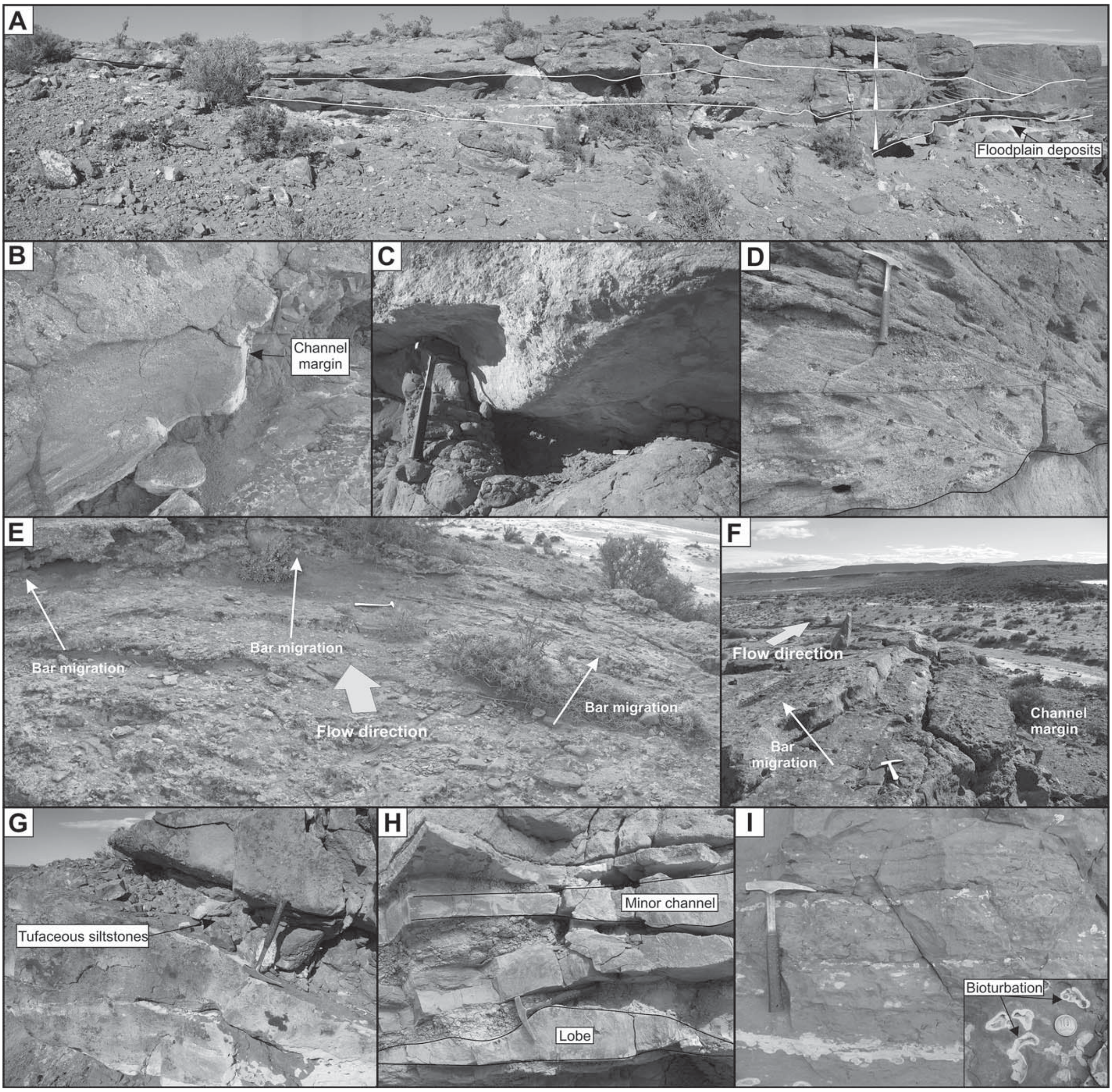

Fig. 6. Sedimentological features of fluvial palaeochannels. A, low-sinuosity, multi-storey palaeochannel with well-defined fining-upward trends; Jacob stick is 1.5 m long. B, erosional base of palaeochannel with abrupt channel margins. C, asymmetric hollow in an erosional base of palaeochannel. D, reactivation surfaces. E, convex morphology (transverse to the flow) of braid-bar deposits (braided palaeochannels). F, oblique migration of a macroform from the palaeochannel margin, interpreted as an alternate bar in a low-sinuosity palaeochannel; hammer is 0.3 m long. G, fine-grained tuffaceous siltstones preserved in the palaeochannel-fill. H, proximal floodplain deposits, comprising intercalated crevasse-splay deposits (lobes), minor floodplain palaeochannels and tuffaceous siltstones. I, reddish tuffaceous, commonly bioturbated, distal floodplain deposits.

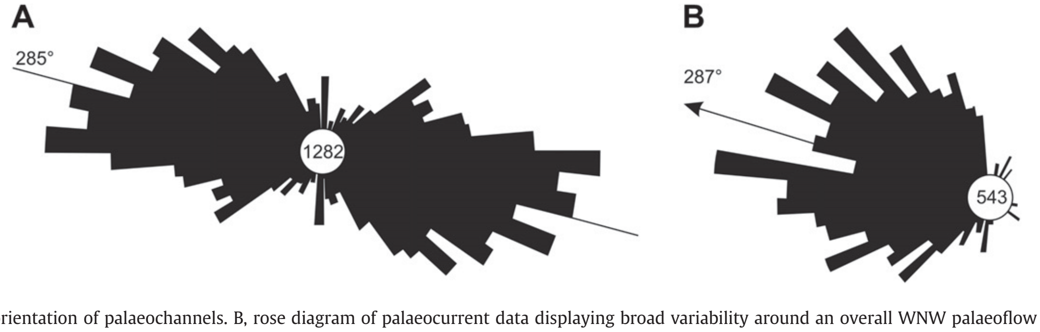

Fig. 7. A, orientation of palaeochannels. B, rose diagram of palaeocurrent data displaying broad variability around an overall WNW palaeoflow direction.

Table 1
Palaeodischarge estimations from channel dimensions, Cerro Barcino Formation (Las Plumas Member). Depths of palaeochannels (d_m) were calculated from measurements of palaeochannel width and *F* ratio ($F = 225 \times M^{-1.08} = 225 \times 10^{-1.08} = 21.21$): $d_m = \text{Width}/F = \text{Width}/21.21$. *Q*, palaeodischarge.

	F (ratio)	Width (m)	Depth (m)	Area (m^2)	Velocity (m/s)	*Q* (m^3/s)
1	21.21	30	1.41	42.4	0.75	31.8
2	21.21	20	0.94	18.9	0.75	14.1
3	21.21	100	4.71	471.5	0.75	353.6
4	21.21	15	0.71	10.6	0.75	8.0
5	21.21	90	4.24	381.9	0.75	286.4
6	21.21	20	0.94	18.9	0.75	14.1
7	21.21	30	1.41	42.4	0.75	31.8
8	21.21	30	1.41	42.4	0.75	31.8
9	21.21	25	1.18	29.5	0.75	22.1
10	21.21	40	1.89	75.4	0.75	56.6
11	21.21	60	2.83	169.7	0.75	127.3
12	21.21	20	0.94	18.9	0.75	14.1
13	21.21	20	0.94	18.9	0.75	14.1
14	21.21	20	0.94	18.9	0.75	14.1
15	21.21	50	2.36	117.8	0.75	88.4
16	21.21	30	1.41	42.4	0.75	31.8

intercalations in multi-storey palaeochannel-fills, providing evidence for periods of slack water during which mud was deposited in shallow parts of the channels (Nichols and Fisher, 2007); (2) multi-storey palaeochannel fills that display vertical variations from braided to low-sinuosity pattern, as recognized by the occurrence of stories containing braid bars among fining-upward stories that lack macroforms or just preserve bars on a single palaeochannel margin. These lines of evidence from discharge variations could indicate seasonal precipitation conditions in the source area during the Late Cretaceous.

Spatio-temporal changes in sinuosity were recognized in some high-sinuosity palaeochannels, where the increase of sinuosity with time represents the normal development of a migrating palaeochannel, whereas downstream changes in the sinuosity (and fluvial style) are attributed to local variations in slope conditions. More typically, rivers undergo minor variations within pattern without undergoing complete shifts in pattern type (Holbrook and Schumm, 1999). The most commonly observed of these intra-pattern adjustments is for a meandering channel to decrease its

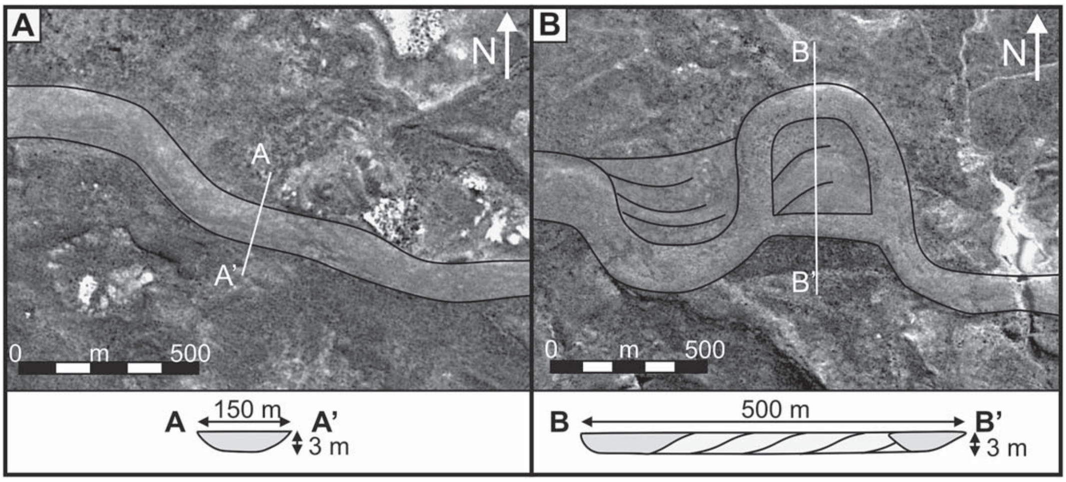

Fig. 8. Changes in the W/Th ratio related to variations in the fluvial style. The vertical scale for palaeochannel schemes is exaggerated.

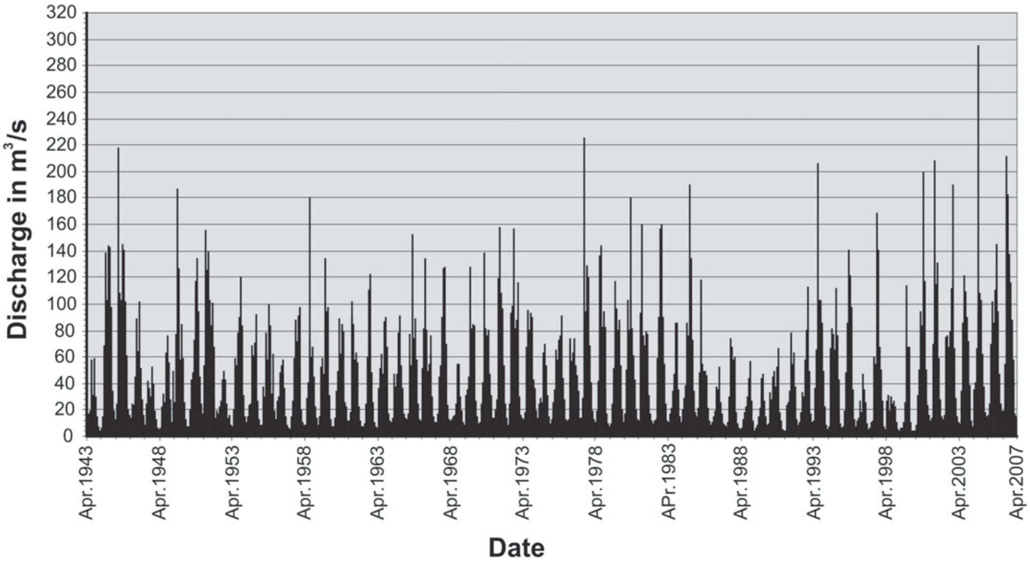

Fig. 9. Hydrograph of the of water discharge (monthly average) from 1943 to 2007 in the Chubut River, Los Altares locality (data from the Secretaría de Obras Públicas – Ministerio de Planificación Federal, Inversión Pública y Servicios de la Nación, facilitated by the Instituto Provincial del Agua de la Provincia del Chubut).

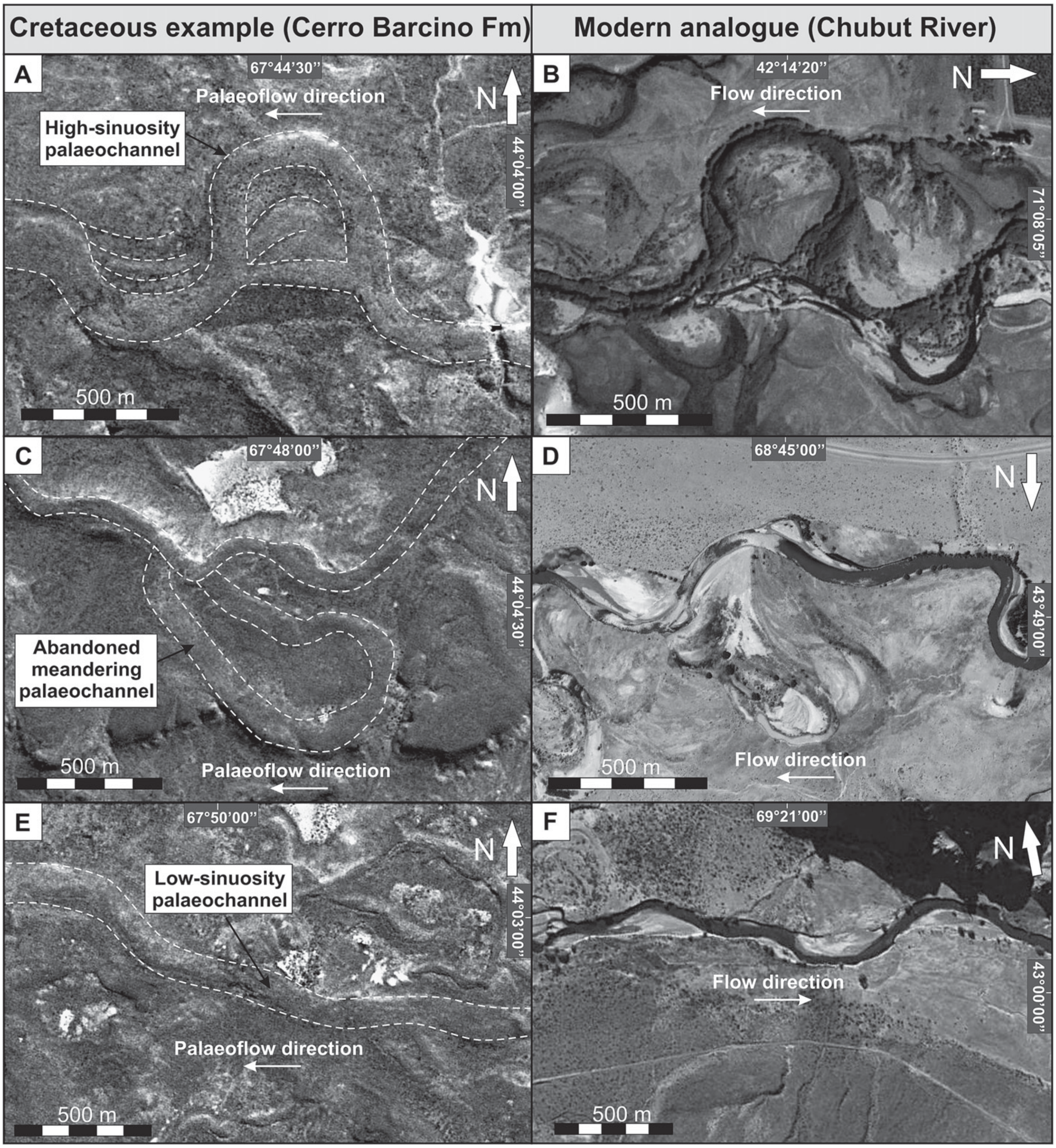

Fig. 10. A, meandering palaeochannel, Cerro Barcino Formation (Las Plumas Member). B, meandering channel of modern Chubut River. C, interpreted abandoned palaeochannel (cutoff), Cerro Barcino Formation. D, abandoned channel (cutoff) adjacent to the modern Chubut River. E, low-sinuosity palaeochannel, Cerro Barcino Formation. F, low-sinuosity pattern with alternate bars, Chubut River.

sinuosity as an adjustment to decreased slope (Ouchi, 1985; Schumm et al., 1994; Holbrook and Schumm, 1999).

Significant variations in the W/Th ratio of sandbodies ($10 > W/Th \sim 100$) are generally related to changes in width and palaeochannel sinuosity, with width increasing in high-sinuosity channels where the sandbodies include a point-bar (Fig. 8). The predominance of low-sinuosity palaeochannels with $W/Th < 15$ implies that the cohesive tuffaceous deposits were an important control on the relatively high stability of the channel margins.

6.2. *A modern analogue*

Further insight into the geomorphology, sedimentology and palaeohydrology of the Cerro Barcino Formation palaeochannels can be provided by a comparison with a modern fluvial system. The Chubut River in central Patagonia is 600 km long, flowing from west to east across Chubut Province. Fluvial style changes downstream several times and includes meandering, low-sinuosity and braided patterns. Hydrological data for the river exist as far back as April 1943, so there is an adequate record of the discharge variations. The hydrograph shows seasonal discharge variation, with values ranging from 3.9 to 295 m^3/s (mean = 48.6 m^3/s; SD = 42.2 m^3/s) (Fig. 9) and maximum instantaneous values up to 478 m^3/s. The annual peak of the hydrograph is mainly related to the melting of snow during the spring in the headwaters of the system in the Andes Cordillera.

The discharge of the Chubut River (3.9–295 m^3/s) and palaeodischarge estimations from the Cerro Barcino Formation (8–353.6 m^3/s) are very similar. These similar variations are also reflected by the near-identical plan-view morphology and channel dimensions of the Chubut River and the exhumed system (Fig. 10).

6.3. *Applications*

This comparative analysis between exhumed and modern channels could have several applications, but can be grouped as follows: (1) It provides a valuable opportunity to test more extensively and perhaps refine the suite of empirical form-process relationships and palaeohydrological equations. (2) It has enabled us to establish an empirical relation between palaeodischarge estimations and sandbody dimensions, showing spatio-temporal changes in the external shape and/or fluvial style of hypothetical reservoir rocks. (3) Future investigation of this Cretaceous example has application not just to understanding terrestrial fluvial evolution, but also will help to constrain the reconstruction of palaeofluvial hydrological parameters from satellite images of another planets.

7. Conclusions

A detailed characterization of three-dimensional exposures of a Cretaceous palaeochannel belt within the Las Plumas Member of the Cerro Barcino Formation (Chubut Group) in the Cañadón Asfalto Basin was carried out. The integration of data from satellite images, field architectural data and palaeohydrological estimations reveal information at several scales regarding the spatio-temporal behaviour of the ancient fluvial system.

The main conclusions of this work are: (1) The plan view shows that the fluvial system is mainly characterized by ribbon-shaped, low-sinuosity palaeochannels encased in a tuffaceous floodplain, and to a lesser extent by meandering palaeochannels. (2) Downstream changes in sinuosity (and fluvial style) are attributed a response to local variations in slope. (3) The fluvial architecture of selected multi-storey sandbodies reveals significant variations in the palaeodischarge, mainly evidenced by preservation of in-palaeochannel muds. (4) The palaeoflow direction obtained suggests that the main depocentre of the Las Plumas Member is located WNW of the study area. (5) The comparison of the size, dimensions and hydrology of the nearby Chubut River with data from the exhumed fluvial succession show a remarkable similarity, suggesting that this river is a suitable modern analogue to the Cretaceous example.

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References

Allard, J.O., Paredes, J.M., Foix, N., Giacosa, R.E., 2010. Variable Response and Depositional Products of Fluvial-Alluvial Fan Systems in Pyroclastic-Rich Successions: Cerro Barcino Formation (Cretaceous) of the Cañadón Asfalto basin, Central Patagonia Argentina. 18th International Sedimentological Congress, Mendoza, 101 pp.

Anselmi, G., Panza, J.L., Cortés, J.M., Ragona, D., 2005. Hoja Geológica 4569-II El Sombrero. Servicio Geológico Minero, Instituto de Geología y Recursos Minerales. Boletín (Buenos Aires) 271, 84 pp.

Bridge, J.S., 1993. Description and interpretation of fluvial deposits: a critical perspective. Sedimentology 40, 801–810.

Brookes, I.A., 2003. Palaeofluvial estimates from exhumed meander scrolls, Taref Formation (Turonian), Dakhla Region, Western Desert, Egypt. Cretaceous Research 24, 97–104.

Butzer, K.W., Hansen, C.L., 1968. Desert and River in Nubia. University of Wisconsin Press, Madison, WI, 562 pp.

Carlston, C.W., 1965. The relation of free meander geometry to stream discharge and its geomorphic implications. American Journal of Science 263, 864–885.

Chebli, G.A., Nakayama, C., Sciutto, J.C., Serraiotto, A.A., 1976. Estratigrafía del Grupo Chubut en la región central de la provincia homónima. Actas 4° Jornadas Geológicas Argentinas 1, pp. 375–392.

Cladera, G., Limarino, C.O., Alonso, M.S., Rauhut, O., 2004. Controles estratigráficos en la preservación de restos de vertebrados en la Formación Cerro Barcino (Cenomaniano), Provincia del Chubut. Revista de la Asociación Argentina de Sedimentología 11, 39–55.

Codignotto, J., Nullo, F., Panza, J., Proserpio, C., 1978. Estratigrafía del Grupo Chubut entre Paso de Indios y Las Plumas, provincia del Chubut, Argentina. Actas 7° Congreso Geológico Argentino, pp. 471–480.

Cortés, J.M., 1987. Estratigrafía del Cretácico entre el arroyo de Las Víboras y la sierra del Guanaco, región central del Chubut, Argentina. Resúmenes, 10° Congreso Geológico Argentino, 28–32, pp. 28–32.

Costa, J.E., 1983. Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range. Geological Society of America, Bulletin 94, 986–1004.

Cuevas Martínez, J.L., Cabrera Pérez, L., Marcuello, A., Arbués Cazo, P., Marzo Carpio, M., Bellmunt, F., 2010. Exhumed channel sandstone networks within fluvial fan deposits from the Oligo-Miocene Caspe Formation, south-east Ebro Basin (north-east Spain). Sedimentology 57, 162–189.

De la Fuente, M.S., Umazano, A.M., Sterli, J., Carballido, J.L., 2011. New chelid turtles of the lower section of the Cerro Barcino formation (Aptian–Albian?), Patagonia, Argentina. Cretaceous Research 32, 527–537.

Edwards, M.B., Eriksson, K.A., Kier, R.S., 1983. Paleochannel geometry and flow patterns determined from exhumed Permian point bars in north-central Texas. Journal of Sedimentary Petrology 53, 1261–1270.

Eriksson, P.G., Bumby, A.J., Brümer, J.J., van der Neut, M., 2006. Precambrian fluvial deposits: enigmatic palaeohydrological data from the c. 2–1.9 Ga Waterberg Group, South Africa. Sedimentary Geology 190, 25–46.

Figari, E., 2011. The Sierra de la Manea Formation (Titho-Neocomian) composite stratotype, Cañadón Asfalto basin, Patagonia, Argentina. XVIII Congreso Geológico Argentino, Resúmenes, 1012–1013.

Figari, E.G., Courtade, S.F., 1993. Evolución tectosedimentaria de la cuenca de Cañadón Asfalto, Chubut, Argentina. 12° Congreso Geológico Argentino, Actas 1 pp. 66–77.

Friend, P.F., Slater, M.J., Williams, R.C., 1979. Vertical and lateral building of river sandstone bodies, Ebro Basin, Spain. Journal of the Geological Society, London 136, 39–46.

Gardner, T.W., 1983. Paleohydrology and paleomorphology of a Carboniferous, meandering, fluvial sandstone. Journal of Sedimentary Research 53, 991–1005.

Genise, J.F., Alonso-Zarza, A.M., Krause, J.M., Sánchez, M.V., Sarzetti, L., Farina, J.L., González, M.G., Cosarinsky, M., Bellosi, E.S., 2010. Rhizolith balls from the Lower Cretaceous of Patagonia: just roots or the oldest evidence of insect agriculture? Palaeogeography, Palaeoclimatology, Palaeoecology 287, 128–142.

Gibling, M.R., 2006. Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification. Journal of Sedimentary Research 76, 731–770.

Holbrook, J.M., Schumm, S.A., 1999. Geomorphic and sedimentary response of rivers to tectonic deformation: a brief review and critique of a tool for recognizing subtle epeirogenic deformation in modern and ancient settings. Tectonophysics 305, 287–306.

King, L.C., 1942. South African Scenery. Oliver & Boyd, Edinburgh, 340 pp.

Köykkä, J., 2011a. Precambrian alluvial fan and braidplain sedimentation patterns: example from the Mesoproterozoic Rjukan Rift Basin, southern Norway. Sedimentary Geology 234, 89–108.

Köykkä, J., 2011b. The sedimentation and paleohydrology of the Mesoproterozoic stream deposits in a strike-slip basin (Svinsaga Formation), Telemark, southern Norway. Sedimentary Geology 236, 239–255.

Leopold, L.B., Wolman, G.M., Miller, J.P., 1964. Fluvial Processes in Geomorphology. Freeman and Company, San Francisco, CA, 522 pp.

Maizels, J., 1990. Raised channel systems as indicators of palaeohydrologic change: a case study from Oman. Palaeogeography, Palaeoclimatology, Palaeoecology 76, 241–277.

Manassero, M., Zalba, P.E., Andreis, R., Morosi, M., 1998. Estratigrafía y composición de sucesiones volcaniclásticas de la Formación Cerro Barcino (Grupo Chubut, Cretácico Superior) entre Los Altares y Las Plumas, Chubut, Argentina. VII Reunión Argentina de Sedimentología, Actas I, pp. 213–215.

Manassero, M., Zalba, P.E., Andreis, R., Morosi, M., 2000. Petrology of continental pyroclastic and epiclastic sequences in the Chubut Group (Cretaceous): Los Altares-Las Plumas area, Chubut, Patagonia Argentina. Revista Geológica de Chile 27, 13–26.

Marveggio, N., Llorens, M., 2011. Nueva edad de la roca hospedante de la mineralización de uranio – Yacimiento Cerro Solo – Provincia del Chubut. XVIII Congreso Geológico Argentino, Resúmenes, pp. 941–942.

Miall, A.D., 1996. The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis and Petroleum Geology. Springer-Verlag, Berlin, 582 pp.

Miller, R.P., 1937. Drainage lines in bas-relief. Journal of Geology 45, 432–438.

Musacchio, E., 1972. Charophytas del Cretácico Inferior en sedimentitas chubutenses al este de La Herrería, Chubut. Ameghiniana 9, 354–356.

Musacchio, E.A., Chebli, G.A., 1975. Ostrácodos no marinos y carófitas el cretácico inferior en las provincias de Chubut y Neuquén, Argentina. Ameghiniana 12, 70–96.

Nichols, G.J., Fisher, J.A., 2007. Processes, facies and architecture of fluvial distributary system deposits. Sedimentary Geology 195, 75–90.

Ouchi, S., 1985. Response of alluvial rivers to slow active tectonic movement. Geological Society of America, Bulletin 96, 504–515.

Padgett, G.V., Ehrlich, R., 1976. Paleohydrologic analysis of a late Carboniferous fluvial system, southern Morocco. Geological Society of America, Bulletin 87, 1101–1104.

Rabelo, I.R., Luthi, S.M., Van Vliet, L.J., 2007. Parameterization of meander-belt elements in high-resolution three-dimensional seismic data using the GeoTime cube and modern analogues. In: Davies, R.J., Posamentier, H.W., Wood, L.J., Cartwright, J.A. (Eds.), Seismic Geomorphology: Applications to Hydrocarbon Exploration and Production. Geological Society, London, Special Publication 277, pp. 121–137.

Rauhut, O.W.M., Cladera, G., Vickers-Rich, P., Rich, T.H., 2003. Dinosaur remains from the Lower Cretaceous of the Chubut Group, Argentina. Cretaceous Research 24, 487–497.

Reeves, T., 1983. Pliocene channel calcrete and suspenparallel drainage in West Texas and New Mexico. In: Wilson, R.C.L. (Ed.), Residual Deposits –Surface Related Weathering Processes and Materials. Geological Society, London, Special Publication 11, pp. 178–183.

Rich, T.H., Vickers-Rich, P., Novas, F.E., Cuneo, R., Puerta, P., Vacca, R., 2000. Theropods from the "Middle" Cretaceous Chubut Group of the San Jorge sedimentary basin, central Patagonia. A preliminary note. Gaia 15, 111–115.

Schumm, S.A., 1968a. River Adjustment to Altered Hydrologic Regimen, Murrumbidgee River and Palaeochannels, Australia United States Geological Survey, Professional Paper 598, 65 pp.

Schumm, S.A., 1968b. Speculations concerning palaeohydrologic controls of terrestrial sedimentation. Geological Society of America, Bulletin 79, 1573–1588.

Schumm, S.A., 1972. Fluvial paleochannels. In: Rigby, J.K., Hamblin, W.K. (Eds.), Recognition of Ancient Sedimentary Environments. Society of Economic Paleontologists and Mineralogist, Special Publication 16, pp. 98–107.

Schumm, S.A., 1985. Patterns of alluvial rivers. Annual Review of Earth and Planetary Sciences 13, 5–27.

Schumm, S.A., Rutherfurd, I.D., Brooks, J., 1994. Pre-cutoff morphology of the lower Mississippi River. In: Schumm, S.A., Winkley, B.R. (Eds.), The Variability of Large Alluvial Rivers. American Society of Civil Engineers Press, New York, pp. 13–44.

Smith, R.M.H., 1987. Morphology and depositional history of exhumed Permian point bars in the southwestern Karroo, South Africa. Journal of Sedimentary Petrology 57, 19–29.

Walker, R.G., Cant, D.J., 1979. Sandy fluvial systems. In: Walker, R.G. (Ed.), Facies Models. Geoscience Canada Reprint Series 1, Waterloo, pp. 23–31.

Williams, G.P., 1986. River meanders and channel size. Journal of Hydrology 88, 147–164.

Williams, R.M.E., Chidsey, T.C., Jr., Eby, D.E., 2007. Exhumed paleochannels in central Utah – analogs for raised curvilinear features on Mars. In: Willis, G.C., Hylland, M.D., Clark, D.L., Chidsey, T.C., Jr. (Eds.), Central Utah – Diverse Geology of a Dynamic Landscape. Utah Geological Association, Salt Lake City, Publication 36, pp. 221–235.

Williams, R.M.E., Irwin, R.P., III, Zimbelman, J.R., 2009. Evaluation of paleohydrologic models for terrestrial inverted channels: implications for application to Martian sinuous ridges. Geomorphology 107, 300–315.