ELSEVIER

Marine and Petroleum Geology 21 (2004) 613–638

Marine and Petroleum Geology

www.elsevier.com/locate/marpetgeo

Sedimentation in a discharge dominated fluvial-lacustrine system: the Neogene Productive Series of the South Caspian Basin, Azerbaijan

D.J. Hinds[a,b,c], E. Aliyeva[d], M.B. Allen[b,*], C.E. Davies[b], S.B. Kroonenberg[e], M.D. Simmons[b,f], S.J. Vincent[b]

[a]Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen AB24 3UE, UK
[b]CASP, Department of Earth Sciences, University of Cambridge, 181A Huntingdon Road, Cambridge CB3 0DH, UK
[c]ExxonMobil, Greenspoint 8, 222 Benmar, Houston, TX 77060, USA
[d]Geology Institute of the Azerbaijan Academy of Sciences, 29A H. Javid Prospect, Baku, Azerbaijan
[e]Department of Applied Earth Sciences, Delft University of Technology, Mijnbouwstr 120, NL-2628 RX Delft, Netherlands
[f]Neftex Petroleum Consultants Ltd, 71, The Business Development Centre, Milton Park, Abingdon, Oxfordshire OX14 4RX, UK

Received 13 July 2002; received in revised form 10 January 2004; accepted 20 January 2004

Abstract

The largely lower Pliocene Productive Series and its regional equivalents contain the major hydrocarbon reservoirs of the South Caspian Basin. Examination of outcrops in the Apsheron region, Azerbaijan, has resulted in re-interpretation of the depositional environments of the Productive Series. The lower part of the Productive Series consists of sandstones and mudstones interpreted as channelised and sheetflood fluvial deposits, intercalated with mudstones that represent short-lived lacustrine transgressions of a regional Caspian lake. The upper Productive Series (Pereriva and younger suites) comprises sandstone-prone intervals, interpreted as deposition during periods of increased fluvial discharge and sediment supply, and mudstone-prone intervals, interpreted as deposition during periods of decreased discharge and therefore coarse-grained sediment starvation. Sand-prone reservoir intervals in the Pereriva and overlying Balakhany suites mainly comprise amalgamated low sinuosity, braided fluvial sheet sandstones. Mudstone-rich intervals form inter- and intra -suite seals, comprising alluvial plain and lacustrine facies. The succession displays an overall fining-up trend, which is controlled by long-term climatic cooling, decreased fluvial discharge and reduced coarse clastic input. The modern Volga/Caspian system is a partial analogue for the lower Productive Series in the Apsheron region, where fluvial and lacustrine conditions alternate on a low-gradient ramp, without evidence for a shelf-break. Lake Eyre, Australia, may be a modern analogue for the upper Productive Series, where there are fewer lacustrine influences discernible in the sedimentology and the overall setting resembles a dryland river/terminal fan.

Keywords: South Caspian; Basin; Fluvial; Terminal fan; Dryland river

1. Introduction

The main reservoir unit and the principal exploration target in the South Caspian Basin (Fig. 1) is the Productive Series, which is a non-marine clastic succession that reaches 5–7 km thickness in the basin interior (Ali-Zade, Salaev, & Aliev, 1985). It was deposited over ~2 million years, mainly in the early Pliocene (Jones & Simmons, 1996). This paper describes the sedimentology of these rocks from the Apsheron Peninsula area, onshore Azerbaijan (Fig. 2), and interprets their depositional setting. It aims to provide an improved understanding of the local and basin-scale distribution of potential reservoir sands in the South Caspian, and to illustrate an example of rapid non-marine clastic deposition during major tectonic subsidence (Allen, Jones, Ismail-Zadeh, Simmons, & Anderson, 2002).

Reynolds et al. (1998) published the first modern process sedimentology-based review of Productive Series outcrops, which are thought to be largely analogous to their offshore equivalents adjacent to the Apsheron Peninsula. Reynolds et al. (1998) interpreted the alternation of sandstone- and mudstone-dominated facies, which characterise the Productive Series, as representing the repeated juxtaposition of proximal and distal fluvio-deltaic environments, principally in response to high frequency base-level fluctuations.

* Corresponding author. Tel.: +44-1223-337-068; fax: +44-1223-276-604.
E-mail address: mark.allen@casp.cam.ac.uk (M.B. Allen).

0264-8172/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpetgeo.2004.01.009

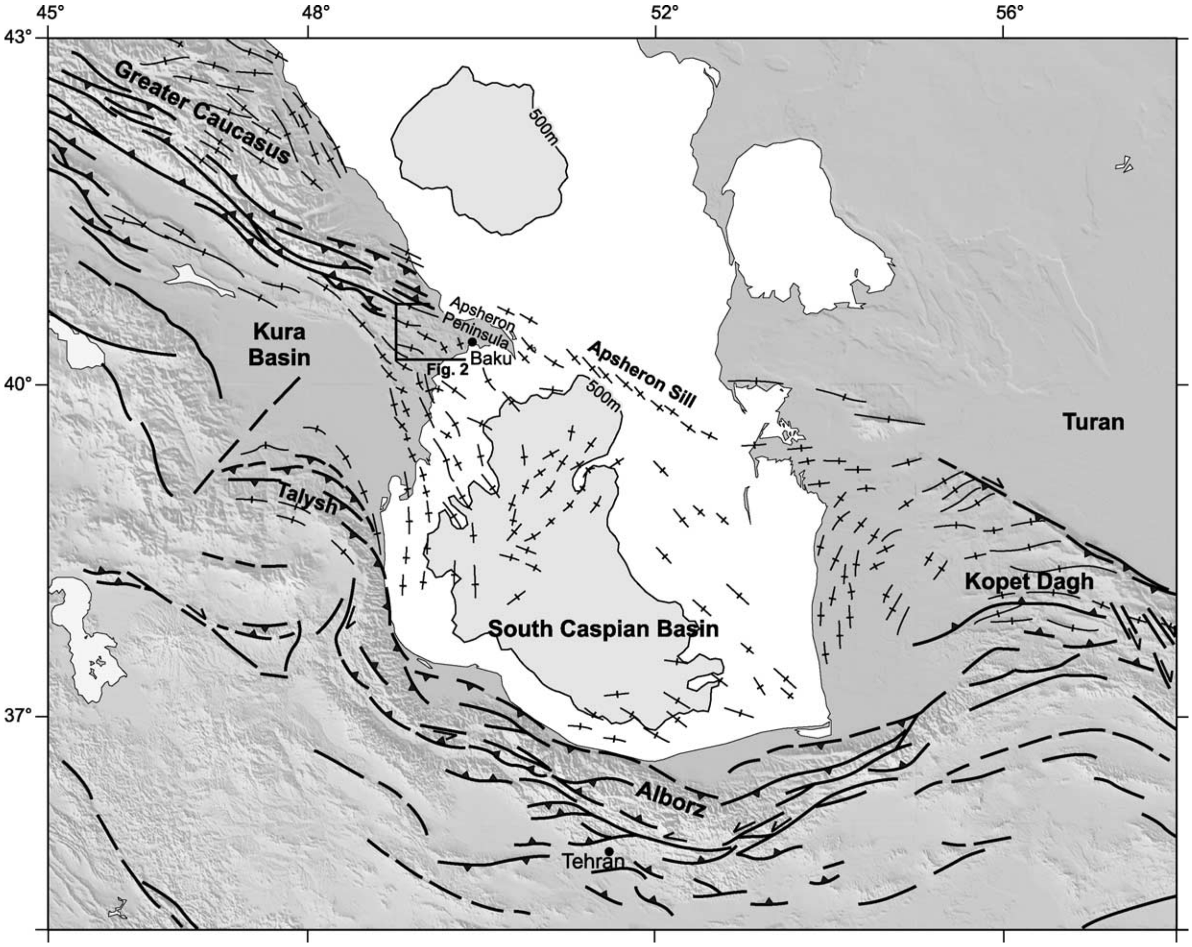

Fig. 1. Neotectonic structures of the South Caspian Basin and adjacent areas. From Jackson et al. (2002).

This paper presents new sedimentological observations, which indicate that much of the Productive Series in the Apsheron area was deposited in more fluvially dominated settings than previously proposed. We propose partial analogies with the modern Volga/Caspian system (Kroonenberg, Rusakov, & Svitoch, 1997) for the lower Productive Series (up to the top of the Post-Kirmaky Clay Suite; Fig. 3), and with dryland rivers for the upper Productive Series (Pereriva and overlying suites), of the kind in central Australia (e.g. Croke, Magee, & Price, 1996; Tooth, 2000). The origins of the mudstones in particular are re-interpreted in the light of new field data. The interpretations presented here suggest that discharge variations, perhaps climatically controlled, were the dominant control on the development of the sedimentary succession.

2. Geological setting

2.1. Regional tectonics

The South Caspian Basin has basement with the geophysical properties of either unusually thick oceanic crust, or thinned, high velocity continental crust. This basement is overlain by ~20 km of sediments (Mangino & Priestley, 1998). The age of the basement and the origin of the basin are in dispute. Most published models postulate ages between the Jurassic (Zonenshain & Le Pichon, 1986) and Paleocene (Berberian, 1983), in back-arc settings to the Neo-Tethyan subduction under Eurasia.

The South Caspian basement is in the initial stages of subduction under its northern margin (Jackson, Priestley, Allen, & Berberian, 2002), and is overthrust from other margins (Allen, Vincent, Alsop, Ismail-zadeh, & Flecker, 2003). Complex fold patterns deform the basin interior (Fig. 1); many folds began to form near the end of Productive Series deposition (Devlin et al., 1999).

2.2. Stratigraphy

Deposition of the Productive Series is thought to have been initiated by a dramatic drop in base level (of between 600 and 1500 m) following the complete isolation of the South Caspian Basin from the global ocean system in the latest Miocene (Reynolds et al., 1998). Jones and Simmons (1996) tentatively correlate basin isolation and base level lowering in the South Caspian Basin to the 5.5 Ma late Messinian isolation of the Mediterranean Sea. As a result,

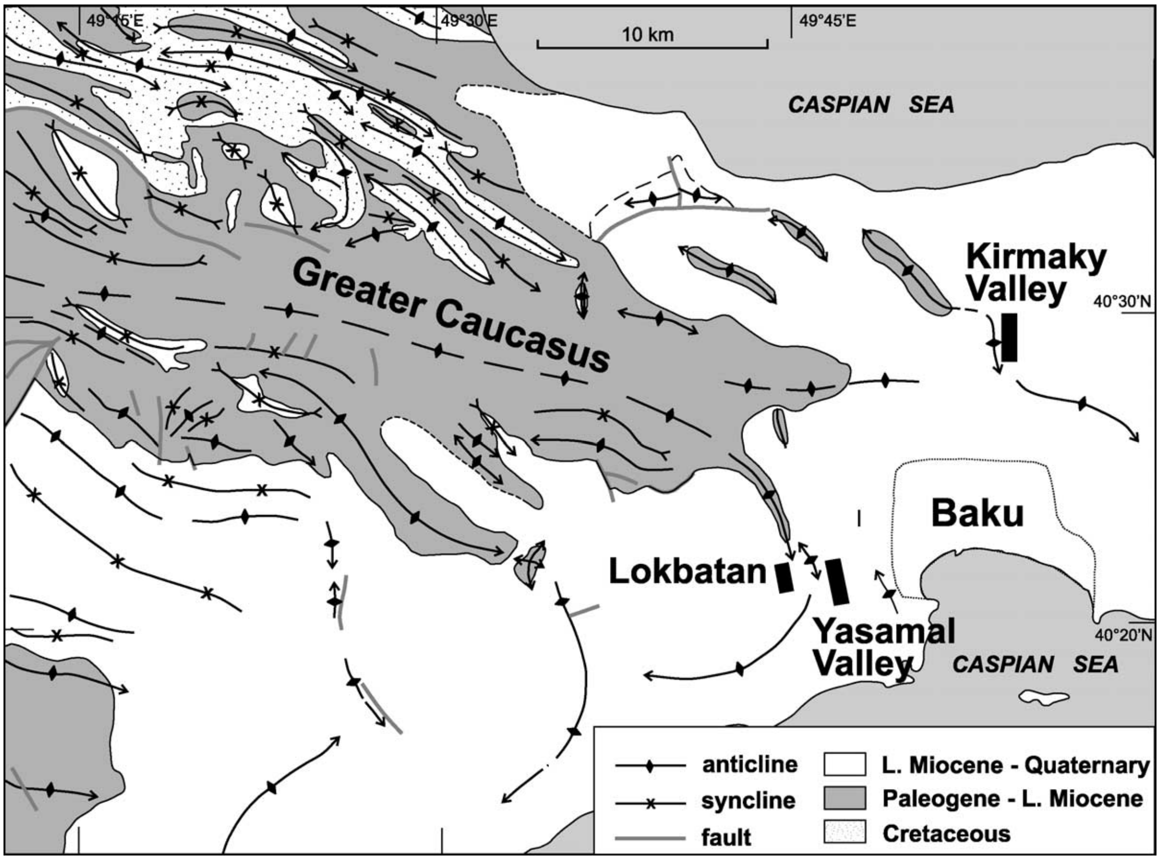

Fig. 2. Geology of the eastern Greater Caucasus and the western portion of the Apsheron Peninsula, showing the location of the study areas of this paper.

major river systems such as the palaeo-Volga and palaeo-Amu Darya were focused into the South Caspian Basin, resulting in deposition of the Productive Series, which accumulated to a thickness of between 5 and 7 km in the basin interior (Abrams & Narimanov, 1997; Abdullaev et al., 1998). Thicknesses across the Apsheron Peninsula and along the Apsheron Sill are lower, in the order of 1.5 km.

Productive Series deposition is thought to span the latest Miocene—early Pliocene from around 5.5 until 3.4 Ma (Jones & Simmons, 1996). Together with upper Pliocene and Pleistocene units, as much as 10 km of sediment have been deposited in the basin interior since ~5.5 Ma. Therefore about half the basin fill has accumulated in less than the last tenth of the basin's history, coincident with a marked increase in tectonic subsidence rate (Allen et al., 2002).

In the Apsheron Peninsula region, the Productive Series is conventionally sub-divided (Uskin, 1916) into nine suites based on gross lithological characteristics (Fig. 3; the lowermost Kalin Suite is distributed basin-wide, but does not crop out, and is not discussed in this paper). The Balakhany Suite is further divided into six lithologically defined subunits numbered X–V from base to top. These suites and subunits of suites are readily identifiable on wireline logs, and are thought to be roughly equivalent to regionally mappable formations.

Despite poor biostratigraphic control, regional lithostratigraphic correlation of individual suites is possible. This led Reynolds et al. (1998) to speculate that individual suites may be bound by surfaces of chronostratigraphic importance. In addition, the Productive Series is informally divided into lower and upper parts, with the boundary at the base of the Pereriva Suite.

3. Field localities and methods

This work is based on three localities on the Apsheron Peninsula: Kirmaky Valley, Yasamal Valley, and at Lokbatan (Fig. 2). Note that the Productive Series also crops out west of the Caspian near the modern Kura River, but these strata are deposits of the palaeo-Kura and represent a different depositional system to the exposures described in this paper. Deposits of both the lower and upper Productive Series crop out in Kirmaky Valley, 12 km north of Baku. Strata are exposed across a Quaternary wave-cut platform on the eastern limb of Kirmaky anticline. The north-south orientation of Kirmaky Valley, parallel to the mean palaeocurrent direction of Productive

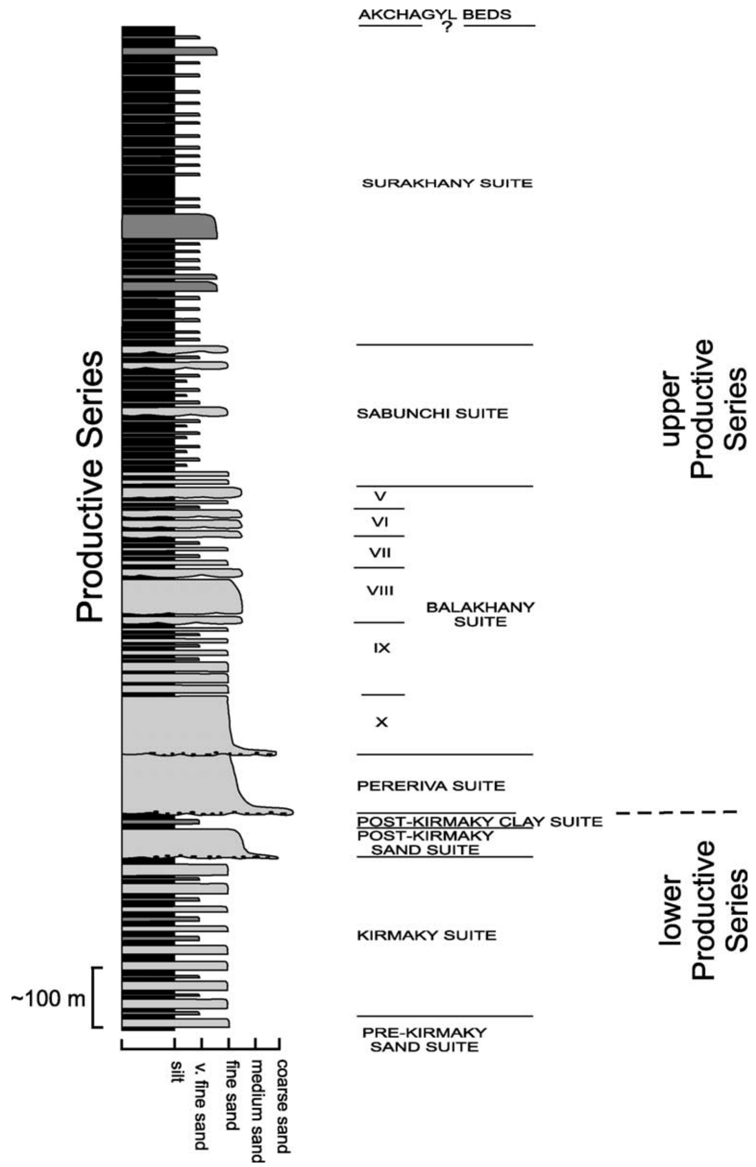

Fig. 3. Schematic composite stratigraphic column based upon tentative correlation of measured sections at Kirmaky valley, Yasamal Valley, and Lokbatan outcrops. Diagram summarises the gross vertical changes in lithology through the Productive Series that are conventionally used to define suites and their subunits (The Kalin and Pre-Kirmaky suites which underlie the Kirmaky Suite are not part of this study).

Series deposits, results in dominantly depositional dip-orientated exposure.

The upper Productive Series is exposed at Yasamal Valley, 10 km west of Baku. Strata are best exposed along a section along the axis of a south-southeast plunging anticline. The east-west orientation of the outcrop along the anticline's axis gives excellent depositional strike-oriented exposure. The Surakhany Suite (uppermost Productive Series) is exposed on the western flank of an anticline at Lokbatan, located 12 km west of Baku. Exposure is of moderate quality as the succession is predominantly fine-grained, poorly consolidated and disrupted by a number of small-scale faults. However, it is possible to demonstrate continuity of section from the underlying Sabunchi Suite (Fig. 3).

About 2 km of sedimentary logs were measured at a centimetre scale at the three localities. Maps of the vertical and lateral variability in sedimentary architecture were constructed in the field and on photomosaics.

4. Lithofacies description and interpretation

This section describes and interprets the sedimentary characteristics of each suite in turn. Outcrop photographs are shown in Fig. 4, sedimentary architecture maps in Fig. 5, and palaeocurrent rose diagrams on Fig. 6. Representative sedimentary logs of each suite are shown in Figs. 7 and 8, and photomosaics for parts of the Balakhany Suite in Fig. 9. The Pre-Kirmaky Sand Suite is poorly exposed within Kirmaky Valley and so is not described.

4.1. Kirmaky Suite

4.1.1. Lithofacies

In Kirmaky Valley, the Kirmaky Suite is approximately 270 m thick, although the contact with the underlying Pre-Kirmaky Sand Suite is gradational and its base is nowhere clearly defined. The Kirmaky Suite can be divided into sand-prone upper and lower portions, separated by a slightly more argillaceous mid-section (Fig. 3). The large-scale vertical sedimentary architecture displays regular

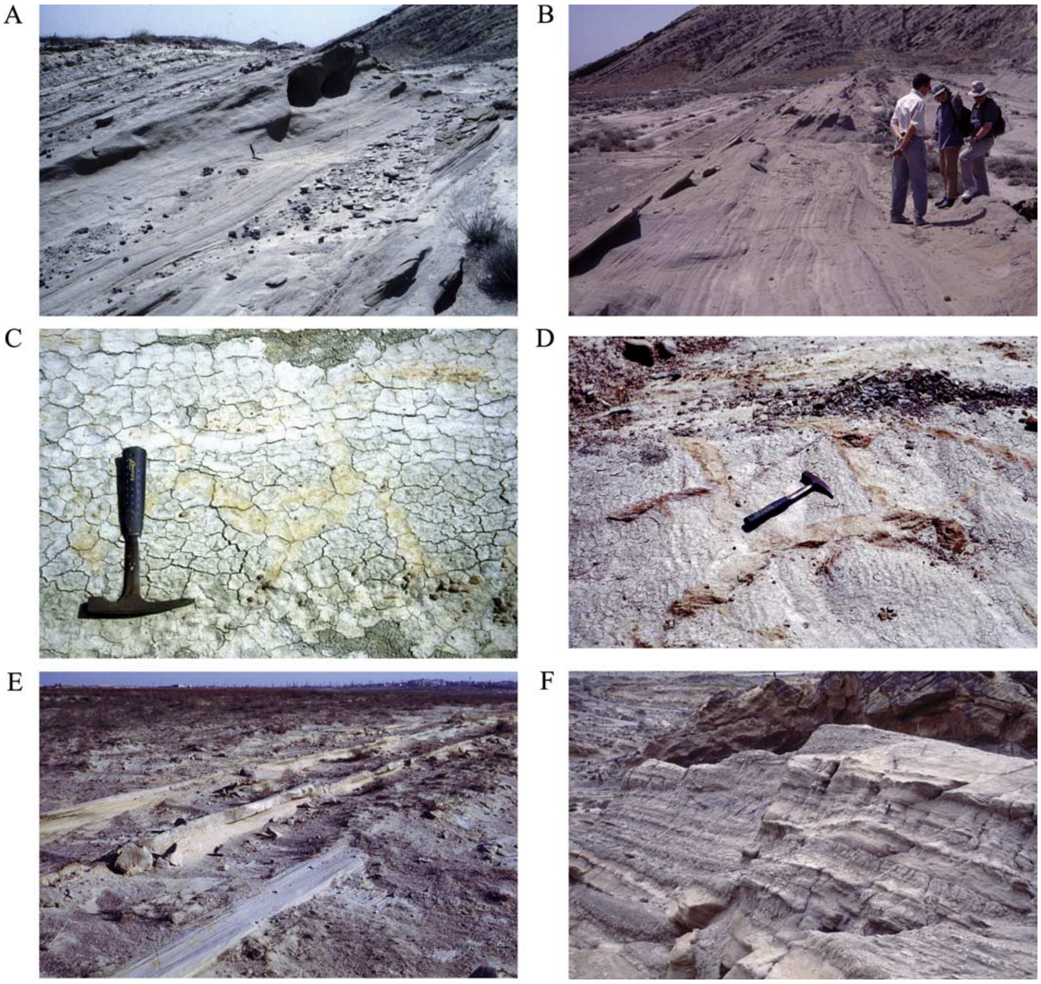

Fig. 4. (A) Kirmaky Suite type (a) sandstone package about 5 m in thickness (correcting for tectonic dip) and extends laterally for more than 100 m. Channel is approximately 1.5–2 m in thickness and 30 m in width. Heterolithic mudstone package facies directly overlie the planar upper contact of the sandstone package. The channel has higher relief than surrounding sandstone and encasing mudstones due to intense bitumen staining. (B) Kirmaky Suite type (b) sandstone package comprised predominantly of parallel laminated sandstone displaying local internal scour surfaces. Sandstone package is approximately 2 m in thickness (correcting for tectonic dip) and laterally continuous for over 100 m. Note local bedding-parallel calcite cementation. (C) Reddened, sand-filled desiccation cracks in mudrocks from a bed 116 m above the base of the Kirmaky Suite, Kirmaky Valley. (D) Large, reddened, sand-filled desiccation cracks in mudstones of the basal portion of the Post Kirmaky Clay Suite. Several similar exposure surfaces are present throughout the suite. (E) Sheet sandstones of the Pereriva Suite comprised predominantly parallel laminated and low-angle cross-bedded medium to fine sand. Note laterally discontinuous bedding-parallel calcite cementation. (F) Balakhany Suite subunit IX. 4 m thick coarsening- and thickening- upward package comprised of climbing ripple laminated, amalgamated beds of siltstone, silty-sandstone and fine sandstone. Mudstone filled channel partially erosively truncates the topmost and thickest sandstone bed. Capping mudstone displays desiccation cracks. (G) Contact of the cliff-forming, sand-prone Balakhany subunit VIII (left) with the underlying mudstone-rich subunit IX (right). Note the thin, laterally continuous, tabular silty-sandstones of subunit IX and the relatively planar erosive base of subunit VIII. (H) Detail of Balakhany Subunit V, Yasamal Valley. The sandstone (B) is ~1 m thick and forms the top of a weakly developed coarsening- and thickening-upward package, ~3.5 m thick. The body of (B) comprises parallel to low-angle cross-stratified, and climbing ripple cross-laminated fine-grained sandstone, with trough shaped, cut and fill channels (F). A heterolithic filled channel bisects the bed (C). A reddened horizon represents abandonment and stabilization of the upper surface of the sheet (R). The outcrop is at ~262 m on the log of Fig. 8C. (I) Panorama of part of the Sabunchi Suite displaying the highly ordered vertical stacking of 4–6 m thick, laterally continuous, sheet-like, coarsening- and thickening-upward packages. Vegetated flat irons commonly mark the coarser grained tops to packages. (J) Varicoloured (grey, brown and red) mudstone, siltstone and silty-sandstone of the Surakhany Suite. The tops of weakly developed coarsening-upward packages are defined by the lighter coloured silty-sandstones which display a regular spacing of approximately 5 to 6 m. (K) Cumuloform in situ gypsum precipitation, Surakhany Suite.

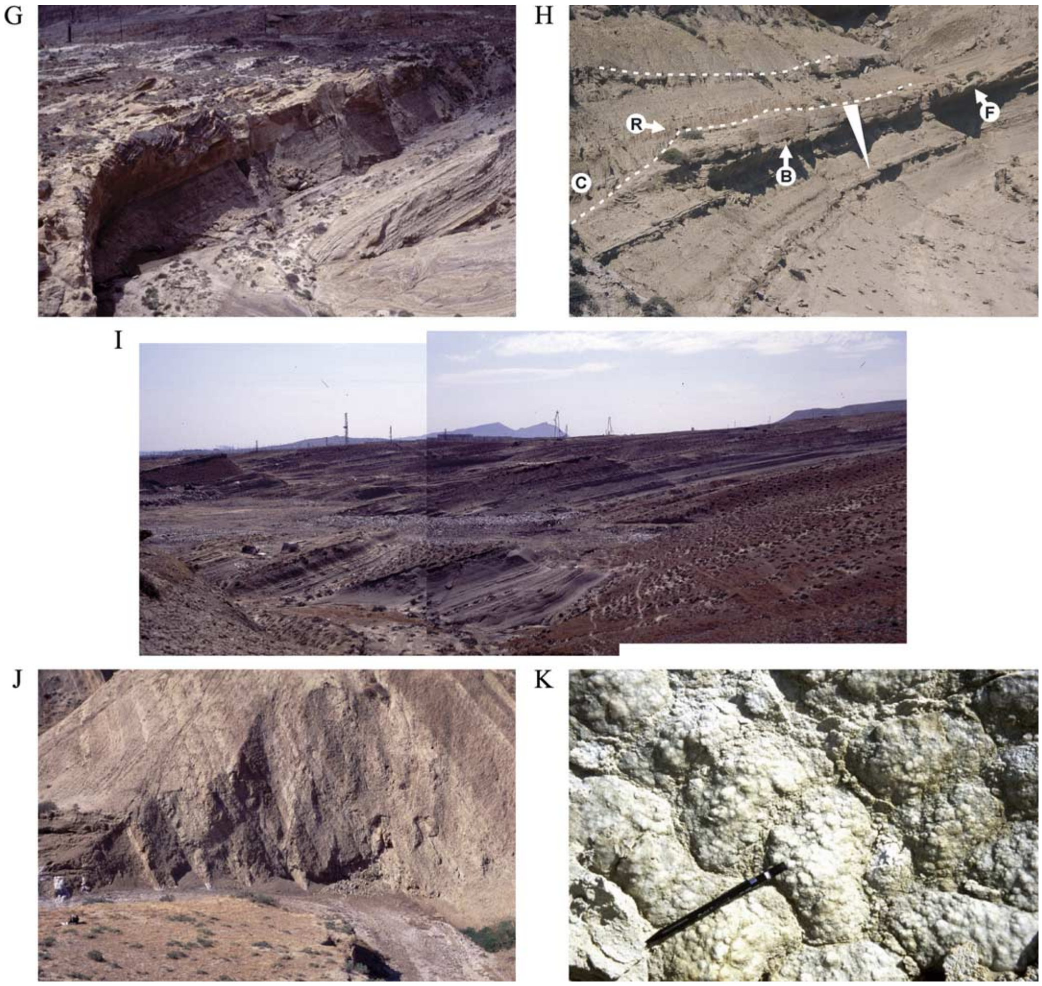

Fig. 4 (*continued*)

alternations between packages of mudstones and sandstones between 2 and 8 m in thickness (Fig. 7A). Laterally, these packages have a sheet-like geometry in dip section, and are continuous over many hundreds of metres showing only minor changes in thickness.

Sandstone packages can be broadly divided into type (a) and type (b) architectural geometries, although some features are common to both types (Fig. 4A and B). For example, sandstone package grain-size ranges from fine to very fine sand throughout. Individual sandstones display little change in grain size (Fig. 7A). Coarsening-up packages are not strongly apparent in the log of Fig. 7A, although note the interval between 110–115 m. Rare gutter casts, and basal lags may occasionally contain small amounts of very coarse sand. Sandstone colour varies from yellow, to bitumen stained brown and calcite cemented steel grey sandstone. Cemented sandstones comprise localised doggers or more laterally continuous horizons coincident with sedimentary bounding surfaces (Fig. 4B). The tops of beds locally display reddened rootlet casts.

Type (a) sandstone packages range from between 2 to 7 m in thickness, and are composed of amalgamated, sharp-based, channels, commonly 1–2 m in thickness and 30–40 m in width (Fig. 4A). Intraformational mud clast conglomerate may line basal contacts. Channels predominantly display a simple fill of low-angle cross bedding or parallel lamination, which passes upwards to climbing ripple cross lamination. Higher angle foresets and chaotic bedding form a lesser component of their fills. Locally, type (a) sandstones thicken as they incise between 1 and 2 m into type (b) sandstones and mudstone packages. These incised sandstones are highly amalgamated, display sub-vertical channel margins, shallow dipping foresets oriented oblique to the channel axes, and cross-bedded and chaotic fills (Fig. 5A). Type (a) sandstone packages comprise approximately 60 to 70% of the succession.

Type (b) sandstone packages range in thickness from between 1.5–7 m, and comprise individual beds between 0.5 and 3 m in thickness. Individual beds commonly display a sharp, planar base locally lined with intraformational mud clasts (Fig. 4B). The dominant sedimentary structures include parallel or subparallel lamination, with very low-angle internal truncation surfaces, which pass upwards into climbing ripple lamination. Convolute

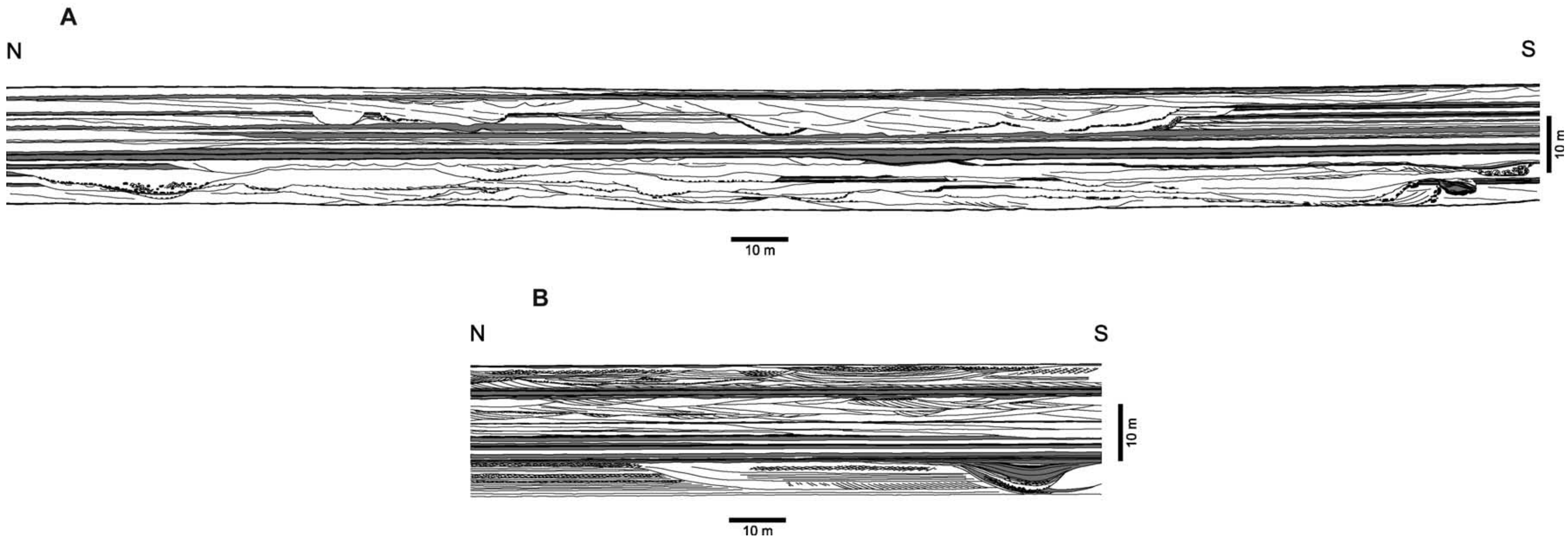

Fig. 5. Maps of the sedimentary architecture of portions of the Kirmaky Suite. (A) Channel complex exhibiting both abrupt channel margins with bank collapse features, and lateral gradation away from the channel axis into overbank sheetsands. (B) Abandoned channel fill truncating amalgamated sheetflood sandstone.

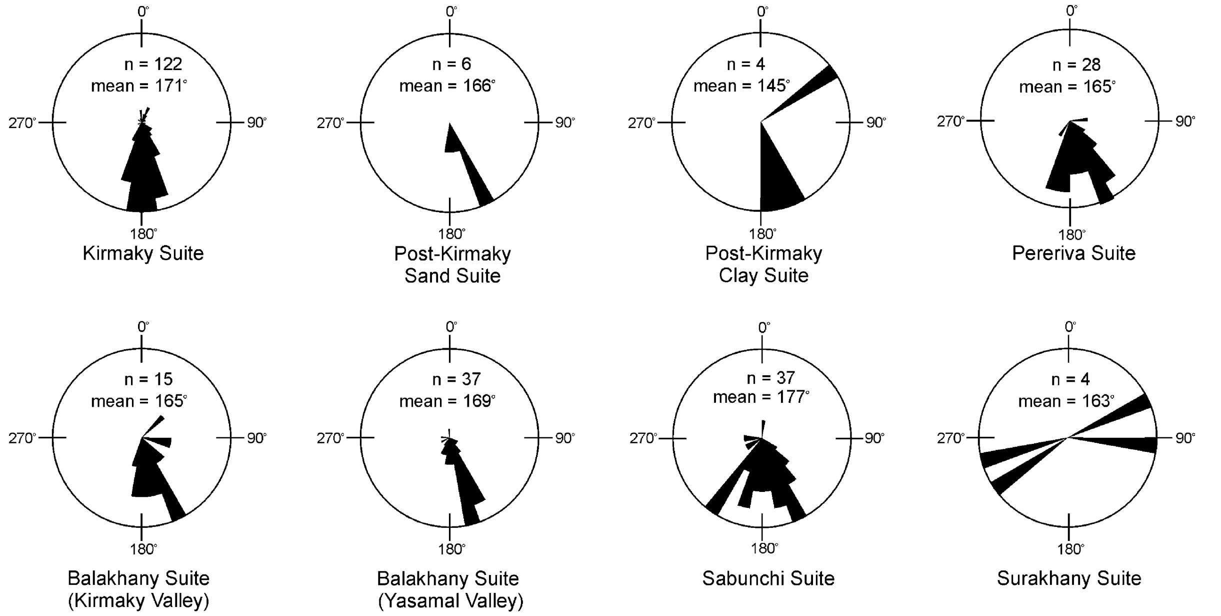

Fig. 6. Palaeocurrent rose diagrams. See text for discussion.

lamination is common. Composite bedsets display repeated motifs of parallel and climbing ripple cross lamination (Fig. 5B).

Fine-grained packages vary in thickness from between 2 to 8 m and comprise centimetre to decimetre thick, interbedded, clay, silt, silty sand, and very fine sand (Figs. 7A and 4A). Black, dark brown and grey silt form the dominant lithology. Clay forms a relatively minor component of the lithofacies, but distinctive, thin, laterally continuous, black, plastic clays are associated with most fine-grained packages. Some of these mudstones have sand-filled desiccation cracks (Fig. 4C): there are at least six beds with desiccation cracks in the lower 170 m of the section. There are at least nine beds with mottling and/or rootlets in the upper 110 m of the section.

Beds of very fine sand and silty-sand up to 1 m in thickness exhibit sharp, planar bases, which are occasionally lined with intraformational mud clasts. Sedimentary structures include parallel lamination, climbing ripple lamination, and convolute lamination. Rare, thin, orange-brown sandstone beds effervesce strongly in dilute HCl. At least ten shallow (<5 m), massive, structureless, clay- or silt-filled, scours and channels erosively truncate the tops of sandstone beds, such that sandstones thin laterally and typically disappear completely. Alternatively, mudstone-filled scours rest entirely within clay and siltstone facies. In one location a single mudstone-filled channel truncates an entire 5 m thick sandstone package (Fig. 5B). In this case the fill consists of at least 10 thinly bedded clay, silt and sandstone beds.

Palaeocurrent vectors within the Kirmaky Suite are dominantly towards the SSE (Fig. 6), based principally on cross-bedding and cross-lamination. However, there are oblique cross sectional views of channel forms in the N–S oriented valley floor, indicating that there is more variation in palaeocurrent orientation than is apparent on Fig. 6. A few vectors display a northerly orientation.

Microfauna and microflora recovered from some, but not all, of the mudstone packages within the Kirmaky Suite at Kirmaky Valley *(unpublished data and work in progress)* suggest high frequency lacustrine transgressions. Some mudstone intervals contain significant numbers of low salinity/?freshwater tolerant dinocysts. Such microflora, coupled with the presence of rare low salinity tolerant foraminifera and ostracods, suggests that these mudstones were deposited in a brackish standing body of water (i.e. expansion of the palaeo-Caspian Sea/lake). However, other and often juxtaposed mudstones do not contain such microfossils, and instead contain pollen and spores either derived from vegetation of the hinterland or which could live on an arid, sometimes desiccated, floodplain. *Pediastrum*-rich mudstones were probably deposited in standing bodies of freshwater on the floodplain (i.e. ephemeral or ox-bow lakes). Freshwater ostracods and charophytes may also be present in these types of mudstones. Fungi-rich horizons may represent the proximity of palaeosols.

4.1.2. Interpretation

Our interpretation of the Kirmaky Suite at Kirmaky Valley is of packages deposited in sheetflood-dominated, alluvial plain settings, intercalated with lacustrine and fluvial overbank mudrock intervals. The suite is 'deltaic' in the sense that the lacustrine intervals suggest drainage terminated in a standing body of water, but little evidence for delta front processes is obvious in our data. We propose that fluvial and lacustrine environments alternated during frequent regressions and transgressions on a gently-dipping

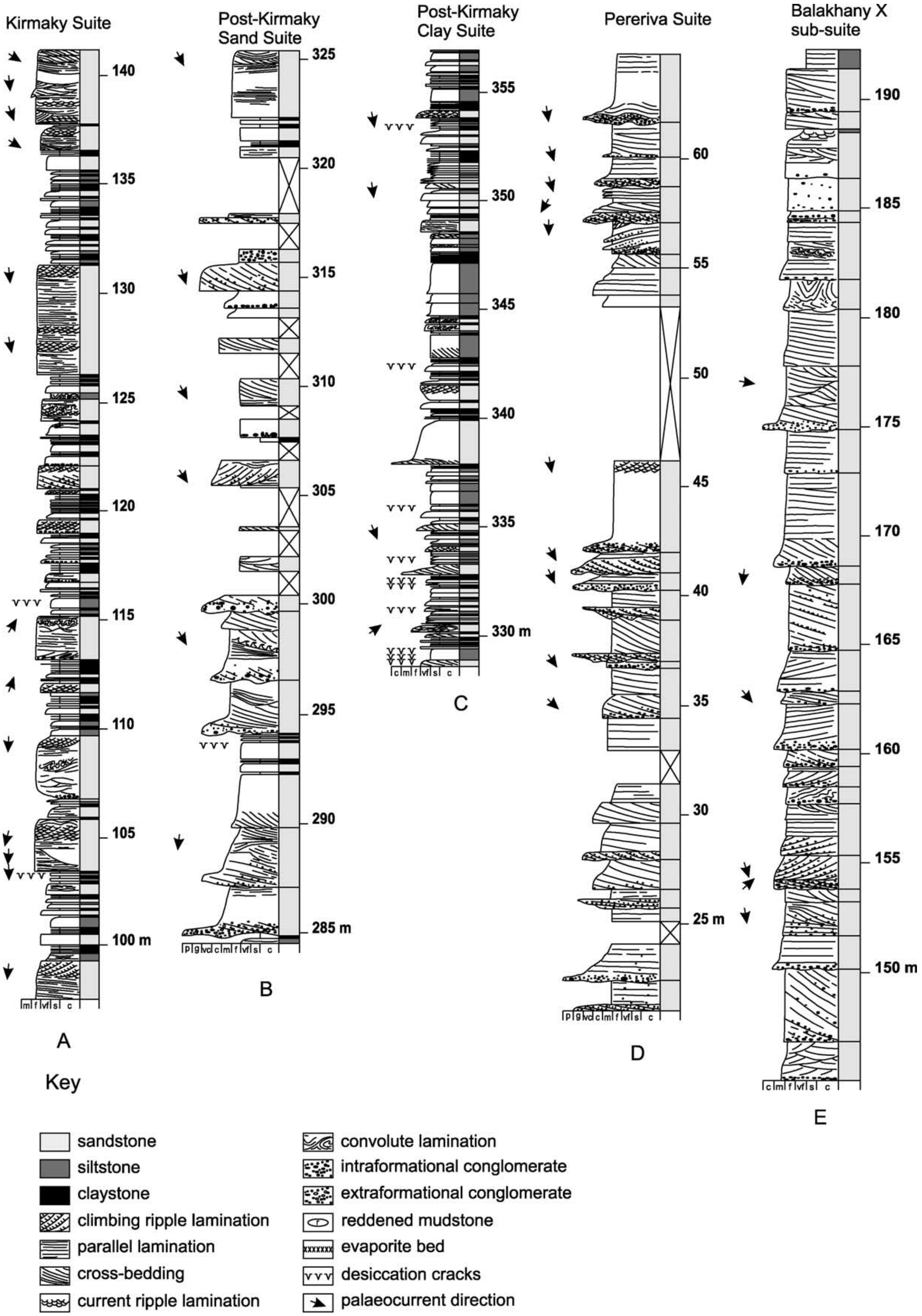

Fig. 7. Representative sedimentary logs of (A) the Kirmaky Suite, (B) the Post-Kirmaky Sand Suite, (C) the Post-Kirmaky Clay Suite, (D) the Pereriva Suite, and (E) Balakhany subsuite X (Kirmaky valley).

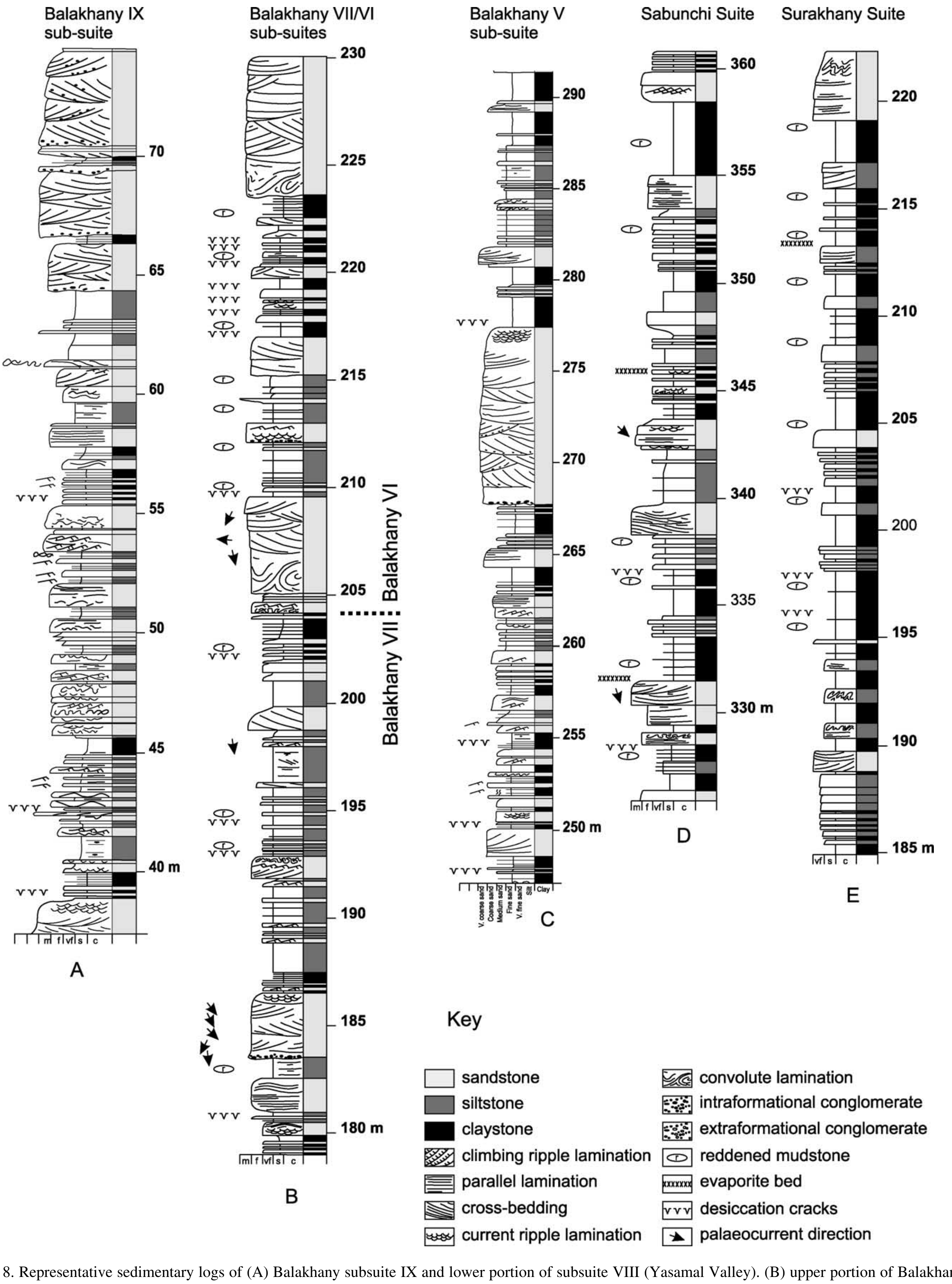

Fig. 8. Representative sedimentary logs of (A) Balakhany subsuite IX and lower portion of subsuite VIII (Yasamal Valley). (B) upper portion of Balakhany subsuite VII, and lower portion of subsuite VI (Yasamal Valley), (C) lower portion of Balakhany subsuite V (Yasamal Valley), (D) the Sabunchi Suite, and (E) the Surakhany Suite.

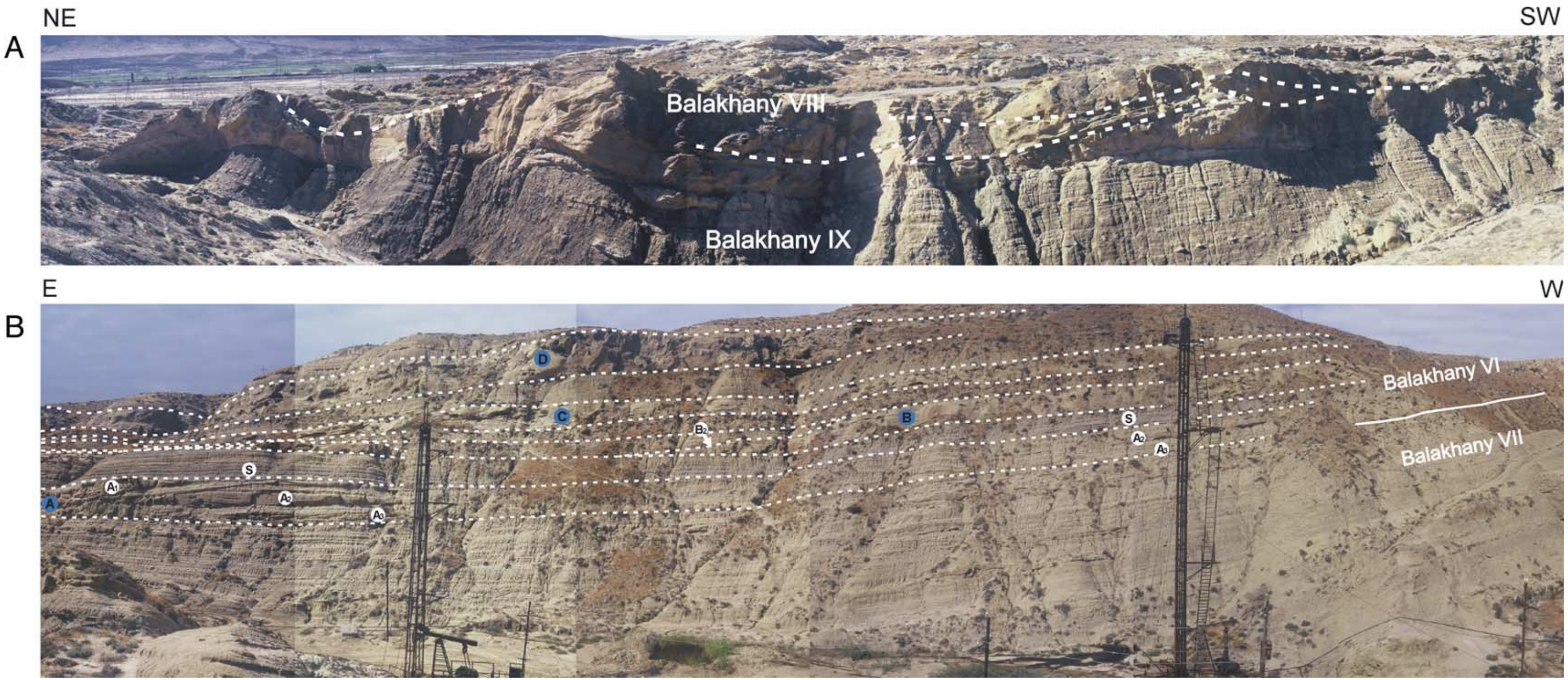

Fig. 9. (**A**) Photomontage showing the contact between the sandstone-prone Balakhany Suite Subunit VIII and the underlying, mudstone-prone Subunit IX at Yasamal Valley. Several channel forms are highlighted within the cliff face (dashed lines). Each shows a similar broad, shallow, trough-like geometry and probably represents a single channel of a larger braided fluvial system. Many such channels may have been active at the same time resulting in rapid aggradation and deposition of the extensive sheet sandstone. The cliff face is approximately 7 m in height in its central section. (**B**). Balakhany Suite subunits VI and VII as exposed at Yasamal Valley. Palaeoflow is into the face of the cliff. The dashed lines mark the upper and lower surfaces of four sandstone packages (A) to (D). The base of Subunit VI is at the base of (A). (A) consists of three units. Both (A3) and (A2) form laterally continuous sheets which thicken and amalgamate eastwards. As they thicken they become increasingly channelised. (A3) and (A2) are interpreted as the transition from unconfined sheetflood sandstones to increasingly axial, but poorly channelised flow. (A1) represents axial channelised flow. The channel is approximately 4 m in thickness and filled with convolute, large-scale cross-stratified sandstone. Sandstone package (A) is capped by distinctive dark shale (S). Sandstone package (B) thickens westwards to a maximum of ~4 m above underlying overbank facies of sandstone package (A). This suggests a compensational stacking style to channel belts (A) and (B). Sandstone package (C) shows little change in thickness across the entire outcrop. Sandstone package (D) measures 7 m in thickness at the east of the image and forms a laterally continuous sheet of medium grained, cross-stratified sandstone.

ramp, similar to the extremely gentle ramp of the modern Volga delta (Kroonenberg et al., 1997).

Type (b) sandstone packages display characteristics consistent with deposition from single or amalgamated, unconfined sheetflood events (Parkash, Awasthi, & Gohain, 1983). The dominance of parallel and sub-parallel lamination with low-angle truncation surfaces is most probably the result of high flood discharge rates and a high suspended load of fine to very fine sand, which dampened incipient bedforms (Saunderson & Locket, 1983; Cotter & Graham, 1991). The upward transition to climbing ripple lamination marks the waning of the flood event. Type (a) sandstone packages represent the migration and amalgamation of barforms within simple cut and fill channels. What appear to be sheet-like geometries, given the limitations of the exposure, are interpreted as the product of rapid aggradation and frequent channel avulsion across the flood plain. Examples of channelised sandstones that pass laterally into type (b) sandstones (Fig. 5A), are interpreted as distributary systems feeding sheetfloods.

Some of the parallel laminated sandstone beds truncate desiccated mudstones, suggesting that the sandstones were not deposited in a lake, but more likely in an overbank setting. In this context, the poorly exposed, sharp-based, climbing ripple laminated, very fine sandstones interbedded within the mudstone packages may represent thin sheetflood deposits (or crevasse splays). The rare, poorly defined thickening- and coarsening-upward motifs may reflect progradation of successive sheetfloods, precursers to larger flooding events which deposited the sandstone packages (George and Berry, 1993).

The reddened rootlet casts discovered at the tops of sandstone packages indicate shallow water depths. The cast morphology resembles reeds growing at the modern Volga delta in 2–3 m of water (Kroonenberg et al., 1997).

The common dark colouration of the mudstones and the lack of mottling may reflect generally reducing conditions during deposition. Clay- and silt-filled channels, which partially truncate the tops of sandstones, may represent the waning of flood events reworking the sandstone tops (Stear, 1983). As discharge continued to decrease the channels were abandoned and passively filled by clay and silt deposited from suspension in shallow, slow moving or standing bodies of water. When floodwaters finally subsided, the mudstones were subaerially exposed and desiccated. The mudstones may not have been exposed for a sufficiently long period of time for palaeosol development before the next sheetflood deposit again inundated the flood plain.

At first sight, the biostratigraphic evidence for repeated lacustrine conditions conflicts with the largely fluvial reinterpretation of the sediments given above. However, the lacustrine microfossils are only found in thin, discrete mudstone intervals. Thus the micropalaeontological evidence coupled with the sedimentological evidence points to high frequency juxtaposition of fluvial/floodplain and lacustrine environments. This alternation may be climatically mediated as the pollen spectra show variations from humid tolerant taxa to arid tolerant taxa within a cycle.

In the low angle ramp depositional setting of the palaeo-Volga (Reynolds et al., 1998) water depths would have increased only slightly over large distances down depositional slope, and any slight increase in lake level would have rapidly flooded vast areas of the surrounding plain. This relationship is similar to the modern Volga delta where water depths 80 km from the distributary mouths are only up to 4 m (Kroonenberg et al., 1997).

4.2. Post-Kirmaky Sand Suite

4.2.1. Lithofacies

In Kirmaky Valley the Post-Kirmaky Sand Suite is approximately 35–40 m thick at outcrop (Fig. 3). Its base is taken at a prominent erosive contact with the underlying Kirmaky Suite. This undulatory surface displays erosive relief of 2 or 3 m and is lined with a thin conglomeratic lag of lithic, igneous, and carbonate clasts with a maximum clast size of 4 cm. Mean grain size is medium to fine sand and the suite shows an overall fining-upwards trend into the overlying Post-Kirmaky Clay Suite, although locally scours are filled with coarse sand- to granule-grade material. Internally, the suite is comprised of amalgamated, fining-upward, channelised sandstones between 2 and 4 m in thickness, which exhibit large-scale (1.5 m) planar and trough cross-bedding, and convolute lamination (Fig. 7B). Channel bases are commonly lined with intraformational mud clast conglomerate and their tops may preserve laterally continuous mudstones occasionally containing black plastic clays. Palaeocurrents are oriented unidirectionally SSE (Fig. 6).

The subsurface log published by Reynolds et al. (1998) demonstrates that the Post-Kirmaky Sand Suite is a pulse of coarse-grained sediment relative to the Kirmaky Suite, consistent with the outcrop observations.

Palynology analyses of two mudrocks from this unit suggest two environments: freshwater (algal assemblages) and reworking of palaeosols (fungal assemblages).

4.2.2. Interpretation

The characteristics of the Post-Kirmaky Sand Suite indicate deposition in a major, high energy, low sinuosity fluvial system in which there was only limited preservation of overbank mudstones. This contrasts with the interpretation of Reynolds et al. (1998) who describe the Post-Kirmaky Sand Suite as representing deposition in a fluvially dominated delta-front environment.

The regional extent of the sand-prone Post-Kirmaky Sand Suite suggests that deposition occurred during a period of increased discharge and sediment supply, in a major fluvial system which rapidly aggraded over an extensive fluvial floodplain, resulting in the regionally mappable sheetsand. Algal palynomorph assemblages (*Pediastrum*-dominated) indicate standing body/bodies of freshwater:

they probably relate to freshwater ponds on a floodplain—given the sand-dominated nature of the suite, but could represent freshwater lacustrine influences. Fungal assemblages indicate the proximity of palaeosols, and therefore subaerial exposure and oxidation of overbank deposits.

4.3. Post-Kirmaky Clay Suite

4.3.1. Lithofacies

The Post-Kirmaky Clay Suite is between 30 and 35 m in thickness (Fig. 3). It is generally poorly-exposed forming an area of low relief, and its base is gradational with the underlying sand-prone Post-Kirmaky Sand Suite. Structureless, dark brown, reddish-brown, and grey silt with thin, black plastic clays dominate, interbedded with laterally continuous, climbing ripple laminated sandstone beds less than 0.5 m in thickness (Fig. 7C). Small intraformational mudclasts may line the basal contacts of sandstone beds. At least 10 horizons of sand-filled desiccation cracks are present within the mudstones (Fig. 4D). Some of the larger (5 cm wide) desiccation cracks are filled with prominant rusty-brown coloured sand and the surrounding mudstones display mottling, but the majority of the desiccation cracks are relatively small (mm to 1–2 cm), show no colour change in the sandstone fill, and are commonly indistinct. The suite includes shallow, broad scours filled with reddened, cross-bedded, coarse and very coarse sand. There is also a prominent, sharp-based, laterally continuous, 2 m thick, yellowish-grey sandstone bed containing quartz-rich very coarse sand- to granule-grade material in gutter casts at its base. No clear coarsening-upward or fining-upward grain size trends were identified within the succession (Fig. 7C).

4.3.2. Interpretation

Mudstones of the Post-Kirmaky Clay Suite are interpreted as periodically desiccated floodplain deposits. The lack of observed palaeosols may indicate rapid alternations of flooding and emergence. Interbedded, laterally continuous thin sands represent crevasse splay or sheetflood deposits. Cross-bedded coarse sand-filled, broad, shallow scours represent poorly channelised flood-related incursions on to the floodplain. Although internal architecture is poorly exposed, the large sand body identified within the suite is similar in thickness and lateral extent to the better-exposed sandstone packages within the Kirmaky Suite and, therefore, probably represents a similar large sheetflood or partly confined sheet sandstone.

Reynolds et al. (1998) interpreted the Post-Kirmaky Clay Suite as a distal delta front succession based, in part, on the recovery of microfauna and microflora indicating a low salinity, shallow marine depositional environment. We have not been able to reproduce these results, but cannot rule out such assemblages. However, the sedimentary architecture described above is not consistent with a wholly subaqueous depositional setting. In common with Kirmaky Suite mudstone packages, it is unclear whether the transgressive event(s)—apparently recorded in the Post-Kirmaky Clay Suite by the microfauna and microflora recovered by Reynolds et al. (1998)—were basin wide or only of local significance. The Post-Kirmaky Clay Suite is readily identifiable on the subsurface log published by Reynolds et al. (1998), but this need not suggest regional transgression, merely an extended period of much reduced fluvial discharge and coarse-grained sediment input to the South Caspian Basin from the palaeo-Volga. Sedimentation was probably dominated by distal sheetfloods with only the power to transport and deposit mud- and silt-grade material. Rare, larger flood events deposited beds of sandstone.

Outcrop features of the Post Kirmaky Clay Suite support the interpretation of a period of reduced coarse clastic input by fluvial systems into a broad lacustrine plain, and at least intermittent subaerial emergence.

4.4. Pereriva Suite

4.4.1. Lithofacies

The Pereriva Suite forms one of the most important reservoir intervals of the Azerbaijan sector of the South Caspian Basin. At outcrop in Kirmaky Valley the Pereriva Suite is approximately 100 m thick, and is comprised almost exclusively of amalgamated, sharp-based, broad, shallow, channelised sandstone units between 2 and 5 m in thickness (Figs. 3 and 7D).

The basal contact of the Pereriva Suite is not deeply incised into the underlying mudstone-rich Post Kirmaky Clay Suite as previously reported (Reynolds et al, 1998), but exhibits a maximum erosive relief of only 5 m. A thin veneer, of poorly sorted, coarse sand- to granule-grade, conglomeratic sandstone, overlies the basal contact. Where erosive relief is at a maximum, trough cross-bedded conglomeratic sandstone-filled channel units amalgamate to a thickness of approximately 5 m. The conglomerate is composed of sub-rounded to sub-angular, lithic, igneous, and carbonate clasts and contains rare cobbles up to 8 cm in diameter. Limestone clasts resemble Cenozoic and Mesozoic units exposed in the Greater Caucasus, consistent with heavy mineral data for an increase in the component of Greater Caucasus sand in the Productive Series at the base of the Pereriva Suite (Morton et al., 2003).

The basal conglomeratic facies is overlain by a sheetsand composed of trough cross-bedded, low-angle trough cross-bedded, and horizontally bedded fine and very fine-grained sandstone (Fig. 4E). Cross-beds commonly preserve top and toesets with cross-bed heights of between 0.3 and 3 m. Horizontally bedded sandstones can be traced laterally until they are truncated by low-angle surfaces or, alternatively, until they pass into the preserved top and toesets of low-angle cross-beds lending bedforms a swept-out appearance. Coarse sand- to granule-grade material fills small scours and comprises basal channel lags.

Sandstone colour varies from steel grey, through yellow and brown, to dark red. Carbonate cementation decreases upwards from the basal contact and is generally restricted to discontinuous doggers. Local cementation of laterally continuous horizontal bedding planes also occurs.

Above the basal conglomerates, the Pereriva Suite shows no marked grain size trend. Relatively thin, laterally continuous, coarse grained packages, associated with increased amalgamation of coarse grained lags and scours, regularly punctuate the succession, separating the finer grained, sheetsand packages which show a lesser degree of amalgamation (Fig. 7D). Up-section there is a progressive substitution of extraformational conglomerate by sub-rounded, intraformational mud clast conglomerate and armoured mudballs in basal lags and scour fills. Rare, thin laterally discontinuous siltstones also become apparent towards the top of the succession. Throughout the Pereriva Suite, palaeocurrents display a dominantly SSE orientation although, several vectors are oriented at relatively high angles to this trend (Fig. 6).

4.4.2. Interpretation

The Pereriva Suite displays characteristics consistent with deposition in a major low sinuosity fluvial system (Reynolds et al., 1998). The abundance of swept-out trough cross-bedding, low-angle trough cross-bedding, and horizontal bedding reflects rapid aggradation and migration of low amplitude 3D dunes at transitional to upper flow regime conditions within shallow, sandy bedload channels (Cowan, 1991). Palaeocurrent deviation most probably reflects limited lateral accretion on the flanks of in channel barforms, rather than high sinuousity channels in the fluvial system. Intraformational mud clasts may originate from coeval fine-grained deposits that are not preserved in situ, but were cannibalised and incorporated as the fluvial system avulsed across its alluvial plain. The upward increase in the preservation of mud intraclasts at the base of channel sandstones probably represents their limited preservation potential in the coarse grained, high energy systems which characterise the basal portion of the suite.

The alternation between highly amalgamated intervals composed of the basal parts of channel fills, channel lags and scours, and less amalgamated sheet sandstones comprising more complete channel fill sequences, may reflect either climatically controlled fluctuation in discharge and sediment supply, variable subsidence rates, or intrinsic channel avulsion processes (Hinds, Simmons, Allen, & Aliyeva, 2004).

Reynolds et al. (1998) interpreted the basal contact of the Pereriva Suite as representing a major episode of base-level driven incision resulting in a significant basinward shift in facies. Although displaying 5 m of erosive relief at its base, the Pereriva Suite is only locally incised into deposits of the Post-Kirmaky Clay Suite, which are here re-interpreted to represent sedimentation in proximal depositional settings. The switch from the fine-grained sediments of the Post-Kirmaky Clay Suite to the conglomerates and sandstones of the Pereriva Suite may have been the result of a dramatic increase in discharge and sediment supply, and not a major drop in base level.

4.5. Balakhany Suite (Kirmaky Valley)

4.5.1. Lithofacies

The Balakhany Suite is locally more than 300 m in thickness with six subunits numbered X–V from base to top. These include important reservoir successions both onshore and offshore Azerbaijan. From its basal contact with the underlying Pereriva Suite, approximately 150 m of the Balakhany Suite crops out in the Kirmaky Valley area. This probably includes all of Balakhany subunits X, IX, and a portion of subunit VIII (Fig. 3). This sub-division is based upon lithological contrast and appears consistent with the established Soviet-era nomenclature. Balakhany subunits IX and VIII are better exposed at Yasamal Valley, but are described briefly below.

The Balakhany X subunit is approximately 80 m in thickness, and shows a gross fining-upward grain size profile from a thin, basal conglomeratic sandstone to fine and very fine sandstone. It displays similar characteristics to the underlying Pereriva Suite being composed almost exclusively of channelised sandstones between 2 and 5 m in thickness displaying varying degrees of amalgamation (Fig. 7E). Where amalgamation is at a maximum, channels preserve just their basal intraformational mudclast conglomerate, trough cross-bedding or low-angle cross-bedding to horizontal bedding (e.g. at ~154 m on Fig. 7E). Such horizons of increased amalgamation differ from those seen in the Pereriva Suite as there is no associated increase in grain size. Where amalgamation is less, the basal portion is capped by current rippled fine and very fine sand and rare silt thus preserving the entire channel fill (Fig. 7E). Increasingly complete channel fill sequences are preserved towards the top of subunit X. Convolute bedding may comprise portions of, or an entire channel fill (e.g. at ~181 m on Fig. 7E). Sandstones are for the most part, brown to yellow and orange in colour, cementation is rare.

The first appearance of laterally continuous mudstone packages in situ are interpreted to mark the base of the Balakhany IX subunit in Kirmaky Valley (Fig. 3). The subunit is approximately 25 m in thickness, considerably thinner than at Yasamal Valley, (see below) and comprises poorly exposed, interstratified mudstone and sandstone packages. Mudstone packages are laterally continuous for at least 100 m (the width of available outcrop) and reach up to 3 m in thickness. They comprise light brown, grey and reddish-grey thinly interbedded clay, silt and very fine sandstone. The 3–5 m thick sandstones within the subunit display similar features to those of the underlying Balakhany X subunit.

Approximately 50 m of Balakhany subunit VIII is exposed at Kirmaky Valley marking a return to sandstone-rich facies. Subunit VIII displays similar sedimentary architecture to subunit X being predominantly composed of amalgamated, channelised sandstones between 2 and 5 m in thickness. Laterally continuous mudstone packages similar to those observed within subunit XI become increasingly interstratified with sandstone packages towards the top of the exposed section.

Palaeocurrents from the three Balakhany Suite subunits exposed at Kirmaky Valley are oriented predominantly to the SSE but display a greater degree of dispersal when compared with the distribution of palaeocurrent vectors of the Pereriva Suite (Fig. 6).

4.5.2. Interpretation

The Balakhany X subunit represents the continuation of the high energy, low sinuosity fluvial depositional regime established in the Pereriva Suite. Contorted bedding most probably reflects the rapid deposition of large quantities of sand and their subsequent dewatering. As with the Pereriva Suite, the degree of channel amalgamation varies, and reflects a complex interplay of autocyclic and allocyclic controls (Hinds et al., 2004).

The mudstone packages of the Balakhany IX subunit are interpreted as laterally continuous floodplain deposits. Based upon observations of the Kirmaky Suite and the Balakhany Suite at Yasamal Valley, it is also likely that some of the mudstones represent more localised abandoned channel fills. These are interstratified with channel sandstones and represent the alternation between proximal and more distal fluvial floodplain environments. Balakhany subunit VIII sandstones mark a return to a low sinuosity, high energy fluvial depositional environment.

Comparison of the results from the present study and those of Reynolds et al. (1998) is problematical as their understanding of the Balakhany Suite was based on observations made at a quarry west of Kirmaky Valley. The stratigraphic relationship between strata here and in Kirmaky Valley is not clear, but examination of the quarry outcrop revealed sedimentological features similar to those of the Balakhany IX subunit described above. Reynolds et al. (1998) interpret the quarry section as representing deposition in stacked fluvial channels and floodplain settings of upper and lower delta-plain environments respectively, so our study is in broad agreement with their findings.

4.6. Balakhany Suite (Yasamal Valley)

Balakhany Suite subunits IX, VIII, VII, VI and V are thought to be exposed at Yasamal Valley. The assignment of subunits presented here is based upon vertical changes in the proportion of sandstone and mudstone. No independent biostratigraphic scheme exists with which to accurately correlate outcrop subunits to those of the subsurface (Reynolds et al., 1998). A speculative lithostratigraphic correlation is made using a prominent, 80–90 m thick sand-prone succession, which is taken to represent subunit VIII, described by Reynolds et al. (1998) as a key, sandstone-rich, subsurface marker within the Balakhany Suite (Fig. 3).

As the subunits are loosely assigned lithologically, the description and interpretation presented below should be seen as representing the possible range of lithofacies variation and heterogeneity that may be expected throughout the Balakhany Suite.

4.6.1. Lithofacies

Balakhany IX. The lowermost 60 m of sediments exposed at Yasamal Valley most likely represent a portion of Balakhany subunit IX (Fig. 3). The succession is composed of a heterolithic mixture of mudstone and sandstone (Fig. 8A) but can be broadly divided into a lower, relatively coarser grained unit and an upper relatively finer grained unit (partly visible in Fig. 9A). Mudstones of the lower unit alternate with yellowish-brown, sharp-based, amalgamated channelised sandstones between 1 and 3 m in thickness and up to 100 m in width. These display intraformational mudstone conglomerate at their bases and pass up through trough cross-bedded medium and fine-grained sandstone to current and climbing ripple laminated very fine and silty-sandstone. Associated, laterally continuous, planar based, tabular sandstones and siltstones between 0.5 and 1.5 m in thickness commonly display small-scale cross-bedding, parallel, climbing ripple, or convolute lamination. Dark brown rip-up clasts commonly line channels or are aligned along foresets.

The upper, finer grained unit comprises weakly defined, 4 m thick, packages composed of amalgamated beds of convolute and climbing ripple laminated fine to silty-sandstone (Fig. 4F). These increase upwards in the proportion of sand, but not appreciably in grain size. Similar coarsening-upward packages are better exposed and developed within the Sabunchi Suite and are described below. Mudstones within both units are dark brown, grey, and reddish-brown in colour, the latter display prominent sand-filled desiccation cracks - at least nine intervals in the Yasamal Valley section. One interval contains four desiccation horizons in ~50 cm of section. Shallow, silt- and clay-filled scours erosively truncate the tops of some sandstones.

Balakhany VIII. At outcrop subunit VIII is 80–90 m in thickness, although the upper contact is gradational into the overlying subunit and therefore not clearly defined (Fig. 3). Sheet sandstones comprise approximately of 80% of the succession, sheets vary between 5 and 25 m in thickness and comprise amalgamated broad, shallow channels of medium to fine-grained sandstone, typically between 1.5 and 5 m in thickness and between 20 and 30 m wide (Fig. 9A). The bases of sandstone beds exhibit only minor erosive relief and are commonly lined with an intraformational mud clast conglomerate (Fig. 4G). Sedimentary structures include large- and small-scale trough cross-bedding and large-scale convolute bedding. Rare parallel and climbing ripple lamination may be preserved towards the upper, finer grained, portion of channel fills. Sandstones vary in colour from brown and yellow to grey. Calcite cementation is rare, forming only isolated doggers.

There are relatively few heterolithic mudstone intervals interbedded within the sandstone sheets. Where present, they comprise decimetre thick beds of climbing ripple and parallel laminated very fine-grained sandstone, within dark grey, brown and reddish-brown silt and clay. At least four horizons of desiccation cracks are associated with reddish-brown mudstone. In the basal 15–20 m of the succession mudstones form the finer grained tops of channel fills. Mudstones are absent from the lower-middle 25 m of the succession where it is comprised entirely of amalgamated channel sandstones. However, in the uppermost 50 m, subunit VIII begins to exhibit a regular alternation between laterally continuous sheets of sandstone and mudstone, similar in aspect to the Kirmaky Suite. This increase in mudstone content marks the gradational lithofacies change into subunit VII.

Balakhany VII. Subunit VII is ~55 m thick and represents a return to the silt-rich heterolithic facies of subunit IX (Fig. 3). Its lower boundary is interpreted as the top of an 8 m thick sandstone package, and its top as the base of a 5 m thick sandstone package (Fig. 9B). These sandstones are interpreted to belong to subunits VIII and VI respectively. Within subunit VII, planar-based, fine-grained, channelised sandstone packages between 1.5 and 3 m in thickness, display trough cross-bedding and current ripple lamination and are laterally continuous over 100 m along depositional strike. They are interstratified with weakly developed, coarsening upward, mudstone to sandstone packages, between 4 and 6 m in thickness, comprised of amalgamated, tabular beds of convolute, climbing ripple and parallel laminated siltstone, very fine and fine sandstone (lower part of Fig. 8B). Mudstone and siltstone beds vary in colour from brown to grey and reddish-brown; the latter display desiccation cracks in at least nine intervals.

Balakhany VI. The relatively sand-prone Balakhany subunit VI is approximately 40 m in thickness (Fig. 3). Several large sandstone packages crop out along a prominent escarpment forming excellent depositional strike-oriented exposure (Fig. 9B). Medium to fine-grained sandstones are between 6 and 9 m thick. They consist of highly amalgamated channels individually between 3.5 and 4 m thick and up to 45 m wide (upper part of Fig. 8B). Channels display composite fills of several sets of sub-parallel to low-angle tough cross-bedding which commonly pass upwards to current ripple lamination. No fining-upwards in grainsize was observed over the thickness of a sandstone package. The basal contact of a package is often relatively planar, displaying only moderate erosive relief and is generally directly overlain by metre scale convolute bedding. The basal 6 m thick sandstone package within the Balakhany VI unit in Yasamal Valley thins laterally over approximately 200 m by both erosion of the top of the sandstone package by silt- and clay-filled scours, and reduction in the degree of incision on the basal surface. Mudstones are extensively desiccated (Fig. 8B); seven mudcrack intervals were logged in ~6 m of section. Sandstone and mudstones display both laterally discontinuous scour and laterally continuous planar, tabular geometries. Sandstones vary in colour from grey to yellowish-brown, and are rarely cemented.

Balakhany V. Due to gradational lithofacies changes, Balakhany subunit V is difficult to delimit, but is approximately 50–60 m in thickness. Its base is taken at a change in facies from an underlying thick sandstone package of subunit VI. Its upper limit is put at a prominent, laterally continuous grey mudstone, taken to mark the base of the overlying Sabunchi Suite. Subunit V is a fine-grained succession that includes ~4 m thick coarsening-upward packages, such as the one beginning at 260 m on Fig. 8C. The coarsening-upward packages are much better developed than in the other heterolithic subunits of the Balakhany Suite but display similar sedimentological features (Fig. 4H). Scours cut into sheet-like sandstone beds that are 1–2 m thick. A 9 m thick sandstone package has characteristics similar to the thick sandstones described within subunit VI (beginning at ~268 m on Fig. 8C). However, it is distinctive for being truncated by a mudstone filled channel, such that sandstones on either side are not in communication.

The Balakhany Suite of Yasamal Valley, in common with those suites exposed at Kirmaky Valley, displays a dominant SSE palaeocurrent trend (Fig. 6).

4.6.2. Interpretation

Based upon their outcrop investigation in the quarry west of Kirmaky Valley, and on subsurface data, Reynolds et al. (1998) interpreted the Balakhany Suite as representing deposition in a range of fluvial and deltaic environments, where siltstone and sandstone prone-subunits comprise delta-front and delta-plain depositional settings, and sand-rich subunits are composed of stacked channels and proximal mouth bars. They described an overall fining-upwards in grainsize throughout the Balakhany Suite (with the exception of Balakhany subunit VIII) reflecting a change to more distal facies up-section. This general fining-upward trend and increasing preservation of distal facies is observed at outcrop at Yasamal Valley. However, our observations are inconsistent with a wholly deltaic interpretation. The Balakhany Suite represents sedimentation in a range of fluvial, alluvial plain and possible lacustrine plain depositional environments.

Within Yasamal Valley, Balakhany subunit IX represents increasing preservation of overbank mudstones and therefore continues the fining-upward trend observed in subunit IX at Kirmaky Valley. The basal portion of the succession represents continued deposition within a proximal floodplain environment, based on the presence of channelised sandstones up to 3 m thick and 100 m across, and evidence for emergence in mudstones. Thinner, planar-based, tabular sandstones and siltstones are interpreted as overbank sheetflood deposits. Weakly defined coarsening-upward packages are interpreted as coalesced sheetflood lobes, interdistributary bay fill sequences, and lacustrine deltas of more distal floodplain environments (see Sabunchi Suite).

Subunit VIII represents a return to the low sinuosity, high energy fluvial regime of the Post-Kirmaky Sand Suite, Pereriva Suite and Balakhany subunit X. Amalgamated channel sands form a multistory, multilateral sheet sand complex with minor preservation of overbank mudstones. With reference to other sections of the Productive Series, some of the mudstones may represent partial preservation of abandoned channels. Mudstone packages begin to increase in frequency up-section, representing either the progressive avulsion of the fluvial system to lower lying areas of the alluvial plain, or basin scale reduction in discharge and coarse-grained sediment input to the South Caspian Basin. This upper portion of the succession appears architecturally and sedimentologically similar to the Kirmaky Suite, although the stacking pattern of the alternating mudstone and sandstone packages does not display the same degree of regularity.

Both subunits VII and IX display evidence for emergence, bed geometries consistent with fluvial settings, and a mixture of coarse and fine-grained deposits. Therefore, a mixture of proximal and distal floodplain settings seems more appropriate than delta front settings (Reynolds et al., 1998).

Subunit VI marks a return to a sand-dominated deposition, a mixture of proximal floodplain and major channel sands. The planar based, sheet-like geometry of the sandstone packages and their internal architecture (channels up to 45 m wide) resembles Kirmaky Suite type (a) sandstone packages. Type (b) thick, amalgamated, sheetflood sandstones are absent. The large scale convolute bedding observed towards the base of sandstones is interpreted as dewatering structures pointing to rapid rates of deposition (e.g. at 205 m on Fig. 8B). Intensely desiccated, heterolithic packages overlying the basal 6 m sandstone body are interpreted as overbank facies. Scoured and tabular sandstones represent poorly channelised and non channelised deposition lateral to the channel margins. The relatively poorly defined margins of the basal sandstone package, with channelised sheetsands progressively thinning into the heterolithic facies, probably points to the absence of channel levees. This may be expected in an arid climate incapable of supporting channel margin, binding vegetation. No evidence of extensive bioturbation by roots was found. Individual sheetsands stack in a compensational manner representing avulsion of fluvial systems onto the lowest lying portion of the floodplain some distance from coeval, topographically higher, vertically aggraded channel sandstones. If the sheet sandstones of Yasamal Valley represent the depositional strike-oriented sections of the dip-oriented sections exposed in Kirmaky Valley, the compensational stacking of the former suggests an autocyclic component to the apparently regularly stacked sandstone/mudstone couplets of the latter.

The coarsening-upward packages of subunit V are identical to the thick succession of coarsening-upward lithofacies seen in the overlying Sabunchi Suite (see below). These are seen as representing more distal deposition than the fine-grained portions within the underlying subunit VII. The large sandstone package at 268 m on Fig. 8C marks temporary re-establishment of the fluvial regime of subunit VI. As with other isolated fluvial sandstones within the Sabunchi Suite, it is not clear whether this fluvial sandstone represents a basin wide change in depositional regime or simply represents avulsion of a coeval fluvial system onto a lower lying portion of the floodplain. The large mudstone-filled channel is interpreted as an abandoned channel.

4.7. Sabunchi Suite (Yasamal Valley)

4.7.1. Lithofacies

At outcrop the Sabunchi Suite is approximately 220 m thick. Its lower contact is marked by a prominant grey mudstone, and a 10 m thick sandstone package forms the upper contact (Fig. 3). Two lithofacies types are recognised, coarsening-upward silty sandstone packages, and channelised sandstone packages.

The majority of the succession consists of vertically stacked coarsening-upward silty-sandstone packages ranging from between 4 and 6 m in thickness with some up to 8 m in thickness (Figs. 8D and 4I). Laminated, dark grey, brown, and reddish brown mudstone and clayey-siltstone pass upwards into sharp-based, amalgamated, relatively tabular beds of siltstone and silty-sandstone, which commonly display climbing ripple, convolute, or parallel lamination; alternatively these beds may be structureless. These coarsening- and thickening-upward bedsets are capped by sharp-based, amalgamated, parallel laminated, and climbing ripple laminated silty-sandstone bedsets, or by cross-bedded very fine sandstone beds up to 1.5 m in thickness. Each coarsening-upward package is laterally continuous over the extent of available outcrop (~150 m) although in a few cases lateral thinning and fining can be demonstrated over this distance. Horizons of desiccation cracks and thin gypsum beds are associated with the reddened mudstone; there are at least two gypsum beds within the lowermost 30 m of the suite (Fig. 8D). Their distribution appears to be random as they were observed lying within the clay-rich basal portion, and both directly above and below capping sandstones (Fig. 8D). Darker coloured clays commonly, but not exclusively, lie above capping sandstones of an underlying coarsening-upward package, therefore forming the base of the succeeding package. Some coarsening-upward packages show neither reddening of mudstone or desiccation features. Small sandstone dyke injection structures are associated with some packages.

The fine-grained nature of the succession is interrupted by several 2–10 m thick sandstone packages, e.g. at 339 m on Fig. 8D. Each sandstone package displays a relatively planar base and comprises amalgamated channels filled with cross-bedded, parallel bedded or convolute bedded fine-grained sandstone between 1.5 and 4 m in thickness. Erosive surfaces are often lined with intraformational mudclast conglomerate. Sandstones are light grey and yellow in colour and for the most part uncemented. Sandstone packages display a random distribution but are interstratified with vertically stacked coarsening-upwards packages only in the lowermost and uppermost portions of the succession. Although only patchily exposed, a prominent well drained topographic ridge suggests that at least one of the thicker sandstone bodies may be laterally continuous for 1 km. Palaeocurrent vectors display a dominant SSE trend; however, they display a much greater degree of dispersal in comparison with those of the underlying suites.

4.7.2. Interpretation

According to Reynolds et al. (1998), the Sabunchi Suite represents deposition in a range of fluvially dominated deltaic environments. They interpreted fining-upward sandstones as fluvial distributary channels, coarsening-upward packages as fluvially dominated distributary mouth bars, and thin silt and sandstones as hyperpycnal underflows in a distal delta-front setting. Their interpretations are based upon observations made along a wave-cut platform on the west limb of the Kirmaky anticline.

The Sabunchi Suite as exposed at Yasamal Valley also represents deposition in a range of terrestrial and subaqueous environments. However, here it displays characteristics more consistent with a fluvial flood dominated, mud- and silt-rich lacustrine plain which may have undergone periodic inundation and desiccation. This re-interpretation is based in large part upon the presence of indicators of subaerial exposure, including desiccation horizons, reddened clays, and gypsum beds.

The main architectural component of the Sabunchi Suite is the repeated coarsening-upward packages that exhibit sub-aerial exposure. George and Berry (1993) also describe coarsening and thickening-upward sequences from the Permian Southern North Sea Basin, interpreted to result from the deposition of prograding unconfined sheetfloods on an alluvial plain. These were termed terminal progradational sheetflood lobes by George and Berry (1993), and may be expected to display evidence for sub-aerial exposure. Sabunchi Suite coarsening-upward packages are interpreted to represent similar depositional environments on a lacustrine plain, with sediment supply from sheetflood lobes and crevasse splays.

The variable distribution of desiccation surfaces, reddened clays and gypsum beds through a coarsening-upward package makes it difficult to idealise a climatically controlled depositional cycle. Autocyclic switching of the depocentres of individual sheetflood lobes could result in subsidence driven, local transgression (Mertz & Hubert, 1990), or merely lead to the establishment of isolated flood plain lakes with no connection to a palaeo Caspian lake. Support for this comes from palynology work in progress, which shows floodplain rather than lacustrine assemblages dominate in the Sabunchi Suite mudrocks.

Channelised sandstone packages are interpreted as large fluvial distributaries. They may represent major fluvial influxes into the basin which resulted in significant basinward shifts of facies belts or mark the periodic avulsion of a coeval fluvial system onto a low lying, long abandoned portion of the alluvial plain. Although poorly exposed within the Sabunchi Suite they are comparable to the better exposed channelised sandbodies within the underlying Balakhany Suite.

4.8. Surakhany Suite (Lokbatan)

4.8.1. Lithofacies

The Surakhany Suite is the uppermost lithostratigraphic subdivision of the Productive Series (Fig. 3). At outcrop it is estimated to be approximately 500 m thick. The Surakhany Suite is an extremely argillaceous succession dominated by thick beds of claystone and siltstone, with minor quantities of sandstone (Fig. 4J) and rare, isolated channel bodies.

Varicoloured mudstone packages between 5 and 25 m in thickness are composed almost exclusively of massive or finely laminated clay and silt. Mudstone colour is dominantly olive brown but ranges from dark grey and greenish-grey through grey brown to reddish brown. No regular up-profile pattern of colour change was observed. Desiccation cracks are developed within reddened clays. Rare centimetre thick gypsum beds punctuate the mudstones and become more abundant towards the top of the Surakhany Suite, where there are extensive surfaces of cumuloform gypsum (Fig. 4K).

Siltstone and very fine-grained sandstone contain massive, parallel to ripple cross lamination with rare trough cross-stratification and climbing ripple lamination. Beds up to 50 cm in thickness form laterally continuous sheets with flat tops and bases, commonly preserving symmetrical ripples on their upper surface. Siltstones contain sub-vertical burrows and root traces. Very fine to fine-grained sandstones have massive, parallel to cross-laminated and cross-stratified structures. These sandstones usually have a sharp, flat to undulating base with limited erosion, and from single or stacked packages, typically with sheet-like geometries. There are rare channelised sandstones, in places in amalgamated packages or as isolated channels 17 m wide and 2.5–3 m deep. Centimetre scale mudstone clasts occur at the base of the chanel fills. Palaeoflow indicators show a variety of directions from ESE to SSW.

Silty-sandstone packages form a minor part of the Surakhany Suite. For the most part, they resemble type (a) sandstone packages of the Kirmaky Suite, forming sharp based, laterally continuous sheets between 1 and 6 m in thickness composed of broad, shallow, trough-like channels. Sedimentary structures include cross-bedding, parallel lamination, current ripple lamination and convolute lamination. There are also isolated channels with widths of ~17 m and depths of 2.5–3 m. Silty sandstone packages of the Surakhany Suite appear randomly and infrequently distributed throughout the succession (Fig. 8E). Thin layers of gypsum are sporadically interbedded within the siltstones.

4.8.2. Interpretation

The argillaceous Surakhany Suite represents an extended period of coarse grade sediment starvation. Nonetheless, enormous quantities of fine-grained material were delivered by fluvial distributaries. Deposition most likely took place in both terrestrial and subaqueous environments on a muddy plain. Coarsening-upwards siltstone packages probably represent the frequent progradation of mud and silt rich terminal sheetflood lobes on to the lacustrine plain or crevasse splay progradation onto the floodplain or into long-lived or ephemeral, evaporitic lakes and ponds (George & Berry, 1993; Elliott, 1974; Tye and Coleman, 1989).

These progradational events were interrupted by periods of exposure, desiccation and palaeosol formation. Channelised sandstones represent the fluvial distributaries which fed the sheetfloods. As with other muddy successions in the Productive Series it is not clear from the sedimentology if the darker coloured clays represent periodic inundation of the lacustrine plain by the palaeo Caspian lake, but initial palynology results suggest that floodplain depositional settings prevail.

Varicoloured mudstone packages suggest both frequent sub-aerial exposure and at least periodic increase in the height of the water table throughout the entire succession. We speculate that a significant proportion of the silt and mud grade material may also have been delivered to the basin by aeolian processes. The present day Apsheron Peninsula region is renowned for its strong winds. Dust may have been derived locally from deflation of the broad lacustrine plain, or from distant sources such as the Caucasus and the then exposed area of the present day Mid and North Caspian Basins. Pedogenesis could give the silt and mud a massive appearance (Talbot et al., 1994).

The distal regions of terminal fluvial systems are often characterised by the development of aeolian dune and sheetsand depositional environments (Kelly and Olsen, 1993; Tooth, 2000). Large areas of present day Volga delta plain are overlain by longitudinal dunes believed to be a relict landform from the early Holocene lake-level lowstand (Kroonenberg et al., 1993). It is speculated that during climatic periods of increased aridity, aeolian reworking of an expanded lacustrine plain may have resulted in Pliocene equivalents of the upper Pleistocene aeolian deposits. The absence of aeolian deposits at outcrop may reflect either the marginal location of the outcrop belt, or limited preservation potential of aeolian deposits in response to any subsequent lacustrine or fluvial reworking.

5. Depositional controls

Several orders of variation in stratal architecture can be detected through the Productive Series of the Apsheron Peninsula. There is a first order fining-up trend, ending in the mud-prone strata of the Surakhany Suite (Fig. 3). Part way through the Productive Series there is an alternation between sand- and mud-rich suites and sub-suites; the former are the major reservoir units in the South Caspian Basin (Fig. 3). In the lower Productive Series the Post-Kirmaky Sand/Post-Kirmaky Clay form one such couplet. The Pereriva + Balakhany X/Balakhany IX, Balakhany VIII/Balakhany VII and the Balakhany VI/V comprise similar couplets in the upper Productive Series. Each couplet has a cumulative thickness of many 10 s of metres. The Kirmaky, Sabunchi and Surakhany suites lack the same large-scale sand-rich/sand-poor couplets, but show finer-scale, presumed higher frequency alternation of mudstone and sandstone packages with cumulative sandstone thicknesses generally of 10 m or less (Fig. 7). The exact timescales represented by both the large- and small-scale alternations are not known. This section discusses some of the possible causes of these trends.

5.1. Autocyclicity

Cyclic depositional sequences are often produced in response to intrinsic controls of sedimentary systems. The vertical stacking of interdistributary bay fill sequences often results from localised subsidence due to sediment compaction (Elliott, 1974). Autocyclic subsidence driven, 'lobe' switching may have controlled the distribution of some of the 4 to 8 m thickening-and coarsening-upward packages of the upper Productive Series.

Discharge variation, especially flood recurrence, is a major control on river avulsion, pointing to a degree of allocylic, climatic control. However, floodplain topography exerts an equally strong influence as fluvial systems avulse to take advantage of gradient differences between their own elevated, aggrading alluvial ridge and topographically lower floodplains. The fluvial deposits of the Pereriva Suite and Balakhany Suite subunits VIII and VI all overlie darker brown and grey 'distal' floodplain deposits suggesting that these areas were topographically depressed prior to avulsion. Similarly, the compensational stacking style of some of the sand bodies within the Balakhany Suite suggests local topographic control of fluvial distributary courses.

5.2. Tectonics

The evolving Greater Caucasus would have influenced deposition of the Productive Series to the east of any areas directly affected by syn-sedimentary deformation, both as a source of sediment via tributaries of the palaeo-Volga and as an increasing topographic influence on the position of the tributaries themselves. Provenance studies by Morton et al.

(2003) suggest that the Russian Platform/Urals was an important source of sand-grade sediment throughout Productive Series deposition, with a continual, but temporally variable contribution from the Greater Caucasus. This influence is greatest in the upper Productive Series, with a sharp increase at the base of the Pereriva Suite.

The eastern Greater Caucasus is a thrust stack dominated at outcrop by fine-grained Mesozoic clastics (Azizbekov, 1972). Speculatively, a greater contribution of mudrocks from this region over time may have contributed to the first order fining-up nature of the Productive Series. Evidence presented in this paper for the repeated emergence of the upper part of the Productive Series rules out previous models of large-scale transgression of the palaeo-Caspian Sea being the cause of this fining-up trend.

5.3. Climatic variability

Deposition of the Productive Series occurred during a period of elevated global temperature compared to the present day (Crowley & North, 1991), although climate cooled through the Pliocene towards the Pleistocene glaciations (Zhang, Molnar, & Downs, 2001). The Caspian is believed to have been a hydrographically closed basin during this period (Jones and Simmons, 1996). The basin was likely to have been very sensitive to climatic fluctuations, thus any major variation in discharge ought to be reflected in the sedimentary succession (Kelly, 1993).

Recently it has been suggested that the internal architecture of individual suites of both the upper and lower Productive Series reflects orbitally forced, high-frequency, cyclical changes from humid to arid climates linked to precession (19,000–23,000 years) Milankovitch cycles (Clifton et al., 2000; Abreu et al., 2000; Nummedal & Clifton, 2002). But, there are no age data to constrain the interval represented by individual suites, making these ideas speculative.

It is not clear to what degree sand-rich and sand-poor parts of the Productive Series result from a cyclical, climatic control, such as that outlined by Leeder et al. (1998) for Mediterranean-style climates. During the Pliocene the distant catchments of both the palaeo-Volga and the palaeo-Amu Darya rivers were probably located in very different climatic realms to the receiving basin.

6. Depositional models

Reynolds et al. (1998) interpreted their four facies associations (fluvial, delta-plain, proximal delta-front, and distal delta-front) as a genetically linked series of depositional environments. The lithofacies of the upper Productive Series in this study display characteristics more consistent with episodes of deposition in an ephemeral fluvial system, where discharge terminates on a fluvial-lacustrine plain. Some characteristics of terminal fluvial systems include: low depositional gradient, progressive downstream decrease in discharge and channel size, dominance of low sinuosity channels, lack of channel incision, downstream reduction in flow strength leading to basinward thinning and fining of sandstones and increase in mud content, dominance of sheet-like sandstones, with the distal margins of terminal fluvial systems commonly comprising playa mudflat or lacustrine environments (Friend, 1978; Parkash et al, 1983; Hirst, 1991; Kelly & Olsen, 1993; Croke et al., 1996; Tooth, 2000). The lower Productive Series, especially the Kirmaky Suite, contains both fluvial and lacustrine signatures.

The following models are based upon extensive outcrop observation, however, lack of regional subsurface control means they should be applied with caution. Different models are presented for both the lower and upper Productive Series in order to account for differences in their sedimentary architecture.

6.1. Lower Productive Series

Deposits of the lower Productive Series in the Apsheron region are interpreted as alternations of sheetflood dominated fluvial deposits, channelised fluvial deposits and lacustrine muds The overall setting may be thought of as a delta, but one on a very gentle ramp setting, such that fluvial and lacustrine strata alternate without subaqueous delta front development. The modern Volga is an analogue, to the extent that it also deposits sediment over an extremely gentle gradient, influenced by Caspian lake transgressions and regressions. This is not to propose that the sedimentology of modern Volga deposits is the same as the lower Productive Series, given the likely differences in discharge, sediment load, subsidence and climate. In particular, it is unclear from our study area observations whether or not there was a permanent connection between the palaeo-Volga system and a permanent lake within the South Caspian Basin. The Holocene Aral Sea (Boomer, Aladin, Plotnikov, & Whatley, 2000) is a rapidly fluctuating lake at the end of low gradient rivers that currently decrease in discharge downstream (although much of this decrease is due to irrigation schemes), and so may also be a useful analogue for the lower Productive Series.

The presence of black plastic clays and the abundance of thick, tabular, amalgamated sheetflood sandstones throughout the lower Productive Series distinguishes it from the upper portion of the succession as does the regular interstratification of mudstone and sandstone packages which are particularly noticeable within the Kirmaky Suite. The lower Productive Series also has little evidence of the 4–8 m thick progradational bodies which comprise parts of the Balakhany, Sabunchi and Surakhany suites.

Fig. 10A–C shows a series of palaeogeographical reconstructions tied to an idealised depositional cycle (Fig. 10D). The cycle commences with a desiccated alluvial/lacustrine plain at a time of maximum aridity onto which distal sheetfloods and poorly channelised sediments

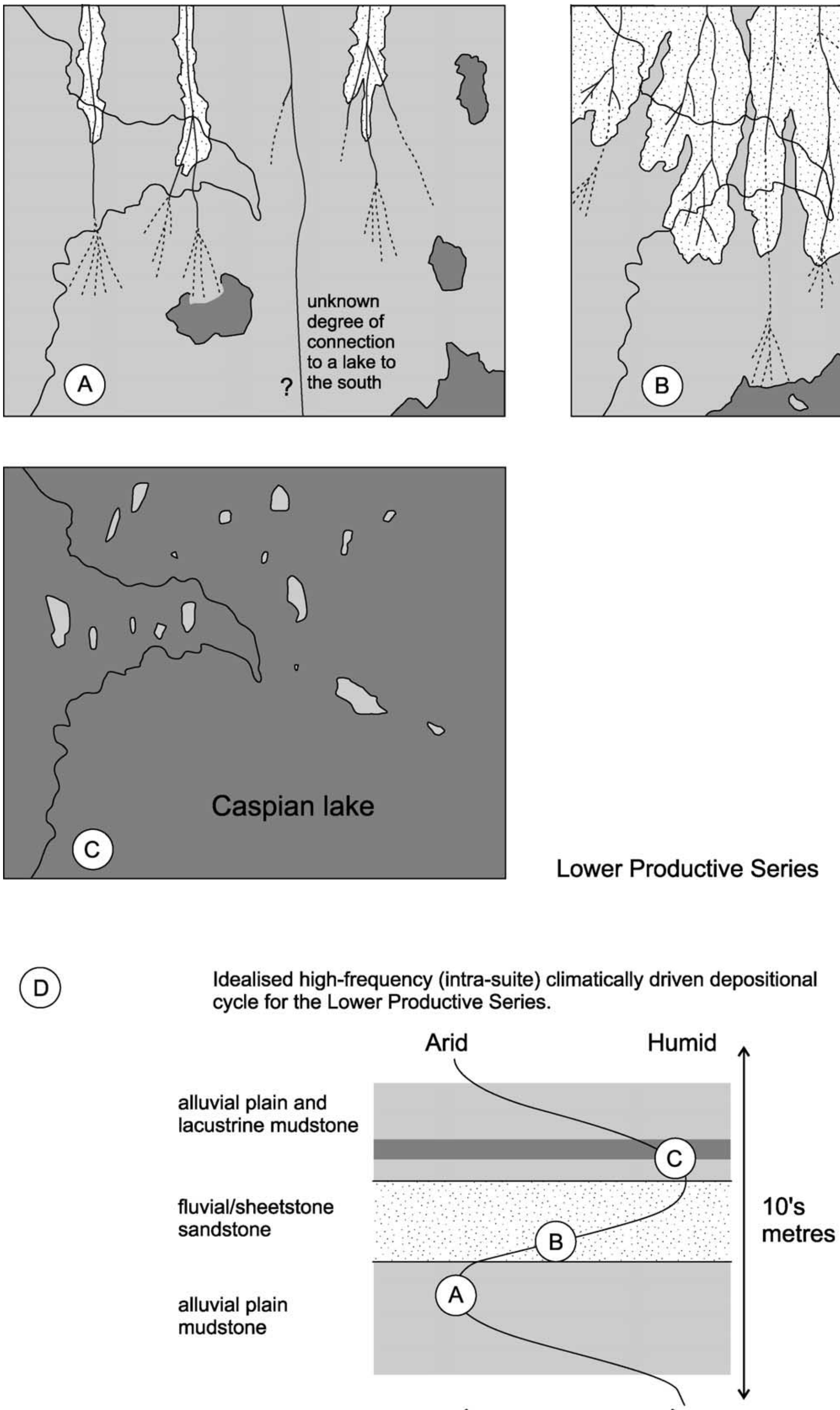

Fig. 10. Palaeogeographic reconstructions for the Apsheron Peninsula and surrounding area at (A) a time of maximum aridity and minimum coarse clastic input, (B) establishment of a sheetflood dominated terminal fluvial system at a time of increasing climatic humidity, and (C) maximum humidity results in lacustrine expansion and inundation of the Apsheron Peninsula area. Fig. 10D relates the palaeogeographic reconstructions A, B, and C to an idealised high frequency (20,000 year) climatic cycle. Based on a model by Clifton et al., 2000; Abreu et al., 2000; Nummedal and Clifton, 2002.

are deposited (Fig. 10A). Upon a climatic shift to increasing humidity, fluvial systems expand resulting in deposition of sheetflood and channelised sandstones and their associated floodplain mudstones (Fig. 10B). The continued progression into a period of maximum humidity results in lacustrine expansion and inundation of the alluvial plain (Fig. 10C). Upon evaporation of the lake, as the climate returns once more to an arid phase, the idealised depositional cycle is completed. This has elements in common with models presented by Nummedal and Clifton (2002), but without better age control it is hard to show that Milankovitch cyclicity was an essential control.

Both the Post-Kirmaky Sand and Post-Kirmaky Clay suites contain laterally continuous black plastic clays, but do not possess the regularly interstratified appearance of the Kirmaky Suite. Perhaps the juxtaposition of the Post-Kirmaky Sand and Post-Kirmaky Clay suites is a longer-term arid/humid climatic fluctuation, similar to that displayed in the upper Productive Series.

6.2. Upper Productive Series

Deposits of the upper Productive Series are interpreted as a terminal fluvial system which repeatedly expanded and contracted across its alluvial plain but experienced only moderate lacustrine influence Modern analogues may include Lake Eyre, Australia. In this case the lake at the end of the drainage systems may dry out completely (Magee et al., 1995; Alley, 1998; Tooth, 2000). Our outcrop observations from the northern side of the South Caspian Basin do not allow us to predict whether or not there was a lake at the end of the drainage system for any particular interval, but the paucity of clear lacustrine or delta front signatures in the sedimentology reduce the likelihood, compared with the lower Productive Series.

The upper Productive Series is distinguished from the lower portion of the succession by an increased abundance of features consistent with subaerial exposure and desiccation, particularly in the Sabunchi and Surakhany suites. The internal architecture of suites of the upper Productive Series do not display the regular interstratification of mudstone and sandstone packages to the same degree as the Kirmaky Suite. There are stacked 4–8 m thick coarsening and thickening upward packages. However, these packages are interpreted to be of mixed affinity (see discussion of Sabunchi Suite) and consequently it is far from clear what frequency of cyclicity they may represent. As with the lower Productive Series, high-frequency cylicity may be present within the upper Productive Series, but exactly how this is expressed in the succession is not clear.

Fig. 11A–C shows a series of palaeogeographical reconstructions related to an idealised depositional cycle, shown in Fig. 11D. The cycle commences within an arid phase climate of low fluvial discharge. Distal sheetfloods and poorly channelised sandstones are deposited along with alluvial plain mudstones (Fig. 11A). This phase is characterised by deposits of Balakhany subunit IX. Upon increasing discharge with increasing humidity, low sinuosity braided fluvial systems expand. This deposits extensive sheet sandstones and their associated floodplain mudstones across the Apsheron Peninsula region. The down depositional dip extent of sand-rich facies is dependant upon the amount of discharge and sediment entering the basin during this time. Fluvial systems are speculated to terminate in either mudstone rich alluvial plain facies (relatively limited fluvial expansion) or construct large sand-rich braid deltas (major fluvial expansion). Balakhany subunit VIII and the Pereriva Suite, which are the main reservoir intervals in the basin, may represent the latter scenario. There is little evidence of lacustrine expansion and inundation across the Apsheron Peninsula. It is speculated that evaporation in the basin during this time probably matched or exceeded the discharge entering the basin even during major phases of fluvial expansion (Fig. 11B). This is supported by the increased sedimentological evidence for aridity in the upper Productive Series. As the climate trends once more towards increased aridity, lower net to gross, low sinuosity, braided fluvial systems become established represented by the interstratified sandstones and mudstones of the upper portion of Balakhany VIII (Fig. 11C). The low net to gross deposits of Balakhany Subunit VII represent the arid phase at the start of the next idealised depositional cycle.

The ability to distinguish such rhythmic lithologic alternations decreases stratigraphically upwards from the Balakhany Suite into the Sabunchi and Surakhany suites. This coincides with an increase in mudstone, sedimentological evidence for increasing aridity, and palynology assemblages with floodplain rather than lacustrine signatures. The inferred long-term trend towards increasing aridity may reflect local climatic change resulting from increasing topographic influence of the Greater Caucasus. Alternatively, the trend could reflect global climate change, given Pliocene-Quaternary trends towards cooler climates (Zhang et al., 2001), if cooler climates meant reduced runoff, and this was more important in controlling lake presence/level than reduced evaporation rates.

Fig. 12 schematically shows high-frequency climatic fluctuations superimposed upon a lower order trend towards increased aridity. The presence or absence of a lake in the South Caspian Basin is a function of both the discharge entering the basin and evaporative loss from the basin. During deposition of the lower Productive Series the water balance of the Caspian Sea was such that any increase in fluvial discharge resulted in lacustrine expansion and inundation of the Apsheron Peninsula region. As the climate in the South Caspian Basin and its catchment area moves towards increased aridity, the discharge-related, lacustrine incursions interpreted in the lower Productive Series no longer occur. This results in reduced lacustrine influence in the upper Productive Series and helps to explain the lack of the distinctive black plastic clays characteristic of the lower Productive Series. Furthermore, as the climate continues

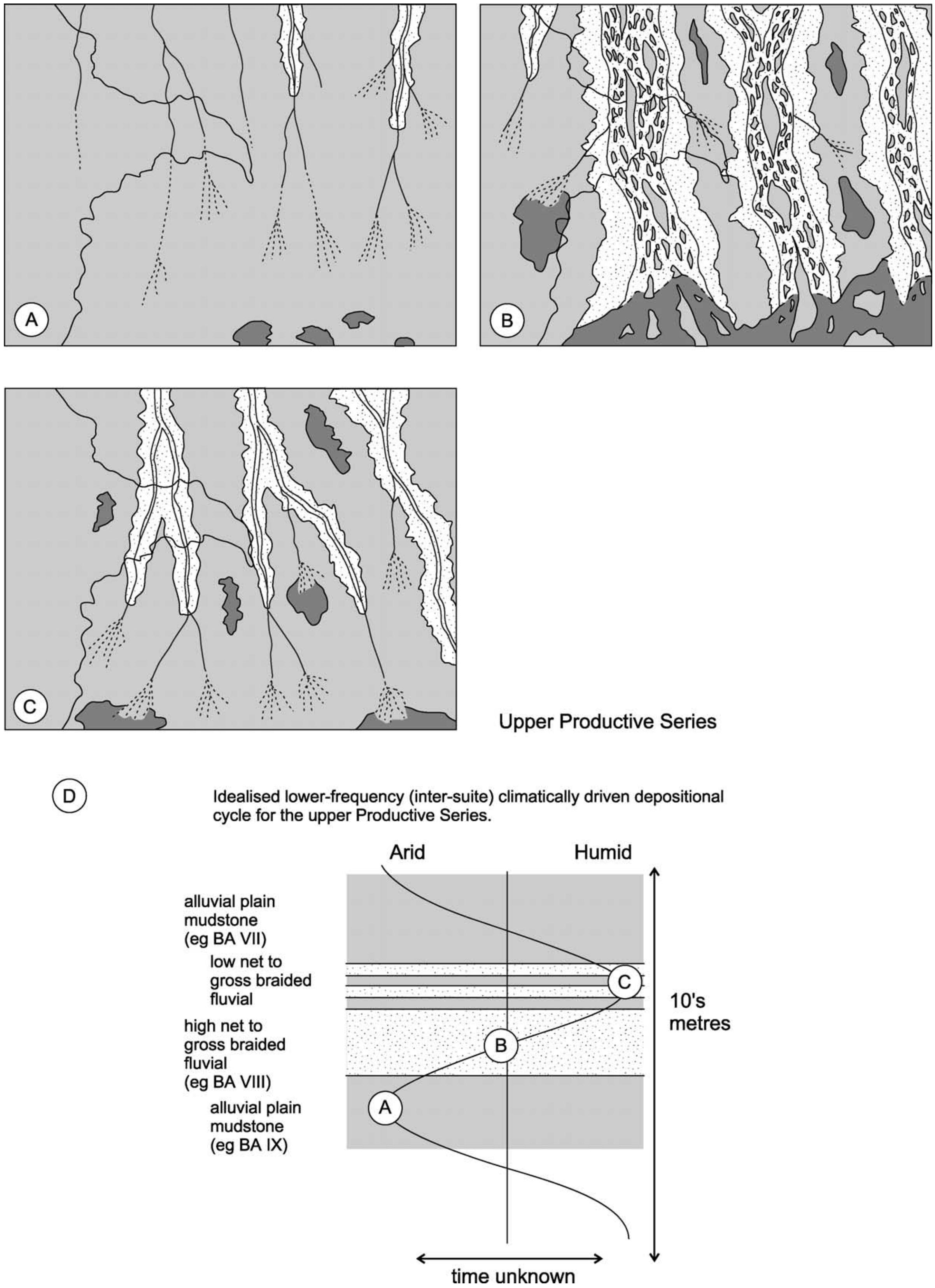

Fig. 11. Palaeogeographic reconstructions for the Apsheron Peninsula and surrounding area at (A) a time of maximum aridity and minimum coarse clastic input, (B) a period of major fluvial expansion during a time of increasing climatic humidity resulting in the establishment of a large sand-rich braid delta down depositional dip of the Apsheron Peninsula, and (C) as discharge decreases, lower net to gross, low sinuousity braided fluvial systems become established. Fig. 11D relates the palaeogeographic reconstructions A, B, and C to an idealised low frequency (1,00,000 year?) climatic cycle.

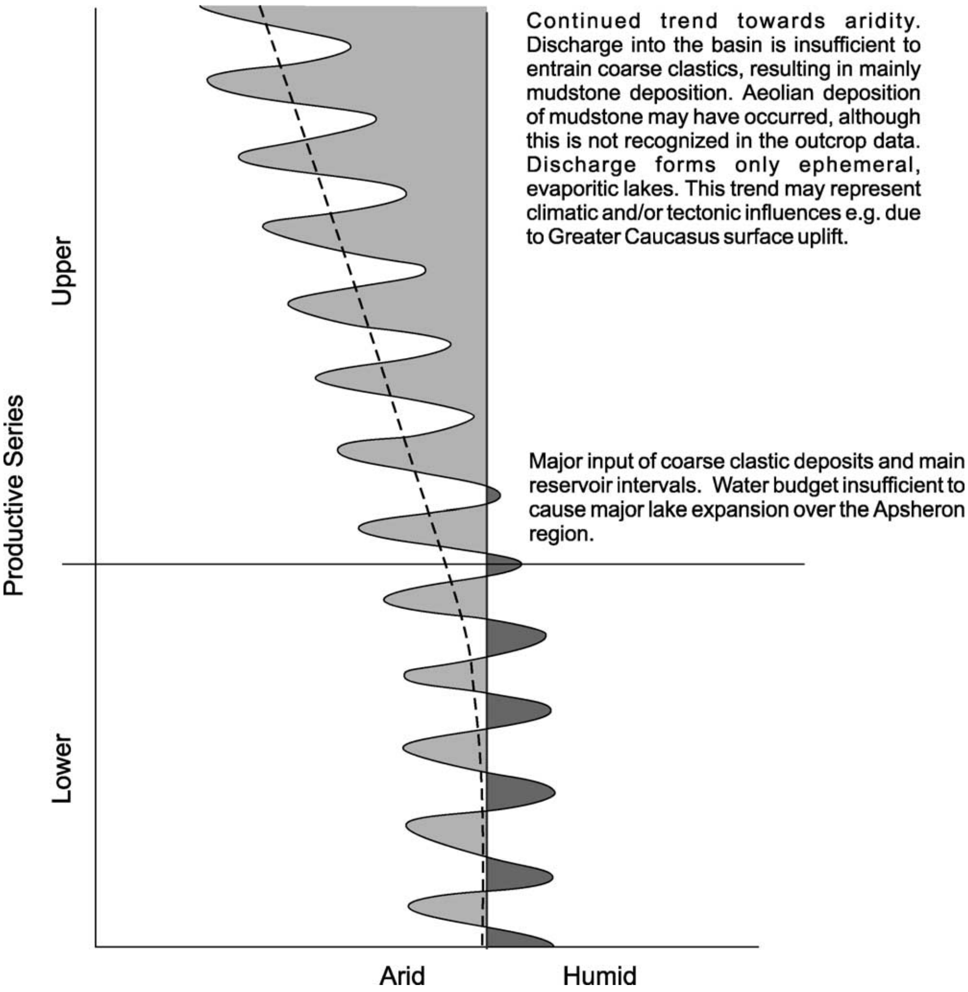

Fig. 12. Schematic diagram in which higher frequency climatic cyclicity is superimposed upon a lower frequency trend towards increasing aridity in the upper Productive Series. Aridity may be the result of long-term climatic change or due to the increased topographic influence of the Greater Caucasus. The long-term trend results in reduced lacustrine influence in the upper Productive Series. This trend culminates in reduced ability of fluvial systems to carry coarse clastic sediment and resulting in mudstone dominated Sabunchi and Surakhany suites.

towards maximum aridity (uppermost Surakhany Suite?) the ability of fluvial systems to transport coarse-grained bedload is drastically reduced, contributing to the overall fining upwards of the Productive Series.

7. Hydrocarbon exploration implications

The best quality reservoirs commonly lie within the lower part of the upper Productive Series (Pereriva and Balakhany suites) and comprise highly amalgamated, low sinuousity braided fluvial deposits characterised by channelised, fine- to medium-grained sandstone. Internal heterogeneity is restricted to local baffles formed by concentrations of intraformational mud clast conglomerate at erosive surfaces and local cementation of bedding planes (see Reynolds et al., 1998, for more detail). These facies are best developed in the Pereriva Suite and Balakhany subunits X and VIII. Potential reservoirs also lie within the lower net to gross subunits of the Balakhany Suite, particularly subunit VI and the upper portion of subunit VIII. The medium-to fine-grained, low sinuosity, braided fluvial sandstones of these subunits display a lesser degree of amalgamation and consequently internal heterogeneity is increased, with laterally continuous floodplain and channel abandonment facies forming vertical and lateral barriers respectively. Baffles formed by intraformational mud clast conglomerate lining erosive surfaces become more widespread. Reservoir sandstone also exists in the Sabunchi Suite. However, connectivity of these isolated fluvial sandstones is predicted to be limited. The Surakhany Suite contains limited reservoir potential in the Apsheron region. The mudstone dominated Post-Kirmaky Clay Suite, Balakhany subunits IX and VII contain little or no reservoir sandstone but may form effective regional seals.

At the regional-scale, a key issue for future hydrocarbon exploration is the distribution of reservoir quality sandstone south of the Apsheron Peninsula and the Apsheron Sill into the present-day deep-water South Caspian Basin (Fig. 1). Thus far, attention has been focused on the presumed presence of Pliocene deep-water clastic reservoirs basinward of sand-prone braid deltas. This assumes that braid deltas were developed in the first place. As discussed above, fluvial systems may have terminated in small, silt-rich deltaic bodies even at times of greatly increased discharge and sediment supply; the fluvial system simply prograded further into the basin. If braid deltas did develop, and deep-water clastics were deposited basinward of them, this requires the presence of a coeval relatively deep-water basin and a shelf gradient sufficient to initiate sediment gravity flows. As noted by Reynolds et al. (1998), Productive Series outcrops show no evidence of sediment mass movement, which would indicate the presence of a deep-water slope. Furthermore, regional seismic data do not reveal the presence of either a shelf break or of clinoform geometries (at least over much of the basin). Rapid, climatically mediated fluvial expansion more readily account for the monotonous sub-parallel seismic profiles characteristic of the basin fill. The relative controls of fluvial discharge and lake evaporation on basin fill are debatable, although we note that the modern Volga discharge plays a key role in the modern Caspian (Kroonenberg et al., 1997).

8. Conclusions

Deposits of the Productive Series in the Apsheron region are interpreted as representing deposition in a range of alluvial environments including fluvial, sheetflood, playa mudflat, and lacustrine settings. Sandbody geometries are characteristic of fluvial distributaries and sheetflood complexes. Lacustrine incursions in the lower Productive Series may indicate the presence of a true delta in the northern South Caspian Basin, albeit with a very low gradient, like the modern Volga, but not necessarily with the sedimentology of Holocene Volga delta deposits. The upper Productive Series in the study area lacks evidence for a standing body of water at the end of the drainage system, and a terminal fan setting seems more appropriate. The overall fining-upwards of the Productive Series is not viewed as a large scale regional transgression, but an extended period of coarse grained sediment starvation, in which deposition of distal mud- and silt-rich coastal plain facies occurred.

Previous workers may have over-estimated the role played by deltaic processes in the deposition of the Productive Series outcrop (Reynolds et al., 1998; Abdullaev et al., 1998). Those authors viewed the alternation between sand-prone and mud-rich suites as the product of repeated progradation and retrogradation of a deltaic complex in response to fluctuating lake-level. The internal architecture of individual suites was interpreted by the same authors as representing juxtaposition of fluvial, delta-plain, proximal delta-front, and distal delta-front lithofacies.

The present study has implications for hydrocarbon exploration. The nature of depositional systems in the deep South Caspian Basin are of prime importance. The new depositional models predict either the presence of extensive sand-rich braid deltas down dip of coeval multistorey/multilateral fluvial systems, or the gradual termination of fluvial systems into silt-rich progradational and shallow lacustrine facies.

Acknowledgements

This paper forms part of the first author's PhD Thesis, funded by the University of Aberdeen and CASP, with additional financial support from ExxonMobil, BP, Lasmo and Amerada Hess. Special acknowledgement is made to the staff of the Geological Institute of the Azerbaijan Academy of Sciences: their scientific and logistical assistance is greatly appreciated. Keith Richards (KrA Stratigraphic) and Mike Bidgood (GSS International) provided some of the biostratigraphic data referred to in this paper. INTAS supported work on the modern Volga Delta. David Puls (Exxon Azerbaijan Operating Company) is thanked for providing invaluable scientific and logistical support and for discussion in the field. Two anonymous referees provided very helpful comments. Thanks to Neflex for helping fund colour figure reproduction.

References

Abdullaev, T., Falt, L.-M., Akhundov, A., Van Graas, G. W., Kvamme, T., Folo, L. H., Mehmandarov, K., Narimanov, A. A., Olsen, T. S., Seljeskog, G., Skontorp, O., Sultanzade, T., Tank, N., & Valieva, E. (1998). A reservoir model for the main Pliocene reservoirs of the Bahar field in the Caspian Sea, Azerbaijan. *Petroleum Geoscience*, *4*, 259–270.

Abrams, M. A., & Narimanov, A. A. (1997). Geochemical evolution of the hydrocarbons and their potential sources in the western South Caspian Depression, Republic of Azerbaijan. *Marine and Petroleum Geology*, *14*, 451–468.

Ali-Zade, A. A., Salaev, S. G., & Aliev, A. I. (1985) (*vol. 250*). *Scientific Assessment of Hydrocarbon Prospects in Azerbaijan and the South Caspian and the Direction of Exploration Work*, Elm: Baku.

Allen, M. B., Jones, S., Ismail-Zadeh, A., Simmons, M. D., & Anderson, L. (2002). Onset of subduction as the cause of rapid Plio-Quaternary subsidence in the South Caspian Basin. *Geology*, *30*, 775–778.

Allen, M. B., Vincent, S. J., Alsop, G. I., Ismail-zadeh, A., & Flecker, R. (2003). Late Cenozoic deformation in the South Caspian region: effects of a rigid basement block within a collision zone. *Tectonophysics*, *366*, 223–239.

Alley, N. F. (1998). Cainozoic stratigraphy, palaeoenvironments and geological evolution of the Lake Eyre Basin. *Palaeogeography, Palaeoclimatology and Palaeoecology*, *144*, 239–263.

Abreu, V.S., Nummedal, D., Ware, P., Self, D., Witmer, R.J., Trevena, A., Williams, E., Trybek, J., (2000). Pliocene/Quaternary sequence stratigraphy of the Caspian Sea region: interplay of deltaic and climatic control on non-marine depositional sequences. Abstract, 1st AAPG Regional International Conference, Istanbul, Turkey.

Azizbekov, S.A., (1972). Geology of the USSR: Azerbaijan SSR. Moscow: Nauka, 433 pp.

Berberian, M. (1983). The southern Caspian: A compressional depression floored by a trapped, modified oceanic crust. *Canadian Journal of Earth Sciences*, *20*, 163–183.

Boomer, I., Aladin, N., Plotnikov, I., & Whatley, R. (2000). The palaeolimnology of the Aral Sea: a review. *Quaternary Science Reviews*, *19*, 1259–1278.

Clifton, H.E., Nummedal, D., Riley, G.W., Sayilli, A., Stein, J.A., Witmer, R.J., Williams, V.E., Bati, Z., Abreu, V.S., Demchuk, T.D., Van Nieuwenhuise, D.S., Fornaciari, M., Narimanov, A.A., (2000). Climatic and other controls on the deposition of the lower and middle Productive Series, Azerbaijan. Abstract, 1st AAPG Regional International Conference, Istanbul, Turkey.

Cotter, E., & Graham, J. R. (1991). Coastal plain sedimentation in the late Devonian of southern Ireland: hummocky cross-stratification in fluvial deposits. *Sedimentary Geology*, *72*, 201–224.

Cowan, E. J. (1991). Morrison Formation (Upper Jurassic), San Jaun Basin, New Mexico. In A. D. Miall, & N. Tyler (Eds.), *The three-dimentional facies architecture of terrigenous clastic sediments and its implications for hydrocarbon discovery and recovery* (*vol. 3*) (pp. 80–93). *Society of Economic Palaeontologists and Mineralogists, Concepts in Sedimentology and Palaeontology*.

Croke, J., Magee, J., & Price, D. (1996). Major episodes of Quaternary activity in the lower Neales River, northwest of Lake Eyre, central Australia. *Palaeogeography, Palaeoclimatology and Palaeoecology*, *124*, 1–15.

Crowley, T. J., & North, G. R. (1991). *Palaeoclimatology*. Oxford: Oxford University Press, pp. 339.

Devlin, W., Cogswell, J., Gaskins, G., Isaksen, G., Pitcher, D., Puls, D., Stanley, K., & Wall, G. (1999). South Caspian Basin: young, cool, and full of promise. *GSA Today*, *9*, 1–9.

Elliott, T. (1974). Interdistributary bay sequences and their genesis. *Sedimentology*, *21*, 611–622.

Friend, P. F. (1978). Distinctive features of some ancient river systems. In A. D. Miall (Ed.), *Fluvial Sedimentology* (*vol. 5*) (pp. 531–542). *Canadian Society of Petroleum Geologists, Memoir*.

George, G. T., & Berry, J. K. (1993). A new lithostratigraphy and depositional model for the Upper Rotliegend of the UK sector of the southern North Sea. In C. P. North, & D. J. Prosser (Eds.), *Characterization of fluvial and aeolian reservoirs* (*73*) (pp. 291–319). *Geological Society of London Special Publication*.

Hinds, D. J., Simmons, M. D., Allen, M. B., & Aliyeva, E. (2004). *Fluvial architecture variability within the Neogene productive Series, Azerbaijan: some implications for reservoir quality. In AAPG Special Studies volume on the Black Sea and Caspian basins*, (in press).

Hirst, J. P. P. (1991). Variations in fluvial architecture across the Oligo-Miocene Huesca fluvial system Ebro Basin, Spain. In A. D. Miall, & N. Tyler (Eds.), *The three-dimensional facies architecture of terrigenous clastic sediments and its implications for hydrocarbon discovery and recovery* (*vol. 3*) (pp. 111–121). *Society of Economic Palaeontologists and Mineralogists, Concepts in Sedimentology and Palaeontology*.

Jackson, J., Priestley, K., Allen, M., & Berberian, M. (2002). Active tectonics of the South Caspian Basin. *Geophysical Journal International*, *148*, 214–245.

Jones, R. W., & Simmons, M. D. (1996). A review of the stratigraphy of Eastern Paratethys (Oligocene–Holocene). *Bulletin of the Natural History Museum London (Geology)*, *52*, 25–49.

Kelly, S. B. (1993). Cyclical discharge variations recorded in alluvial sediments: an example from the Devonian of southwest Ireland. In C. P. North, & D. J. Prosser (Eds.), *Characterization of fluvial and aeolian reservoirs* (*vol. 73*) (pp. 157–166). *Geological Society of London Special Publication*.

Kelly, S. B., & Olsen, H. (1993). Terminal fans-a review with reference to Devonian examples. *Sedimentary Geology*, *85*, 339–374.

Kroonenberg, S. B., Rusakov, G. V., & Svitoch, A. A. (1997). The wandering of the Volga delta: a response to rapid Caspian sea-level change. *Sedimentary Geology*, *107*, 189–209.

Leeder, M. R., Harris, T., & Kirkby, M. J. (1998). Sediment supply and climate change: implications for basin stratigraphy. *Basin Research*, *10*, 7–18.

Magee, J. W., Bowler, J. M., Miller, G. H., & Williams, D. L. G. (1995). Stratigraphy, sedimentology, chronology and palaeohydrology of Quaternary lcaustrine deposits at Madigan Gulf, Lake Eyre, South Australia. *Palaeogeography, Palaeoclimatilogy, Palaeoecology*, *113*, 3–42.

Mangino, S., & Priestley, K. (1998). The crustal structure of the South Caspian region. *Geophysics Journal International*, *133*, 630–648.

Mertz, K. A., & Hubert, J. F. (1990). Cycles of sand-flat sandstone and playa-lacustrine mudstone in the Triassic–Jurassic Blomindon redbeds Fundy rift basin, Nova Scotia: implications for tectonics and climatic controls. *Canadian Journal of Earth Scienc*, *27*, 442–451.

Morton, A., Allen, M., Simmons, M., Spathopoulos, F., Still, J., Hinds, D., Ismail-Zadeh, A., & Kroonenberg, S. (2003). Provenance patterns in a neotectonic basin. *Basin Research*, *15*, 321–327.

Nummedal, D., Clifton, E., (2002). The role of paleoclimate in unraveling the reservoir architecture of the Productive Series of the South Caspian Basin. Abstract, Petroleum Geology of the Caspian Basins International Conference (unpaginated).

Parkash, B., Awasthi, A. K., & Gohain, K. (1983). Lithofacies of the Markanda terminal fan Kurukshetra district, Haryana, India. In J. D. Collinson, & J. Lewin (Eds.), *Modern and ancient fluvial environments. International Association of Sedimentologists* (*vol. 6*) (pp. 337–344). *Special Publication*.

Reynolds, A. D., Simmons, M. D., Bowman, M. B. J., Henton, J., Brayshaw, A. C., Ali-Zade, A. A., Guliyev, I. S., Suleymanova, S. F., Ateava, E. Z., Mamedova, D. N., & Koshkarly, R. O. (1998). Implications of outcrop geology for reservoirs in the Neogene Productive Series: Apsheron Peninsula, Azerbaijan. *AAPG Bulletin*, *82*, 25–49.

Saunderson, H. C., & Locket, F. P. J. (1983). Flume experiments on bedforms and structures at the dune plane bed transition. In J. D. Collinson, & J. Lewin (Eds.), *Modern and ancient fluvial systems. International Association of Sedimentologists* (*vol. 6*) (pp. 49–58). *Special Publication*.

Stear, W. M. (1983). Morphological characteristics of ephemeral stream channel and overbank splay sandstone bodies in the Permian Lower Beaufort Group Karoo Basin, South Africa. In J. D. Collinson, & J. Lewin (Eds.), *Modern and ancient fluvial systems* (*vol. 6*) (pp. 405–420). *International Association of Sedimentologists, Special Publication*.

Talbot, M. R., Holm, K., & Williams, M. A. J. (1994). Sedimentation in low-gradient desert margin systems: a comparison of the late Triassic of northwest Somerset (England) and the late Quaternary of east-central Australia. In M. R. Rosen (Ed.), *Palaeoclimate and basin evolution of playa systems* (*vol. 289*) (pp. 97–117). *Geological Society of America Paper*.

Tooth, S. (2000). Process, form and change in dryland rivers: a review of recent research. *Earth Science Reviews*, *51*, 67–107.

Tye, R. S., & Coleman, J. M. (1989). Depositional processes and stratigraphy of fluvially dominated lacustrine deltas: Mississippi delta plain. *Journal of Sedimentary Petrology*, *59*, 973–996.

Uskin, N. I. (1916). *Stratigraphy and tectonics of the Productive Series of the Balakhany-Sabunchi-Ramany oil-producing region. Baku*, pp. 80, in Russian.

Zhang, P., Molnar, P., & Downs, W. R. (2001). Increased sedimentation rates and grain sizes 2–4 Myr ago due to the influence of climate change on erosion rates. *Nature*, *410*, 891–897.

Zonenshain, L. P., & Le Pichon, X. (1986). Deep basins of the Black Sea and Caspian Sea as remnants of Mesozoic back-arc basins. *Tectonophysics*, *123*, 181–211.