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ORIGINAL PAPER

The Göktaş fan delta complex in Manavgat Basin, South Türkiye: a model for stratigraphic development of coarse-clastic littoral wedges and spatial-facies prediction

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Abstract
The Göktaş fan delta complex is a regressive-transgressive wedge deposited in the late Serravallian to late Tortonian as a wave-dominated, dip-slope coastal system associated with the antithetic hangingwall faultline of the Manavgat Basin (South Türkiye), whose footwall was submerged. The gravelly fan delta was sourced from a pre-existing valley in the basin's mountainous northern hinterland. The composite wedge, more than 230 m thick, consists of a series of regressive-transgressive basic wedges stacked upon one another and extending up to 18 km from the basin margin. A forward-stepping set of forced-regressive wedges is overlain by an aggradational to a backstepping set of normal-regressive wedges, split by a forced-regressive one in the middle. The fan delta complex has a timespan of *ca.* 4 Ma. It is considered to have formed in the transitional, fall-rise turnaround phase of two successive 3rd-order eustatic cycles, punctuated by rapid tectonic subsidence and fan delta drowning (4th-order maximum-flooding surfaces separating the basic wedges). Tectonics was probably responsible also for sporadic, brief events of 5th-order marine flooding, whereas minor shoreline shifts of 6th-order were likely due to climatic fluctuations and autocyclic lateral switching of fluvial activity. Based on the fan delta complexes in the Manavgat Basin and adjoining Köprü Basin, a model is suggested for the depositional architecture and facies anatomy of wave-dominated, shoal-water fan deltaic successions, with emphasis on the sedimentation processes and response to relative sea-level changes. In the hierarchical organisation of the fan delta complex, the normal-regressive basic wedges consist of highstand (HST) and transgressive systems tract (TST). In contrast, the forced-regressive wedges comprise highstand (HST), falling-stage (FSST), lowstand (LST), and transgressive systems tract (TST). The systems tracts differ in geometry and spatial partitioning of facies. The HST has a moderately thick, short-radius alluvium comprising moderately deep palaeochannels and extending basinwards over progradational mouth-bar facies, underlain and passing into a narrow belt of wave-worked shoreface facies grading into tempestitic offshore-transition deposits. The FSST has a thin and poorly preserved alluvium, including basal deposits of overdeepened bypass channels and incised valleys, that passes basinwards into progradational delta-front deposits developed as either mouth-bar facies underlain by shoreface deposits (possibly with offshoot turbiditic channels and lobes in offshore-transition zone) or a large foreset of avalanching strandplain deposits overlying offshore-transition facies. The LST has a moderately thin, basinward-thickening alluvium with mainly shallow palaeochannels, which overlies mouth-bar facies and passes basinwards into an aggradational delta-front succession of alternating beach and shoreface facies, the latter far extended as a passage to offshore-transition deposits. The TST has the thickest alluvium, comprising shallow to moderately deep palaeochannels and thinning basinwards rapidly, truncated by a landward-rising transgressive ravinement; the ravinement surface is overlain by a blanket of alternating upper/lower shoreface facies, passing landwards into beach facies and seawards into offshore-transition deposits. The model may serve to predict facies distribution in fan deltaic littoral wedges and assess reservoir quality in petroleum exploration.

Keywords Fan delta · Sequence stratigraphy · Cyclicity · Sea level · Tectonics · Lithofacies prediction

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1 Introduction

Sequence-stratigraphic studies of the depositional history of shallow-marine basins benefit from the high-resolution record of fan deltaic complexes. A fan delta, even if small, proves to be a highly sensitive recorder of basin-margin coastal conditions, particularly sediment supply, relative sea-level changes and marine energy regime (Nemec and Steel 1988; Wescott and Ethridge1990; Chough and Orton 1995; Marzo and Steel 2000; Lønne and Nemec 2003). The development of fan delta also reflects seafloor bathymetry, coastal morphology and catchment conditions, which all render fan deltaic successions rich in geological information and particularly valuable due to their common association with high-relief basin margins. By comparison, non-deltaic shorelines in such settings result in monotonous facies successions that may reflect little more than the regime of marine processes and some major changes, if not just falls, in relative sea level. When perched on a steep basin margin, a non-deltaic shoreline may be little responsive to sea-level fluctuations regarding nearshore facies change (Ilgar and Nemec 2005; Wathne et al. 2024).

The high resolution of the fan deltaic sedimentary record is demonstrated by the present study of the depositional architecture and facies anatomy of a well-exposed Miocene fan delta complex in the Manavgat Basin (Fig. 1), a fault-bounded eastern compartment of the large Neogene Antalya Basin in southern Türkiye (Çiner et al. 2008). The Göktaş Member of the late Serravalian-Tortonian Karpuzçay Formation is an exhumed gravelly succession of a fan delta that was the largest and longest-active amongst the contemporaneous fan deltaic systems formed along the basin's mountainous margin.

In this paper, the hierarchical stratigraphic organisation of the Göktaş fan delta complex is discussed, with main emphasis on the sedimentary processes/facies and their spatial partitioning within systems tracts and on the principal factors that controlled the varying sedimentation pattern and morphology of the evolving fan delta. In the final section, this geological information is combined with evidence from five other analogous complexes to develop a comprehensive model for predicting spatial-facies distribution in fan deltaic littoral wedges and possible assessment of reservoir heterogeneities in petroleum exploration.

2 Geological setting

The Neogene Antalya Basin, in southern Türkiye (Fig. 1A, B), evolved through alternating pulses of tectonic compression and extension related to the final emplacement phase of the Lycian nappes from the northwest and the process of broad backarc stretching north of the Cyprus subduction arc (Karabıyıkoğlu et al. 2000; Robertson 2000; Çiner et al. 2008; Koç et al. 2016). The basin formed in late Aquitanian as two hangingwall depocentres associated with major normal faults in the peripheral zone of the Lycian foreland (Hayward 1984; Flecker et al. 2003). The resulting asymmetrical grabens, referred to as the Aksu, Köprü and Manavgat basins (Fig. 1B), developed further under the influence of backarc extension during Langhian to Messinian, when the main faults reached a cumulative throw of a few kilometres (Deynoux et al. 2005). The basins had gulf-like geomorphic configuration, semi-surrounded by mountains and hosting alluvial to sublittoral marine environments, with sedimentation controlled by tectonics, relative sea-level changes and climatic fluctuations. Their late Pliocene tectonic inversion (Poisson et al. 2003) was followed by denudation and incision of fluvial valleys.

The Antalya Basin formed on the collapsing southern flank of the Taurus orogen, which is reflected best in the structural configuration of the Manavgat compartment (Fig. 1B, C). This sub-basin developed as a SE-trending graben, oblique to the adjoining Köprü Graben, with a submerged southern footwall (see the Çolaklı Fault in Fig. 1C) and a high-relief northern margin. The mountainous north hinterland consisted of the metamorphic rocks of Antalya-Alanya nappes emplaced towards the northeast onto a thick autochthonous platform of Mesozoic limestones in Palaeocene time (Fig. 1C). The Manavgat Basin was thus fully open to the palaeo-Mediterranean Sea, had a rocky coast, and itself was affected little by the Lycian foreland compression. The basin was tectonically inverted near the end of Pliocene by a pulse of southwesterly compression (Nemec and Özaksoy 2024) attributed the westward tectonic escape of the compound Anatolian platelet (Dewey and Şengör 1979; Şengör and Yılmaz 1981; Şengör et al. 1985; Şengör and Yazıcı 2020).

The Göktaş fan delta formed as a hangingwall depositional system in the western part of the Manavgat Basin (Figs. 1C and 2), near its transition to the adjoining Köprü Basin. The boundary between the two segments of the curvilinear graben system is the buried southern extension of the Kırkkavak Fault (Fig. 1B, C). This pre-Miocene dextral strike-slip fault continued to be active as a normal fault in Miocene time, terminating in the transition zone as a syndepositional, graben-crossing fault-tip flexure in the form of WSW-inclined monocline (Çiner et al. 2008). The maximum subsidence occurred along the Kırkkavak Fault in the Köprü Basin and along the Çolaklı Fault in the Manavgat Basin, reflecting a switch of graben polarity. The Göktaş fan delta thus prograded over a seafloor inclined gently (< 1°) to the

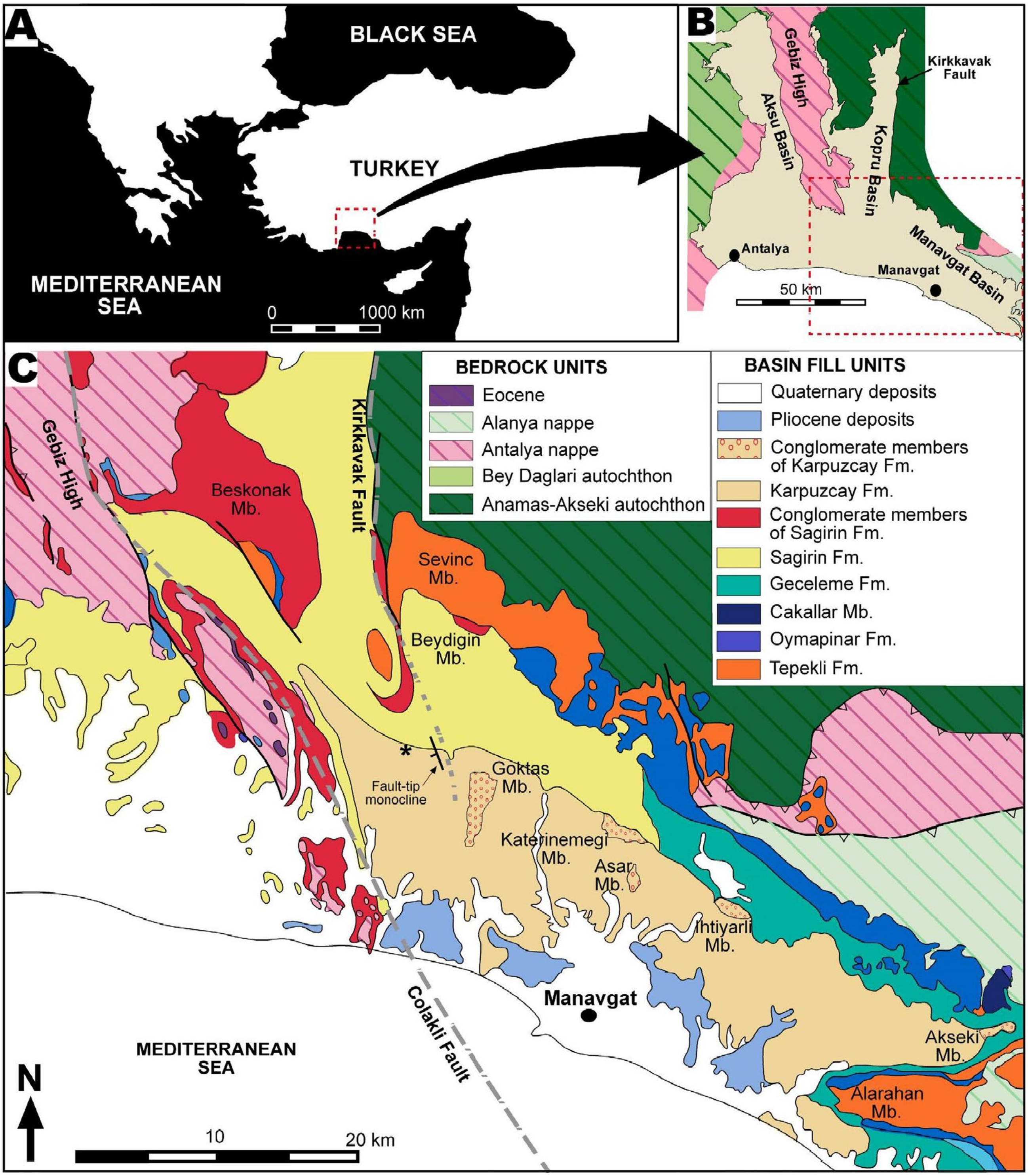


Fig. 1 **A** Location of the Antalya Basin in southwestern Türkiye. **B** Simplified map of the Antalya Basin, showing its Aksu, Köprü and Manavgat compartments. **C** Geological map of the Manavgat Basin and its transition to the adjoining Köprü Basin (based on Akay et al. 1985); note the location of the Göktaş Member of Karpuzçay Formation and the tip zone of Kırkkavak Fault; the asterisk indicates the location of Çardak outcrop section (log in Fig. 14)

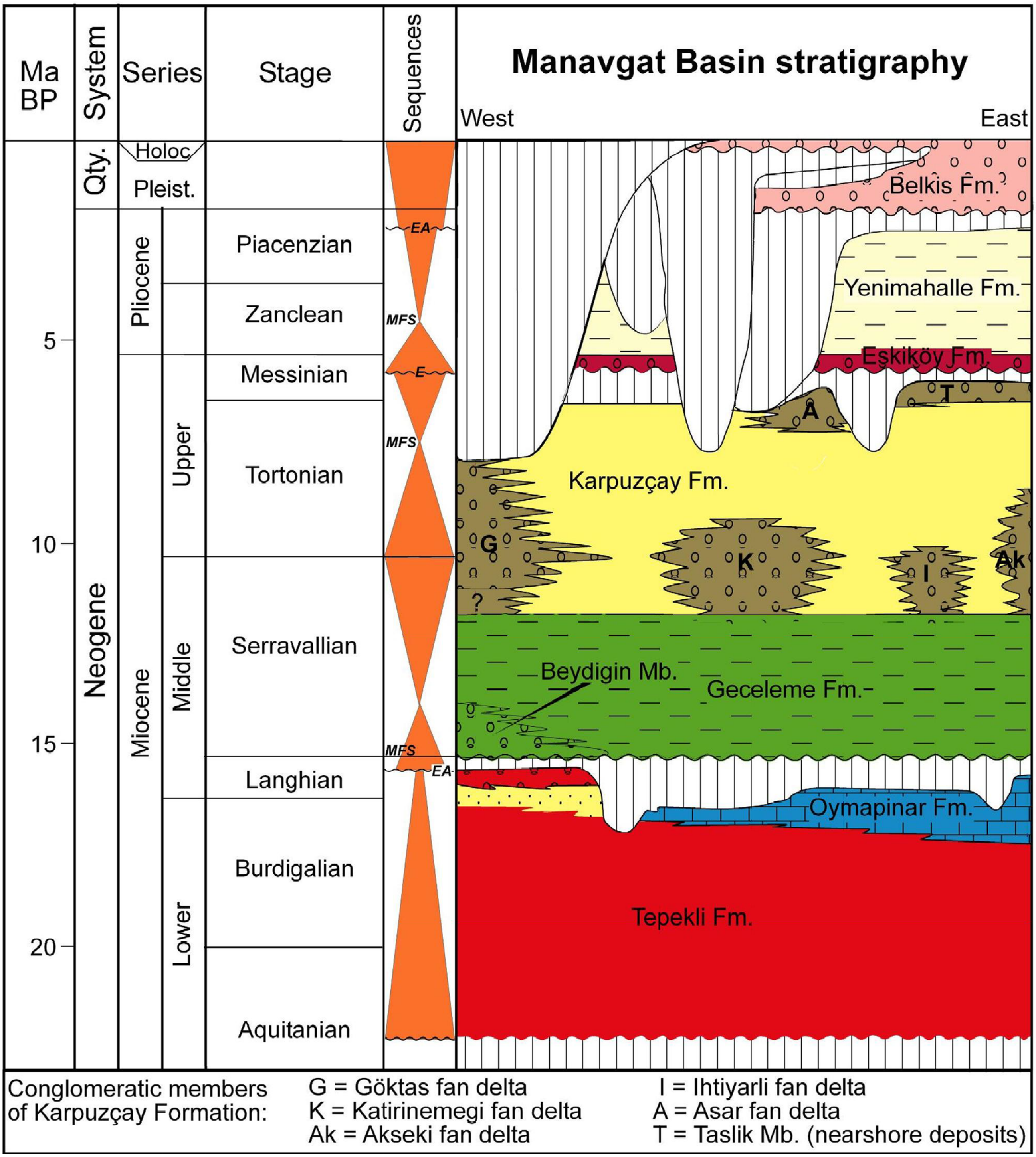


Fig. 2 Stratigraphy of the Manavgat Basin (based on Akay et al. 1985). Note the late Serravallian-late Tortonian Göktaş fan delta complex (G) and the coeval fan delta complexes in the Karpuzçay Formation. The letter symbols in the sequence column: *MFS* maximum flooding surface (sequence boundary), *E* erosional unconformity, *EA* erosional angular unconformity

southwest, away from the basin margin, and hosting a littoral to shallow neritic (offshore transition) environment. This fan delta reached a radial length of *ca.* 18 km. It was the largest of the basin's late Serravalian-Tortonian fan deltaic systems (Fig. 2), whose dimensions are thought to reflect chiefly their catchment sizes (Wathne et al. 2024). The surrounding Karpuzçay Formation is an open-marine tempestitic succession interspersed with tsunamites and *ca.* 400 m thick. The adjacent Katırınemeği, Asar and Ihtiyarlı fan delta complexes to the east (Figs. 1C and 2) are described by Wathne et al. (2024) and Alçiçek et al. (2024). The dynamic stratigraphy of the Manavgat Basin is debated by Akay et al. (1985), Karabıyıkoğlu et al. (2000), Deynoux et al. (2005), Çiner et al. (2008) and Koç et al. (2016).

3 The Göktaş fan delta complex

The Göktaş fan delta was the longest-active of the basin's fan deltaic systems that formed in the middle part of a major regressive-transgressive sequence bounded by the surfaces of end-Langhian and late-Tortonian maximum flooding (Fig. 2). The great radial length of the Göktaş fan delta implies a highly efficient fluvial feeder system, draining a relatively large intramontane catchment (see discussion by Wathne et al. 2024). The fan delta was sourced from a mountain valley incised in the Jurassic-Cretaceous limestones and Triassic shales and greywackes of the autochthonous bedrock complex in the eastern vicinity of the Kırkkavak Fault (Karabıyıkoğlu et al. 2000; Monod et al. 2001; Çiner et al. 2008). The valley was formed much earlier and supplied sediment also for an early Serravallian fan delta (Beydiğin Mb.) and an early Miocene fan delta (Sevinç Mb.) deposited in this area (Fig. 1C). The valley must have been periodically drowned and accumulated sediment. As discussed further in the text, the reactivation of a sediment-filled valley and the topographic effect of the older fan deltaic complexes were the main causes of the high sediment yield and impressive basinward advance of the Göktaş fan delta. The depositional area coincided with the structural switch zone of graben polarity, which probably influenced the development of the fan delta, particularly in its distal part. The fan delta was a dip-slope system and prograded chiefly towards the south but was expanding and probably reaching the WSW-sloping monocline at the southern tip of Kırkkavak Fault (cf. Fig. 1C).

The conglomeratic Göktaş Member of the Karpuzçay Formation (Figs. 1C and 2) is well-exposed in a south-trending cliff section sub-parallel to the fan delta's axis and more than 5 km long (Fig. 3A). The fan delta complex is a composite regressive-transgressive wedge, more than 230 m thick in its preserved northern (proximal) part and thinning to 25 m approximately 5 km further to the south. The north part of the outcrop section is *ca.* 12 km away from the basin's bedrock margin, as the head part of the fan delta complex is not preserved, eroded by a deep incision of a Quaternary fluvial valley roughly parallel to the margin.

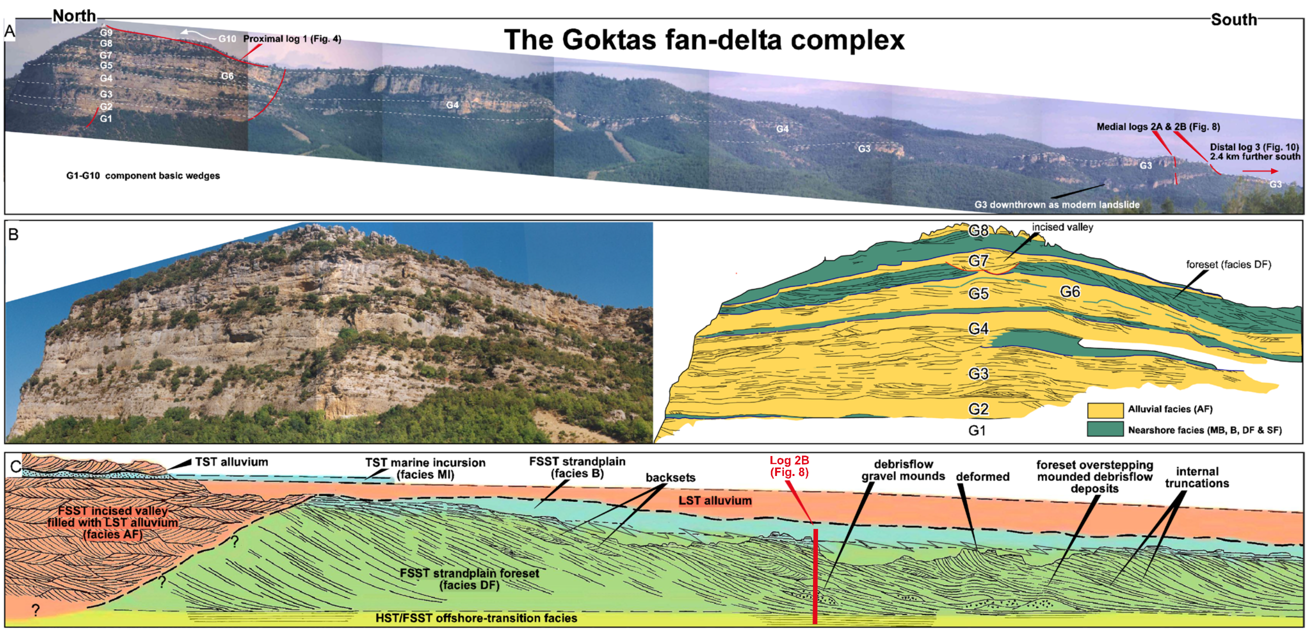


Fig. 3 **A** Photomosaic of the south-trending outcrop section of the Göktaş fan delta complex (*ca.* 230 m thick in its northern part), exhumed by Quaternary erosion; note the component basic wedges G1–G10 and the location of logs 1–3. **B** Photomosaic and corresponding overlay drawing of the northern, proximal part of the fan delta complex; only wedges G2–G8 are visible, with a *ca.* 160 m thickness due to the oblique upward view and foreground forest. **C** Outcrop sketch of the medial part of the outcrop section, showing the progradational foreset of facies DF incised by a south-trending fluvial palaeovalley (10–11 m deep) in the landward part; the palaeovalleys axis is to the right, at *ca.* 30° out of the outcrop section

4 Fan delta facies associations

The sedimentary facies of the Göktaş fan delta complex, studied systematically in several detailed logs along the longitudinal outcrop section (Fig. 3A), provide a high-resolution record of the sedimentation processes involved and the system's general behaviour, particularly in response to changes in relative sea level and sediment supply. The facies record, including evidence of phases of erosion and non-deposition (sediment bypass), reflects the fan delta's short- and long-term morphodynamic evolution that can readily be compared with the development of coeval fan deltaic systems in the basin. The sedimentary facies observed in the Göktaş fan delta complex are summarised in Table 1 and described briefly in the present section, with special reference to the proximal and medial logs (Fig. 3A) and a distal log *ca.* 2.5 km farther to the south. The descriptive terminology is after Harms et al. (1975, 1982) and Collinson and Thompson (1982), and the volumetric percentages of the individual facies assemblages are based on their measured cumulative thicknesses (one-dimensional volume estimates). For a more detailed discussion of the origin of analogous facies, the reader is referred to Larsen et al. (2024a, b).

4.1 Alluvial-fan deposits

Alluvial deposits constitute *ca.* 66 vol.% of the proximal outcrop section of the Göktaş fan delta complex (see facies association AF in Fig. 4). The alluvium is predominantly gravelly and occurs as (a) multi-storey palaeochannels filling isolated incised valleys (see wedge G3 in Fig. 3C and wedge G7 Fig. 3B); (b) multi-storey and multilateral palaeochannels forming thick fan lobe bodies (Fig. 3B); (c) single-storey, multilateral or isolated palaeochannels encased in beach deposits (e.g. see wedges G8 and G9 in Fig. 4); or (d) amalgamated, broad and shallow palaeochannels or non-channelized units (e.g. see the upper part of wedge G3 in Fig. 4). The alluvial conglomerates are submature, mainly clast-supported and composed of fine to coarse pebble gravel, but containing scattered cobbles and boulders as well as intercalations of pebbly sandstone (Fig. 5). The framework clasts are mainly subrounded and moderately sorted, and generally lack shape segregation. Matrix is coarse, poorly sorted sand mixed with granules and small pebbles. The deposits have been divided into four facies (see alluvial-fan deposits in Table 1).

Facies AF.CL. This facies occurs as isolated, erosional lenses of massive, cobble- and boulder-rich, clast-supported conglomerate, several metres wide and up to 50 cm thick, associated with palaeochannel bases and overlain by facies AF.TB or AF.LB (Figs. 4 and 5A, C, log height 57.5 m). These are the coarsest conglomerate beds, with highly uneven bases, interpreted as channel-floor lags deposited in the thalweg zones of stream channels (Miall 1985, 1996; Nemec and Postma 1993). The relatively thick lags in some of the palaeochannels indicate prolonged phases of considerable sediment bypassing.

Facies AF.TB. These deposits are units of high-angle cross-stratified, clast-supported conglomerate and subordinate gravelly sandstone, 1–2 m thick and broadly tabular to wedge-shaped, overlying a channel-floor pavement and commonly also one another (Figs. 4 and 5A, B). The cross-strata are mainly 5–10 cm thick and normally graded, fining in the updip direction and showing angular to tangential basal contacts. These cross-sets of cobble-bearing pebble gravel are interpreted to be mid-channel braid bars, transverse or oblique/rhomboidal, with well-developed slip faces (Boothroyd and Ashley 1975; Boothroyd and Nummedal 1978; Church and Jones 1982; Miall 1985, 1996), formed in relatively deep (1–3 m), well-defined channels.

Facies AF.LB. These beds of clast-supported, pebble-to-cobble gravel, several decimetres thick, show crude planar-parallel stratification, subhorizontal or gently inclined (Fig. 5C). The units commonly show an upward coarsening or fining and a northward (upstream) imbrication of clasts and are isolated or stacked upon one another. The characteristics of this facies indicate gravel deposition by combined aggradation and downstream accretion, as low-relief, lobate longitudinal bars in relatively shallow (< 1 m) and broad channels (Boothroyd 1972; Bluck 1976, 1982; Nemec and Postma 1993; Miall 1996). Some of the fining-upward units have erosional bases and seem to lack stratification, and their isolated occurrences at the top of palaeochannels may be deposits of hyperconcentrated sheetfloods (Nemec and Muszyński 1982; see facies AF.HF of Larsen et al. 2024b).

Facies AF.BC. These non-erosional lenses of stratified pebbly sandstone and/or silty sandstone, a few metres in lateral extent and up to a few decimetres thick, occur as local cappings of the braid-bar facies AF.TB and AF.LB in the uppermost parts of palaeochannels (Fig. 4, log heights 50 and 139 m). The direct association with channel-fill deposits and lack of marine burrows suggest that these sandstones are bar-top caps, deposited during the stream's low stages and preserved mainly at the stage of channel abandonment (Miall 1996).

Table 1 Guide to the sedimentary facies distinguished in the Göktaş fan delta complex

Facies	Main characteristics	Interpretation
Alluvial-fan deposits		
AF.CL	Erosional lenses of cobble- and boulder-rich, clast-supported gravel, 5–70 cm thick	Channel-floor lag deposits
AF.TB	Cross-stratified gravel beds, pebbly to cobbly, 20–254 cm thick, averaging 120 cm	Transverse or oblique, steep-fronted bars
AF.LB	Pebble to cobble gravel beds with planar-parallel stratification, subhorizontal or gently inclined; 10–77 cm thick, averaging 37 cm	Longitudinal bars
AF.BC	Discontinuous, non-erosional layers of stratified sand or silty sand, 1–37 cm thick	Cappings of inactive bars and abandoned channels
Marine-incursion deposits		
MI.TL	Sheet-like beds of wave-worked gravel, 10–30 cm thick, with marine burrows	Transgressive gravel lags
MI.WW	Sheet-like beds of wave-worked pebbly sand, 10–50 cm thick, with marine burrows	Transgressive wave-winnowed deposits
Mouth-bar deposits		
MB.ET	Parallel-stratified gravel and sand forming sigmoidal sets, up to 100 cm thick and inclined gently seawards and sideways	Shoal-water mouth-bar deposits of frictional stream effluent combined with wave swash action
MB.DF	Tongue-shaped or shore-aligned isolated mounds of massive gravel, 40–100 cm thick	Deposits of flood-generated, beach-derived debrisflows, mainly cohesionlass
Delta-front foreset deposits		
DF	Tabular beds of massive gravel, 20–90 cm thick, forming large sigmoidal foreset with internal gravel mounds, backsets, truncation surfaces and a wave-worked topset	Cohesionless debrisflow and rip-current deposits of an avalanching underwater slope of prograding delta-front strandplain
Beach deposits		
B.BP	Coarse to medium gravel rich in discs/blades, with planar strata and landward cross-strata	Beach-platform deposits (berm and backshore)
B.BF	Alternating gravel and sand in units 10–150 cm thick, with gently seaward-inclined strata	Beachface (foreshore) deposits
B.OF	Stratified sand with spherical cobbles and large pebbles, in units 5–112 cm thick	Beach outer-frame deposits
Shoreface deposits		
SF.WT	Wave-worked sand with scattered pebbles, units 20–30 cm thick	Deposits of wave traction
SF.SS	Erosional sheets of stratified pebble gravel, 10–100 cm thick, averaging 39 cm	Deposits of storm or tsunami backsurges
Offshore-transition deposits		
OT.TE	Sheet-like sandstone beds, 5–35 cm thick, with current, combined-flow and wave structures	Tempestites, attributed to infrequent powerful storms
OT.HE	Mudstone beds, 2–25 cm thick, with thin interlayers of silt and fine sand, neritic microfauna and *Ophiomorpha* and *Thallassinoides* burrows	Hemipelagic deposits, including products of common minor storms
OT.TS	Isolated thick (> 45 cm) beds of massive conglomerate and/or coarse sandstone, graded or not, commonly with floating outsized clasts and undulatory, wave-worked tops	Tsunamites

4.2 Marine-incursion deposits

Though associated with alluvial deposits, these thin conglomerate and pebbly sandstone sheets (see deposits MI in Fig. 4) contain marine ichnofauna and hence are separated here from the alluvium. These isolated beds constitute *ca.* 0.6 vol.% of the proximal outcrop section, where

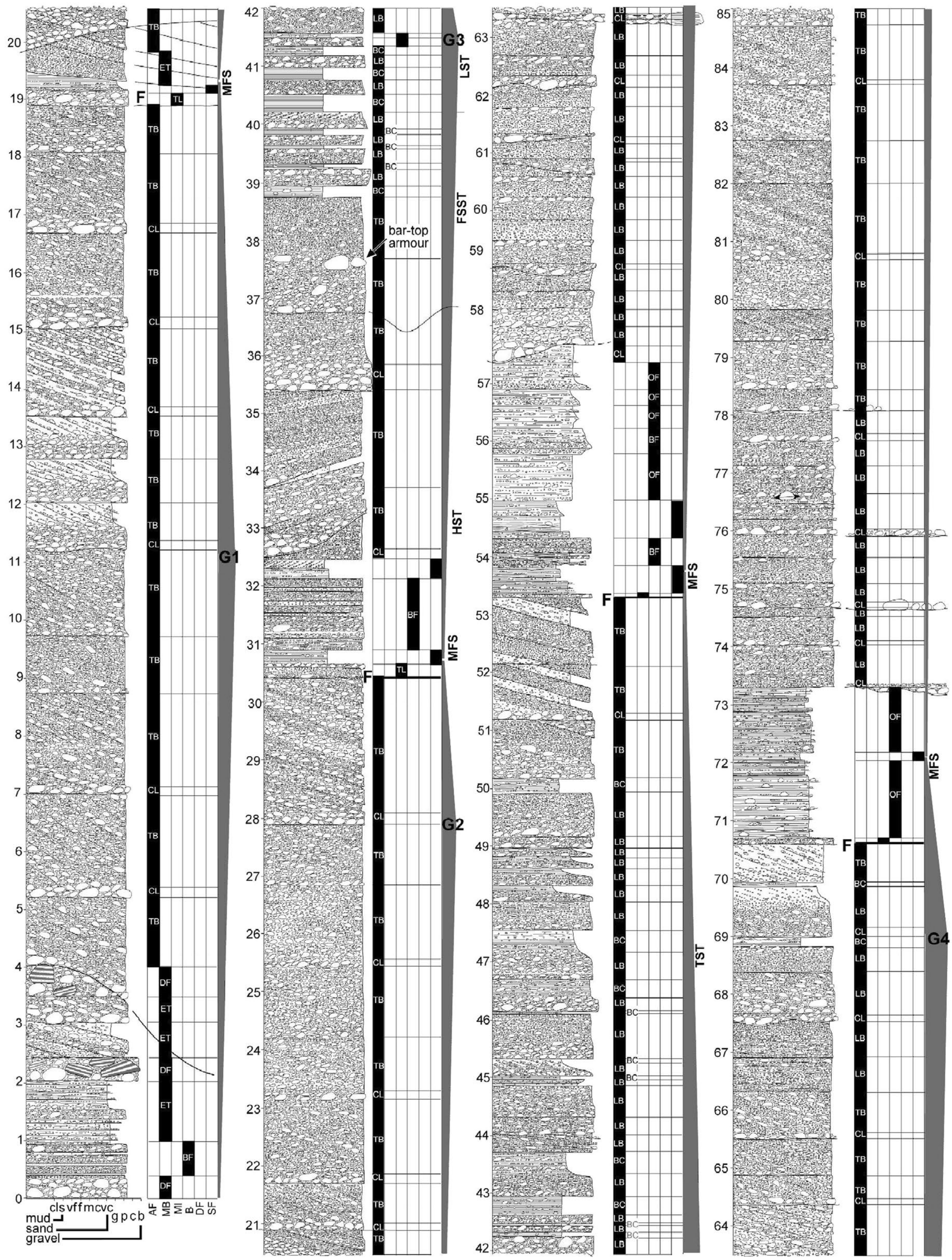


Fig. 4 Sedimentological log 1 from the proximal part of the outcrop section of Göktaş fan delta complex (see location in Fig. 3A). The scale for mean grain size indicates clay (cl) and silt (s), with mud plotted as intermediate class; very fine (vf), fine (f), medium (m), coarse (c) and very coarse (vc) sand; and granule (g), pebble (p), cobble (c) and boulder (b) gravel. The letter code for facies associations (log-margin columns) and facies symbols are as in the text and Table 1. Other symbols: *G1–G10* successive basic wedges (cf. Fig. 3A), *F* marine flooding surface, *MFS* maximum flooding surface (sequence boundary), *HST, FSST, LST and TST* highstand, falling-stage, lowstand and transgressive systems tracts

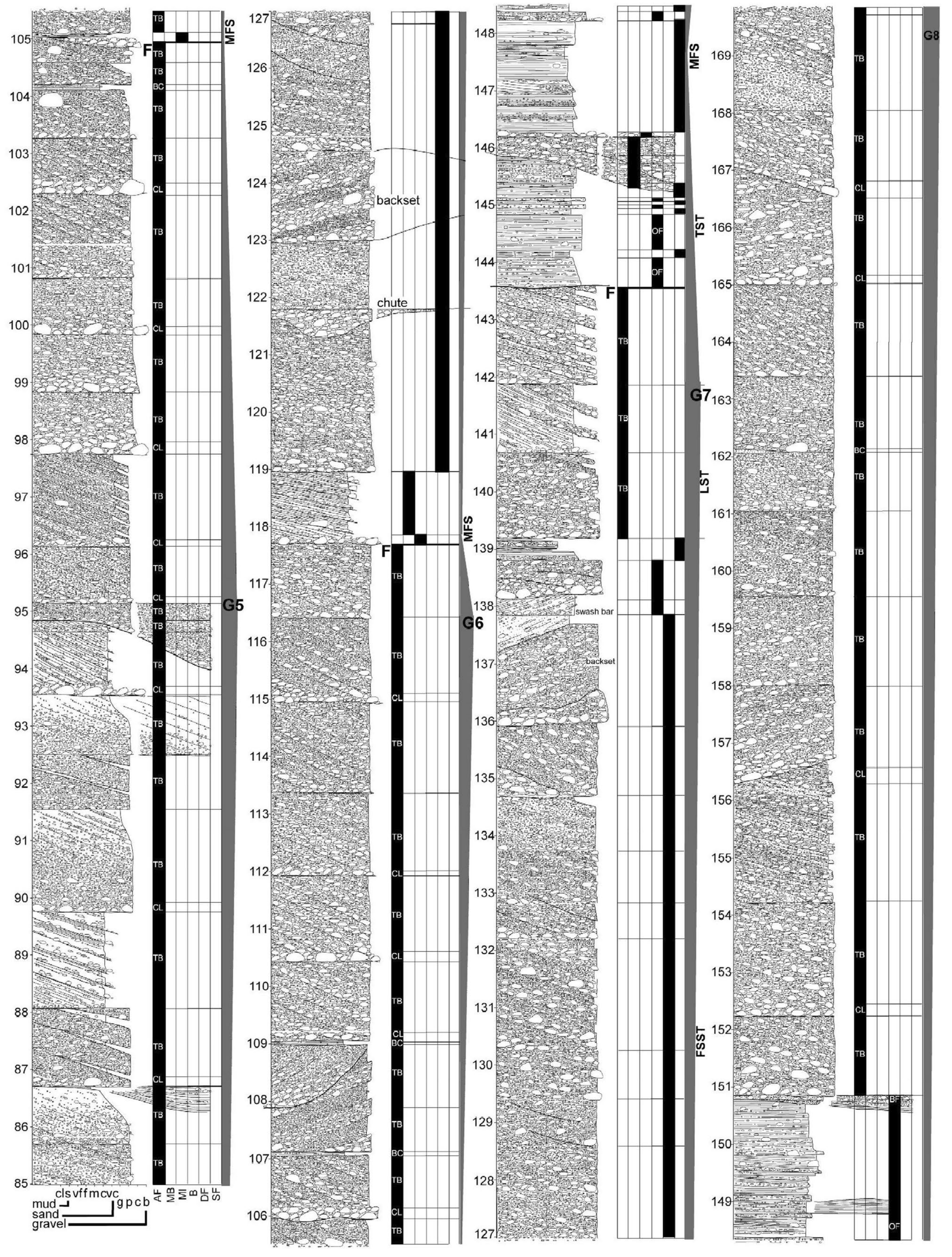
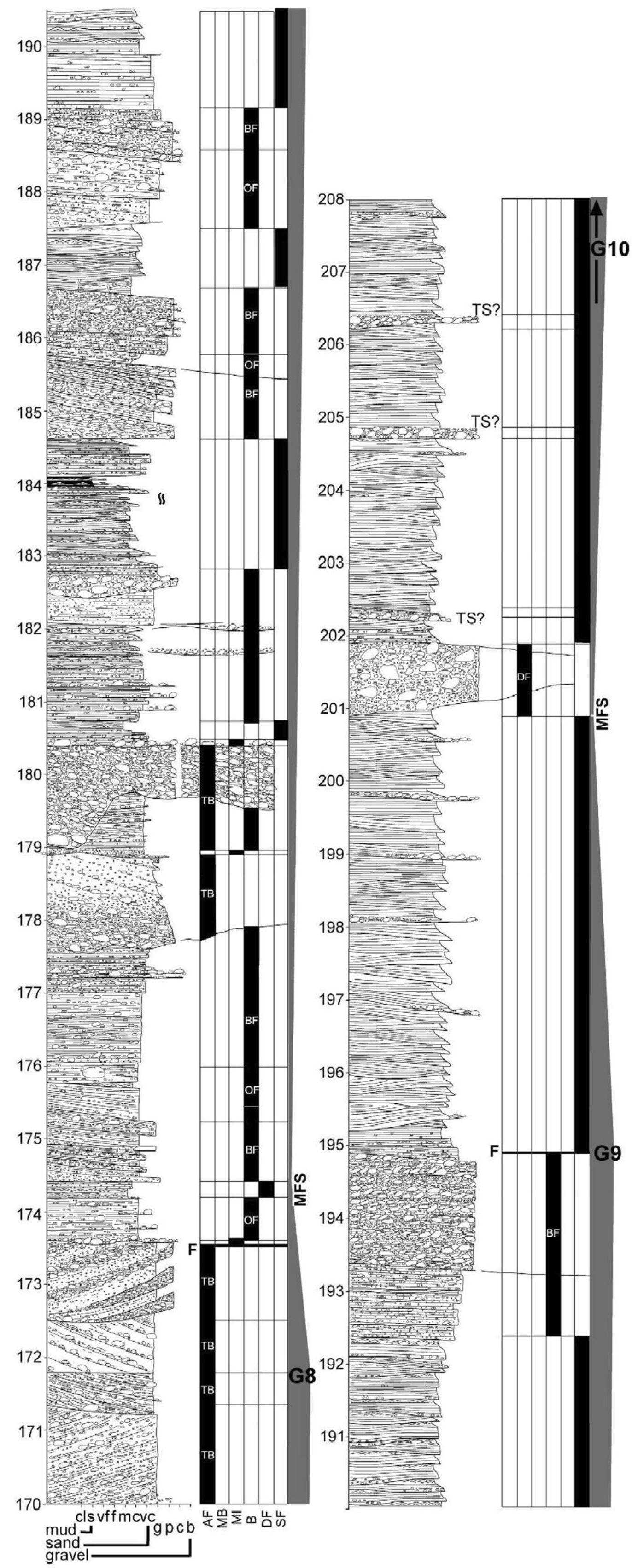


Fig. 4 (continued)



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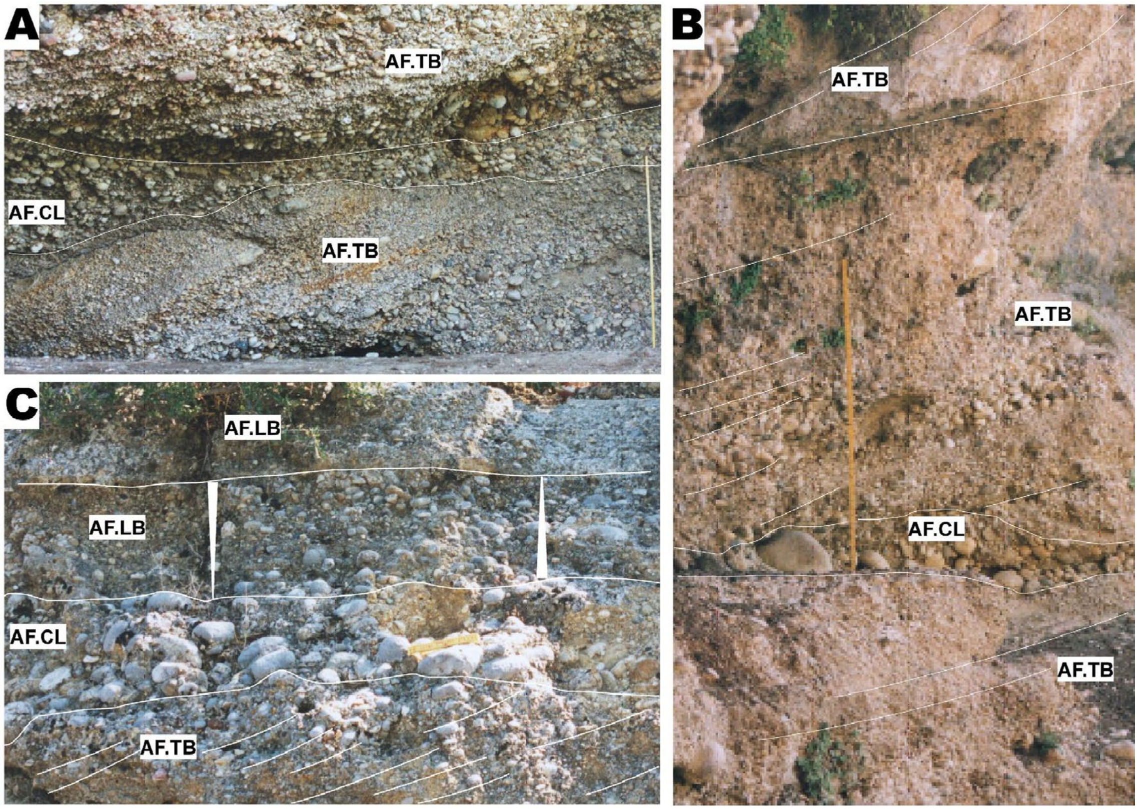

Fig. 5 Outcrop details of alluvial-fan (AF) deposits, Göktaş fan delta complex. **A** Steep-fronted gravelly bars of facies AF.TB separated by channel-floor lag of facies AF.CL; the ruler is 1 m. **B** Vertically stacked channel-fill deposits of facies AF.TB, with facies AF.CL marking the base of the upper palaeochannels; the ruler is 1 m. **C** Cobble-rich bouldery lag of facies AF.CL at the base of a palaeochannel filled with longitudinal bars of facies AF.LB; the ruler is 22 cm

they occur locally in the top parts of some of the fan delta basic wedges (cf. Fig. 3B). Despite their minor volumetric importance, these deposits are significant by indicating marine incursions that briefly inundated the lower fan delta plain, leaving a recognisable fingerprint of the fan surface reworking by sea waves and possibly tides.

Facies MI.TL. These deposits are thin (< 20 cm) and laterally discontinuous sheets of clast-supported conglomerate with large, pipe-like, sand-filled burrows identified as *Ophiomorpha* and *Thallassinoides* traces. Compared to the underlying alluvial conglomerates, the framework gravel is slightly coarser, dominated by coarse pebbles and cobbles, and the matrix is slightly finer, composed of moderately sorted, medium/coarse sand. These conglomerate sheets occur intercalated with facies AF.LB and MI.WW, overlie facies AF.TB or occasionally B.BF, and are covered by facies association B, SF or MB (Fig. 4). The deposits are thought to be transgressive lags (Hwang and Heller 2002), formed by the reworking of substrate by waves and winnowing of fine-grained sediment.

Facies MI.WW. These are laterally discontinuous sheets of pebbly sandstone, weakly parallel stratified and mildly bioturbated (Figs. 4 and 6A, log heights 41.6, 105 and 178.9 m), showing vertical, horizontal and oblique burrows filled with granule sand (Fig. 6B), recognised to be *Ophiomorpha* and *Thallassinoides* traces. The sandstone sheets are spatially associated with the deposits of facies AF.LB or B.BP (Fig. 6A), but are also overlying or occasionally underlying facies MI.TL (Fig. 4, log heights 30.4 and 180.4 m) or occurring as its lateral equivalent (Fig. 6A). The marine trace fossils and relatively fine grain size indicate sediment winnowed by waves from an inundated substrate in areas where wave action was competing with alluvial processes in smoothing the delta-plain surface.

Facies MI.TL and MI.WW occur as horizons which, in stratigraphic terms, represent either a brief marine incursion or a prelude (wave-scoured ravinement surface) to an episode of major drowning that demarcated the fan delta

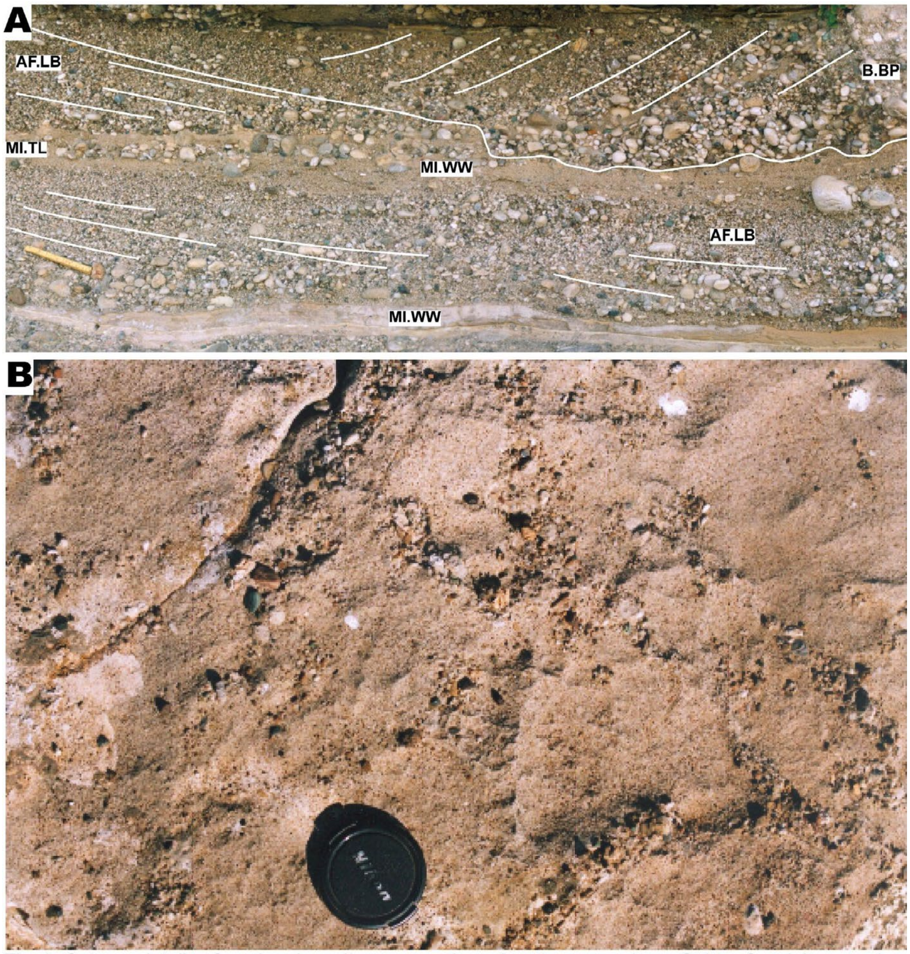

Fig. 6 Outcrop details of marine deposits representing minor transgressions, Göktaş fan delta complex. **A** Channel-mouth deposits of facies AF.LB intercalated with sheets of facies MI and a small wedge of landward-accreted storm washover deposits of facies B.BP; the ruler is 22 cm. **B** Bedding-plane outcrop of a sheet of facies MI.WW, showing granule-filled subhorizontal and vertical borrows ascribed to *Ophiomorpha* and *Thallasinoides* ichnofauna; the lens cap is 5 cm

basic wedges. The former horizons are sandwiched between alluvial deposits, and the latter are overlain transgressively by facies B and/or SF.

4.3 Mouth-bar deposits

These deposits (see facies association MB in Fig. 4 and Table 1) constitute *ca.* 2 vol.% of the proximal outcrop section, where they form bed sets inclined gently seawards, towards the south, as well as sideways, laterally with respect to the fan delta front. The following two component facies have been distinguished, representing different modes of sediment deposition at a stream-channel mouth.

Facies MB.ET. This facies comprises parallel-stratified conglomerates, whose low-angle (≤ 20°) tangential strata consist of alternating fine and coarse pebble gravel (Fig. 7A), with internal truncation surfaces and subordinate interlayers of stratified pebbly sand. The composite strata sets are broadly sigmoidal in shape, with a seaward and lateral inclination and thicknesses of up to 1.5 m. These tractional deposits are associated with both fluvial palaeochannel and foreshore facies (Fig. 4). They are interpreted to be channel-mouth bars formed by a sediment-laden frictional effluent (Wright 1977) combined with episodic storm erosion and wave swash processes (see facies MB.1 of Wathne et al. 2024).

Facies MB.DF. These deposits are isolated mounds of massive conglomerate composed of pebbles, cobbles and scattered boulders (Fig. 4, log height 201 m), mainly up to 1.5 m thick, tongue-shaped and less than 10 m in seaward extent. Some of the mounds seem to be parallel, rather than normal, to the delta-front shoreline. They occur interbedded with facies MB.ET, or the wave-worked facies B.BF and/or SF.WT (Table 1). The conglomerate varies from clast- to sand-supported, commonly on a very local scale, within a single bed, and typically consists of a mixture of subrounded and well-rounded clasts but shows little sorting. Similar conglomerate mounds, some rich in the muddy sand matrix and large mudclasts, occur embedded in the toe part of the foreset deposits of facies DF (Fig. 7B). These conglomerate mounds are thought to be deposits of shore-derived debrisflows generated

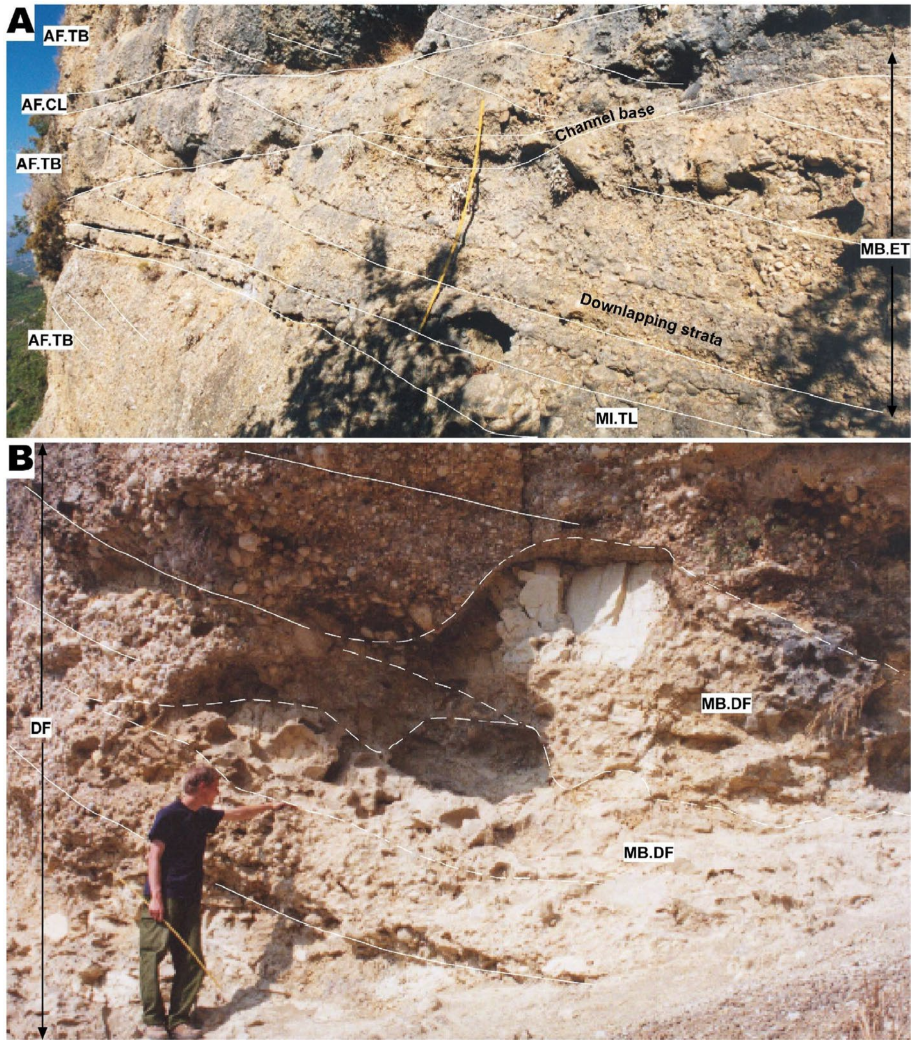

Fig. 7 Outcrop details of fan delta-front deposits, Göktaş complex. **A** Mouth-bar deposits of facies MB.ET sandwiched between alluvial deposits AF; the rule is 1 m. **B** In the lower part of the foreset of facies DF; note the embedded gravel mounds of facies MB.DF with large intraclasts of silty mudstone, apparently derived by river floods and attributed to the cannibalisation of fan delta upper reaches by deep fluvial incision

by an erosional breaching or broader sweeping of beach ridges by stream floods (see discussion of facies MB.DF by Larsen et al. 2024b, their Fig. 5). The muddy sand and intraformational mudclasts reflect deep incision of the stream channel, or fan valley, and erosion of marine substrate.

4.4 Delta-front foreset deposits

These deposits, labelled as facies DF (Table 1), are the principal component of two large foresets, one of which occurs in the outer medial part of wedge G3 (Fig. 3C) and is more than 12 m thick (Fig. 8) and the other forms the medial part of wedge G7 (Fig. 3B), is up to 20 m thick and constitutes nearly 9 vol.% of the proximal outcrop section (Fig. 4, log interval 119–139 m). Each foreset is comprised of steeply inclined (15–30°), sigmoidal beds, dipping southwards in the basinward direction (Fig. 3C). The forest beds are several decimetres thick (Figs. 4 and 8) and consist of clast-supported and mainly rounded to subrounded pebble gravel, which is massive, commonly rich in floating cobbles and occasionally shows weak (coarse-tail) inverse grading. Some units are composite and nearly 2 m thick, comprised of amalgamated thinner beds of massive gravel, with or without internal grading. The foreset bedding includes isolated "backsets", or sets of upslope-dipping gravelly strata; locally shows hydroplastic deformation, recognisable as oversteepened (up to 60°) or folded beds; and also includes internal truncations, downlapped by inclined gravel beds and interpreted to be concave-upward (scoop-shaped) slump scars and convex-upward storm- or possibly tsunami-formed scours. Mound-shaped interbeds of facies MB.DF, some rich in muddy sand, subangular gravel and mudstone intraclasts, occur locally in the tangential lower or basal part of the foreset (Figs. 3C, 7B and 8).

The foreset resembles subaqueous deposits of a Gilbert-type delta (Nemec 1990; Nemec et al. 1999) but lacks an alluvial topset; instead, the gently inclined uppermost part of the sigmoidal foreset consists of wave-worked foreshore/

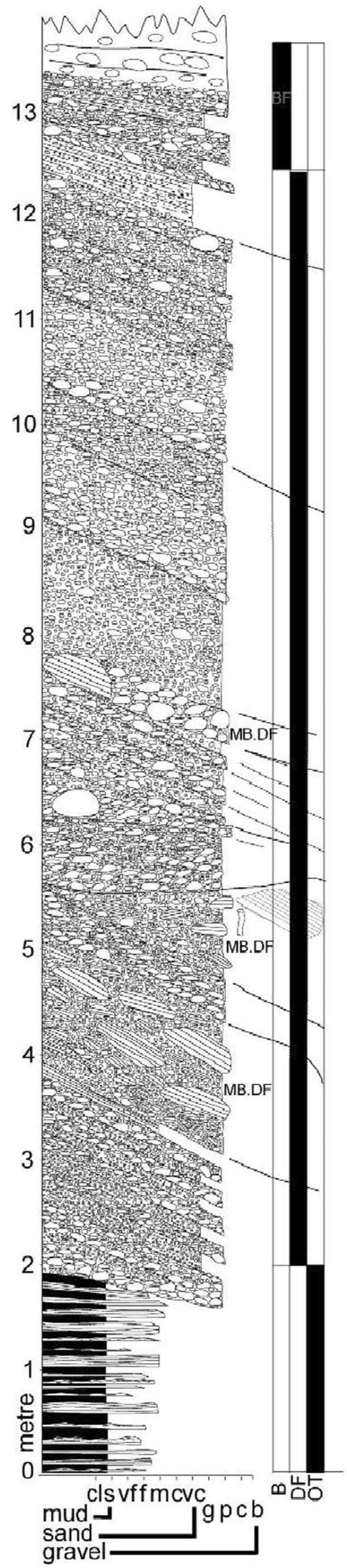

Fig. 8 Sedimentological log 2B from wedge G3 in the medial part ▶ of the outcrop section of Göktaş fan delta complex (see location in Fig. 3A). The thick foreset of facies DF (cf. Fig. 3C) overlies offshore-transition (OT) deposits and has a topset of beach facies B.FS and B.BP. The scale for mean grain size is as in Fig. 4, and the letter code for facies associations (log-margin columns) is as in the text and Table 1

beach facies B.BF and B.BP (Figs. 4 and 8). Similar foreset deposits were described by Massari (1996) and attributed to the progradation of a wave-dominated gravelly strandplain into a relatively deep nearshore zone, with the beach zone accumulating sediment accreted by waves and alongshore currents, and hence collapsing, and the debrisflow processes accompanied by episodic action of rip currents; fluvial supply may or may not be involved, but would undoubtedly contribute to the foreset accretion rate. A similar interpretation is adopted in the present case, where the beachface slope of the strandplain margin was steep and extended below the fairweather wave base. The foreset deposits of facies AF are attributed to beach-derived cohesionless debrisflow avalanches and episodic tractional transport by sediment-laden, plunging rip currents (see process discussion by Massari 1996). Although a reflective shoreline normally lacks rip currents, these can episodically be generated when the coastal setup during a storm briefly changes the morphodynamics into dissipative (Bowen and Inman 1969; Guza and Davis 1974; Bowen and Guza 1978). The local occurrences of the mounded deposits of facies MB.DF emplaced as cohesionless to cohesive debrisflows (Nemec and Steel 1984) are attributed to the foreset collapses instigated by floods of the deeply incised river, deriving sediment from fan delta cannibalisation.

The development of this type of foreset in the present case reflects an extreme morphodynamic state of a fan delta front that has overstepped the nearshore shoal formed by previous clastic wedges, with the trunk channel incised, incapable of spreading sediment. The shoreline is actively accreted by alongshore sediment drift (see Lønne and Nemec 2003). The foreset lacks fluvial topset deposits, had only sporadically accumulated sediment supplied directly by the river and prograded chiefly due to marine and gravitational processes, and may thus be regarded as non-deltaic, although it happens to be an integral part of the delta front. Therefore, it is crucial to distinguish between such a Massari-type (strandplain) foreset and a common Gilbert-type (deltaic) foreset because their implications for the depositional system are quite different.

4.5 Beach deposits

This assemblage of fan delta shoreline facies (beach deposits in Table 1) constitutes nearly 11 vol.% of the proximal outcrop section (see facies association B in Fig. 4) and is

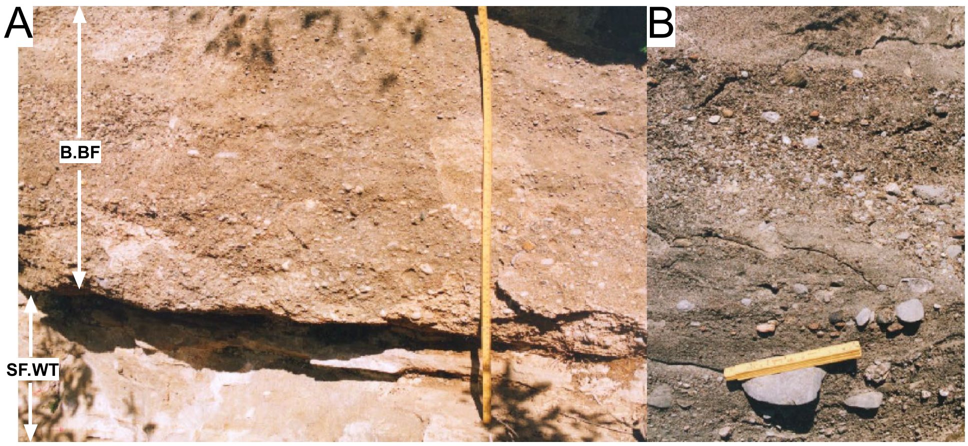

Fig. 9 Outcrop details of fan delta-front beach deposits, Göktaş complex. **A** Planar parallel-stratified shoreface sandstones of facies SF.WT overlain by progradational beach deposits of facies B.BF, composed of a gently inclined, alternating layer of well-sorted pebble gravel and granule-rich, very coarse sand; the ruler is 1 m. **B** Close-up detail of facies B.BF, showing well-developed stratification due to abrupt textural changes, with scattered spherical pebbles and flat-lying, slightly landward-inclined, isolated cobble discs/blades; the ruler is 22 cm

nearly six times more abundant than mouth-bar facies. The deposits include clast-supported conglomerates of granule to pebble grade, locally rich in cobbles, commonly intercalated with and/or passing laterally into pebbly to cobbly sandstones (Figs. 4, 9 and 10). The gravel clasts are mainly subrounded to rounded and generally well sorted, commonly showing also clear shape segregation. Conglomerate matrix is medium to coarse sand, moderately sorted, with granules and small pebbles. The three facies described below are thought to represent different beach zones of the fan delta front, which is thus inferred to have been dominated by wave action.

Facies B.BP. This facies consists of moderately sorted, clast-supported conglomerates that form units with weak planar-parallel stratification, commonly rich in cobble and large pebble discs/blades, or occasionally with landward cross-stratification (Fig. 6A). The units are several decimetres thick (Figs. 4 and 10), showing flat or convex-upward tops in shore-transverse outcrops and mainly tabular geometry in shore-parallel ones. These conglomerates pass seawards into and are commonly underlain by the deposits of facies B.BF. The characteristics of facies B.BP suggest beach platforms and berm deposits (Massari and Parea 1988; Postma and Nemec 1990; Bluck 1999; see also facies B.BP discussed by Larsen et al. 2024b).

Facies B.BF. These are well-sorted conglomerates of granule to pebble grade, with well-developed parallel stratification (Fig. 9) and common evidence of clast-shape segregation. The strata are gently inclined in the seaward direction, include intercalations of granule sand, and are generally rich in spheres and rods but contain scattered, flat-lying outsized discs and blades. These deposits are commonly underlain by facies B.OF and overlain by, or laterally interbedded with, the beach platform deposits of facies B.BP. Facies B.BF, in some cases, is overlain erosionally by fluvial palaeochannel deposits (facies AF.CL and AF.TB) or covered by the marine facies MI.TL or SF.WT (Table 1). This facies is analogous to the beachface facies B.BF of Larsen et al. (2024b) and attributed to the deposition by swash and backwash currents in foreshore zone (Orford 1975, 1977; Massari and Parea 1988; Bluck 1999).

Facies B.OF. This facies consists of well-sorted, parallel-stratified sandstones, medium to coarse-grained, with scattered spherical cobbles and large pebbles. The gravel clasts are isolated or clustered into strata-parallel pockets and stringers. These cobbly sandstones pass landwards into facies B.BF and commonly separate the latter from an underlying facies SF.WT (Fig. 11A, top). Facies B.OF is similar to the beach "outer-frame" deposits of Bluck (1999) and hence interpreted to represent the foreshore/shoreface transition (see discussion of facies B.OF by Larsen et al. 2024b).

4.6 Shoreface deposits

This sandy facies association (shoreface deposits in Table 1) occurs seawards from the gravelly delta-front associations MB and B and is also interfingering with these latter in the stratigraphic section (see facies association SF in Fig. 4). This facies association constitutes *ca.* 11 vol.% of the proximal outcrop section (Fig. 4), predominates in the distal section (Fig. 10) and intercalates further, as wedges, with facies association OT (Table 1) in the basinward direction. The deposits are sandstones and subordinate conglomerates,

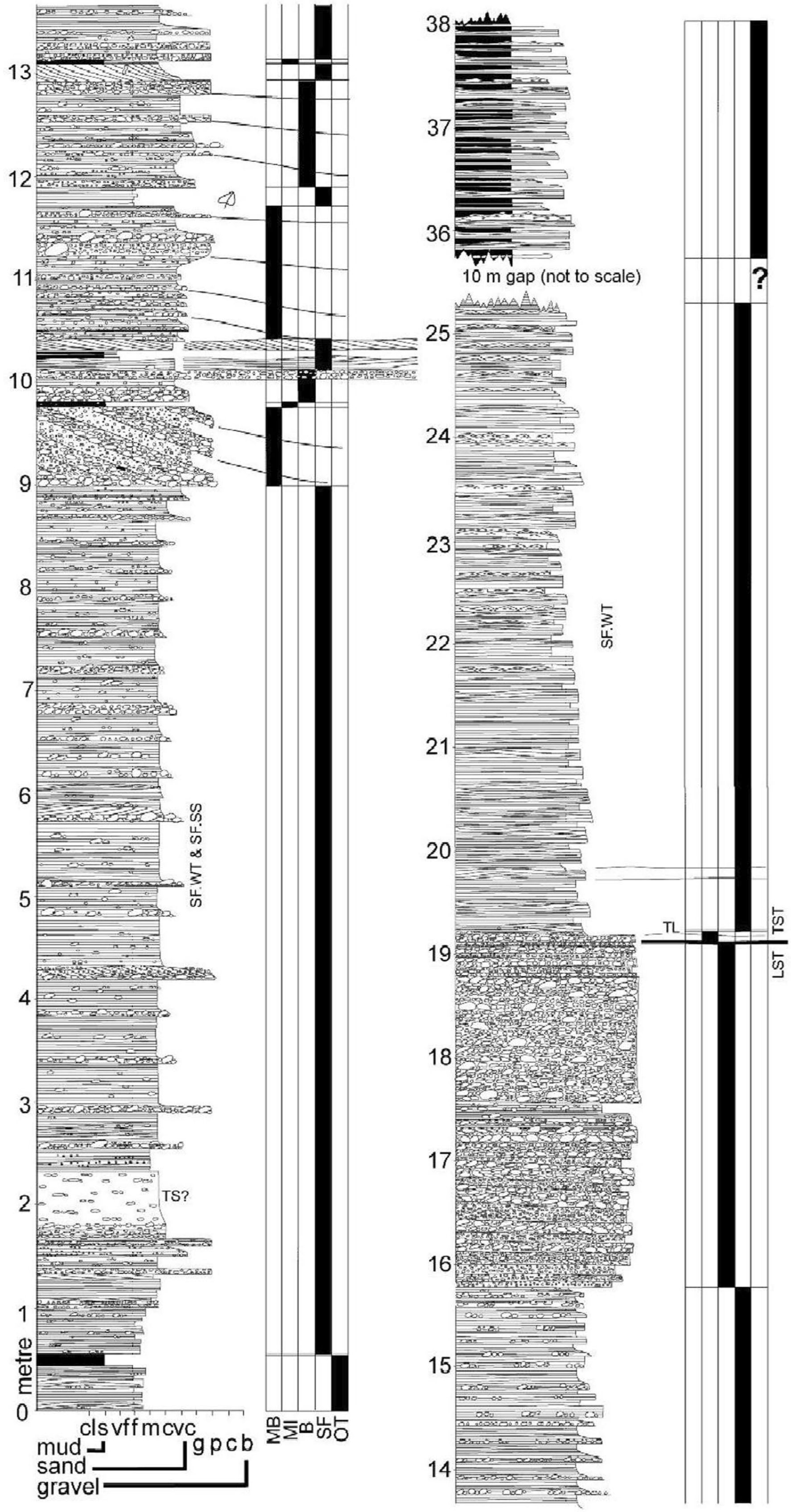

Fig. 10 Sedimentological log 3 from wedge G3 in the distal part of the outcrop section of Göktaş fan delta complex (cf. Fig. 3A). The grain-size scale and letter symbols are as explained in the caption to Fig. 4

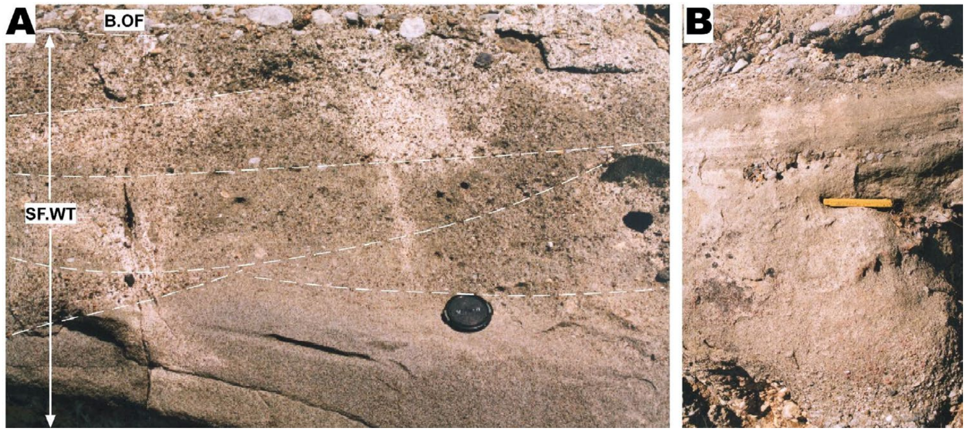

Fig. 11 Outcrop details of fan delta-front shoreface deposits, Göktaş complex. **A** Coarse-grained, uppermost shoreface sandstones with granule-rich swaley cross-sets (facies SF.WT) overlain by pebble-rich granule sandstone with scattered subspherical cobbles (facies B.OF); the lens cap is 5 cm. **B** Parallel-stratified upper shoreface sandstones (facies SF.WT) intercalated with erosional sheets of well-sorted pebble gravel (facies SF.SS); the ruler is 22 cm

representing wave-dominated "normal" sedimentation punctuated by short-lived high-energy seaward gravel transport events.

Facies SF.WT. This facies consists of amalgamated sheet-like sandstone beds separated by gentle truncation surfaces, which are planar on a local scale but commonly appear slightly concave or convex upwards on a lateral scale of several tens of metres. The beds not only show mainly planar-parallel stratification but also include wave-ripple cross-lamination, tabular and trough cross-stratification, as well as hummocky and swaley cross-stratification (Fig. 11). This facies forms units up to 16 m thick (Fig. 10), separated by conglomeratic sheets of facies SF.SS and interfingering with facies association B/MB in the landward direction (Fig. 4) and facies association OT in the seaward direction. The stratified sandstones of facies SF.WT are interpreted to be wave-worked shoreface deposits, accumulated above the prevalent fairweather wave base and episodically scoured by storms (Leithold and Bourgeois 1984; Komar1998; see also facies SF.WT of Larsen et al. 2024b). Where containing minor interlayers of siltstone or silty mudstone, mainly no thicker than 3–4 cm, this facies represents the lower outer shoreface zone (Fig. 4, log height *ca.* 184 m).

Facies SF.SS. This facies forms isolated sheets of stratified pebble conglomerate, 10–20 cm thick, interbedded with the sandstone facies SF.WT (Figs. 10 and 11B). The gravel is mature, well-rounded, and sorted, apparently of beach provenance. The beds have erosional bases and mainly planar-parallel stratification, weak to distinct, but occasionally consist of a solitary set of seaward-inclined cross-strata. The emplacement of beach-derived gravel in the shoreface zone is attributed to short-lived strong seaward currents, which probably included storm-generated compensation currents and powerful tsunami backsurges (see discussion of facies SF.SS and SF.RC in Larsen et al. 2024b).

4.7 Offshore-transition deposits

This heterolithic facies association (offshore-transition deposits in Table 1) consists of alternating sandstone and mudstone sheets, the latter with *Ophiomorpha* and *Thallassinoides* burrows and a microfauna assemblage indicating a neritic environment. These deposits underlie and overlie the fan delta complex and intercalate with the distal to medial parts of its component wedges (Figs. 8 and 10) but are absent in its proximal outcrop section (Fig. 4).

Facies OT.TE. These are tabular beds of very fine- to coarse-grained sandstones, ranging in thickness from less than 1 cm to several decimetres. They are commonly graded but have sharp bases and tops. Most beds show planar-parallel stratification, with or without a basal massive division, and many also contain ripple cross-lamination, hummocky stratification, and occasionally trough or planar cross-stratification. Palaeocurrent indices imply seaward transport, normal or oblique, with respect to the basin margin. These deposits are interpreted to be tempestites, formed by combined-flow currents associated with storms (Dott and Bourgeois 1982; Duke 1985; Myrow and Southard 1996; see also facies OT.TE discussed by Larsen et al. 2024b). The thickest and coarsest of the sandstone beds, some pebbly at the base, are likely to have been deposited from similar but stronger currents generated by tsunami events (see facies OT.TS discussed by Larsen et al. 2024b).

Facies OT.HE. These are dark to light grey mudstone layers and predominantly silty, separating the sandstone beds of facies OT.TE (Figs. 8 and 10). Their thicknesses are mainly between 1 and 20 cm, occasionally up to 30 cm, but nearly all these thicker beds contain thin (< 1 cm) interlayers of siltstone or very fine sandstone. The mudstones are commonly bioturbated and are interpreted to represent the hemipelagic "background" sedimentation in the offshore environment, where the mud suspension was probably supplied from river plumes and the agitation of the nearshore zone by storms (see discussion of facies OT.HE by Larsen et al. 2024b).

Facies OT.TS. These are sporadic, thick (> 45 cm), isolated beds of massive conglomerate and/or coarse, pebbly sandstone, with or without normal grading, commonly containing floating outsized clasts and showing undulatory, wave-worked tops. The conglomerate is typically a varied mixture of mature, beach-derived and submature gravel, commonly with a significant amount of sand or muddy sand. The beds are interpreted to be massflow tsunamites (see discussion of facies OT.TS by Larsen et al. 2024b).

5 Facies architecture of the fan delta complex

The Göktaş fan delta complex (Fig. 3A), exhumed by Quaternary denudation, is a wedge-shaped conglomeratic body thinning southwards, away from the basin margin, from more than 230 m in the proximal part of the outcrop section (Fig. 4) to 25 m in the distal part (Fig. 10), over a distance of 2.6 km. In its distalmost outcrop *ca.* 2.4 km further to the south, the fan delta complex passes into a pinch-out unit of gravel-bearing sandy shoreface deposits (facies SF), less than 10 m thick, interfingering basinwards with heterolithic offshore-transition deposits (facies OT). Similar heterolithic deposits are underlying and overlying the whole coarse-clastic wedge, which is regressive-transgressive in broad terms but composite. The alternation of facies assemblages in its stratigraphic profile (Figs. 3B, 4 and 10) indicates that the fan delta complex consists of ten component basic wedges (sensu Larsen et al. 2024b), each representing a short-term advance and retreat of fan delta (Fig. 3A).

5.1 Basic fan delta wedges

The component basic wedges of the fan delta complex (G1–G10 in Fig. 3A) consist of alluvium that overlies erosionally delta-front and shoreface deposits and is also covered by the latter. The basinward extent and detailed facies anatomy of the individual wedges are varied.

The lower three wedges, G1–G3, are each 20–25 m thick in the proximal part of the outcrop section (Fig. 4). Each wedge is thickest in its medial part and consists of alluvium (facies association AF) that has a highly uneven, erosional base and overlies a blanket of mouth-bar (MB), beach (B) and shoreface (SF) deposits. Wedge G3 thickens to *ca.* 35 m in the medial section and is still 25 m thick at the distal log site, where the alluvium terminates with mouth-bar deposits and a younger regressive package delta-front beach deposits (Fig. 10). This is the largest of the fan delta's basic wedges, exceeding the basinward extent of the previous two by a few kilometres and reaching nearly 18 km from the basin margin. The wedge includes an incised fluvial palaeovalley, 10–11 m deep, in the inner medial part (Fig. 3C) and an even thicker foreset of facies DF in the outer medial part (Fig. 3C). The deep fluvial incision, well-developed channel lags and widespread evidence of mouth bars indicate a forced-regressive character of the three lower wedges (see criteria discussed by Wathne et al. 2024).

The overlying wedges G4 and G5 are 18 m and 34 m thick in the proximal part of the outcrop section (Figs. 3A and 4). The alluvium in each case lacks associated mouth-bar deposits and overlies erosionally a relatively thick (3–4 m), coarsening-upward succession of shoreface (SF) and beach (B) deposits. This facies architecture indicates normal-regressive wedges (Wathne et al. 2024). Wedge G5 is much shorter than wedge 4 (Fig. 3A), and neither extends to the distal log site; their basinward extent from the margin is *ca.* 15 km and 13 km, respectively (Fig. 10).

Wedge G6 is also relatively short, although it has overstepped slightly the previous one in basinward direction (Fig. 3A). It has a thickness of 13 m in the proximal part of the outcrop section (Fig. 4), where it is separated from the underlying wedge by a transgressive horizon of facies MI that passes laterally into a basinward-thickening unit of shoreface (SF) and delta-front beach (B) deposits. The wedge in its proximal part is also overlain by a transgressive gravel lag of facies MI.TL and thin shoreface sandstones (Fig. 4) that pass basinwards into offshore-transition (OT) deposits. No associated mouth-bar deposits have been recognised, and wedge G6 seems normal-regressive.

Wedge G7 is 29 m thick in the proximal part of the outcrop section, where it has markedly overstepped wedges G5 and G6 (Fig. 3A) and consists of a strandplain foreset of facies DF deposits, 20 m in thickness, overlain by associated beach deposits, 5 m thick, and a blanket of transgressive shoreface sandstones (Fig. 4). The foreset itself lacks an associated alluvial topset but passes basinwards into an aggradational succession of delta-front deposits, apparently including mouth bars. An incised fluvial palaeovalley occurs in the proximal part of the wedge (Fig. 3B), where a blanket of alluvium with isolated deep palaeochannels overlies mouth-bar deposits. Alluvial facies also overlie mouth-bar deposits directly seawards of the strandplain foreset, post-dating the latter. The deep fluvial incision, the occurrence of mouth bars and the strandplain foreset with basinward-falling shoreline trajectory indicate a forced-regressive wedge.

The overlying wedges G8–G10 are much shorter and backstepping (Fig. 3A). Wedge G8 is 27 m thick in the proximal part of the outcrop section, where its alluvial deposits overlie erosionally a succession of shoreface and beach facies, more than 4 m thick (Fig. 4). The multilateral and

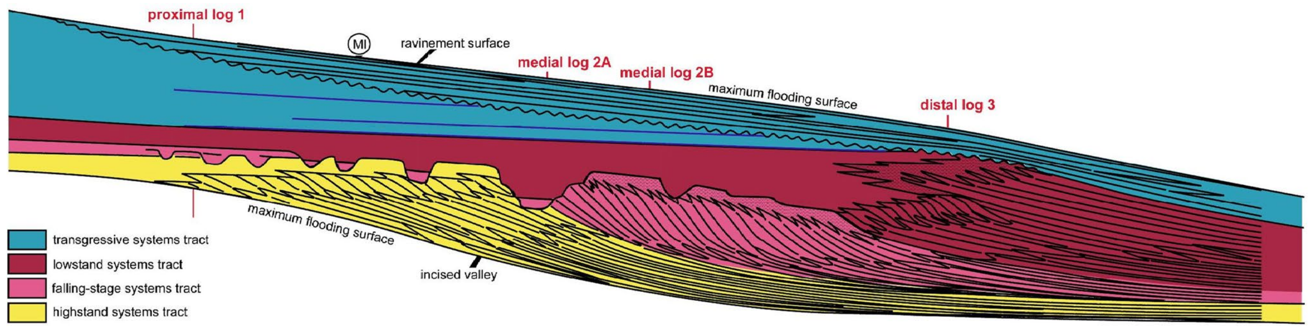

Fig. 12 Schematic longitudinal cross-section (log correlation panel) showing the component systems tracts and facies anatomy of wedge G3 of the Göktaş fan delta complex. The location of logs 1–3 is shown in Fig. 3A; for discussion, see text

multi-storey fluvial palaeochannels and the lack of mouth-bar deposits suggest a normal-regressive wedge (Wathne et al. 2024). Wedges G9 and G10 are 27–29 m thick and inferred also to be normal-regressive. In the proximal outcrop, each wedge consists of a progradational/aggradational to retrogradational succession of shoreface and delta-front beach deposits, with isolated fluvial palaeochannels and evidence of minor shoreline shifts (Fig. 4).

The ten basic wedges represent episodes of the fan delta advance and rapid retreat by drowning. The fan delta complex as a whole has a gently falling trajectory of shoreline advance, with wedge G3 strongly overstepping the underlying two wedges (Fig. 3A), and a rising, moderately inclined trajectory of net landward retreat, with wedges G4–G10 stepping backwards. The latter pattern is broken by wedge G7, which markedly overstepped the underlying wedges G5 and G6.

The normal-regressive wedges G4–G6 and G8–G10, formed under a general rise of relative sea level, can be characterised as twofold sequences comprising a progradational lower part (highstand systems tract) and retrogradational upper part (transgressive systems tract). The forced-regressive wedges G1–G3 and G7 are more adequately characterised as fourfold sequences (sensu Helland-Hansen and Gjelberg1994) composed of a highstand systems tract and a falling-stage systems tract, the latter offset basinwards and passing into an aggradational lowstand tract, and all of them overlain by a transgressive systems tract (Fig. 12). The highstand and transgressive systems tracts are thicker in the landward part of the wedge, whereas the falling-stage and lowstand systems tracts are thicker in its seaward part. The four component systems tracts of forced-regressive wedges are described and discussed below, with particular reference to the characteristics of wedge G3, which is the most extensive, best exposed and most accessible, and – similarly to the younger wedge G7 – shows the widest spectrum of facies.

5.2 Facies anatomy of forced-regressive wedge

Highstand systems tract (HST). The highstand systems tract of wedge G3 (Fig. 12) consists of alluvial-fan facies overlying delta-front and shoreface facies, inclined gently basinwards and passing distally into offshore-transition deposits. It thickens from 7 m in the proximal outcrop (*ca.* 12 km from the basin margin) to a maximum of 15 m, approximately 2 km basinwards, and is thinning further in the basinward direction. The gravelly alluvium pinches out basinwards *ca.* 14.5 km from the margin and hence is absent in the medial outcrop (Fig. 10). The alluvium consists of multilateral palaeochannels, up to 2.5 m deep and overlies erosionally a thin unit (≤ 3 m) of gravelly mouth-bar deposits (MB) and gravel-bearing shoreface sandstones (SF). In the medial and distal outcrops, the HST is represented solely by offshore-transition deposits (Fig. 12). When prograding as an HST, the fan delta appears to have reached a relatively small radius. The fluvial channels were deep, and perhaps often solitary but were shifting widely, distributing coarse sediment across the delta plain and forming mouth bars along the delta front (Fig. 13A). Beach facies tended to be deposited between active mouth bars, and many of the inactive bars were likely reworked thoroughly by waves. The lobate delta front was probably broad and uniform, owing to the wave-worked shoreline and wide dispersal of fluvial sediment.

Falling-stage systems tract (FSST). The falling-stage systems tract (Plint and Nummedal 2000), or forced-regressive tract, of wedge G3 is thickest (> 12 m) in the medial outcrop (Fig. 12), where the advancing fan delta overstepped the two underlying thick wedges and formed a foreset of steeply inclined facies DF deposits (Figs. 3C and 8). The gravelly foreset overlies offshore-transition facies in a basinward direction. An incised fluvial palaeovalley, *ca.* 10 m deep, separates the foreset from the FSST's proximal part (Fig. 12); the valley palaeoflow axis here is to the south, at

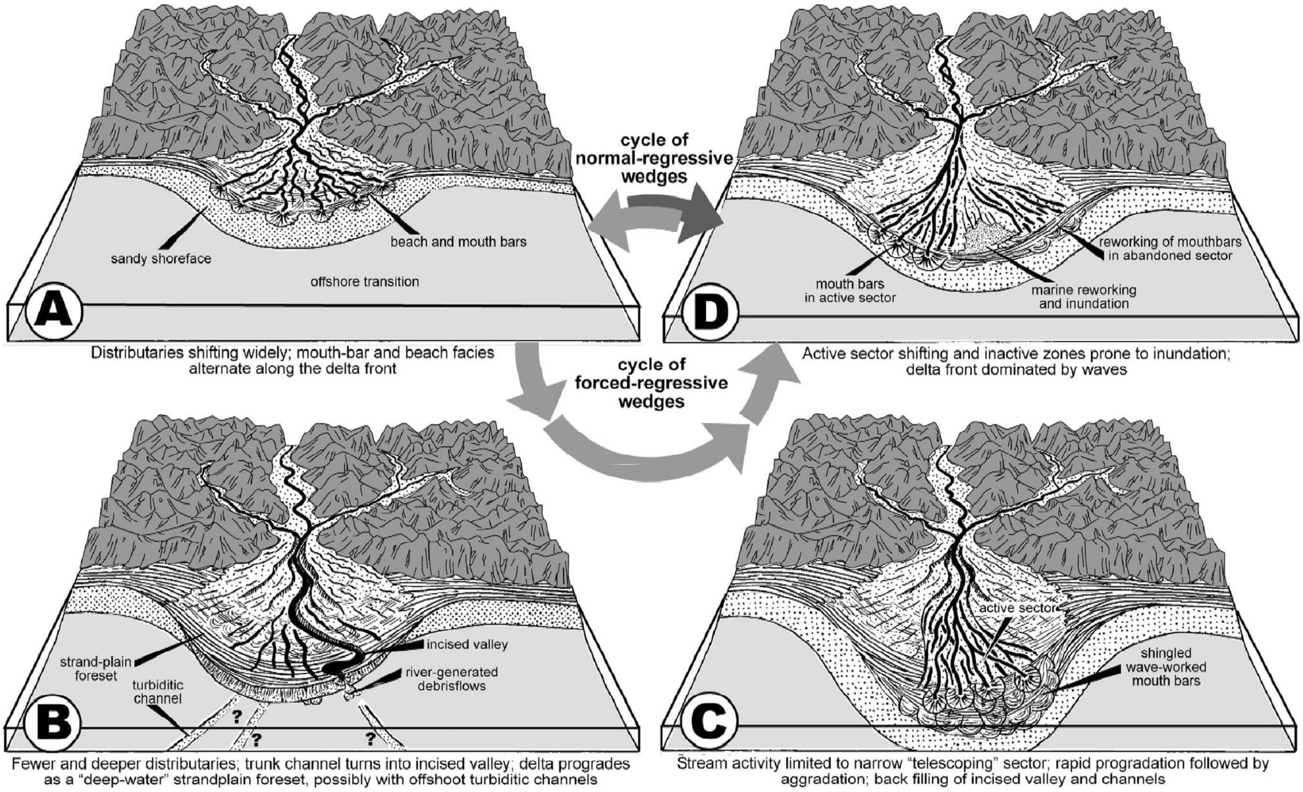

Fig. 13 Interpreted morphodynamic evolution of the Göktaş fan delta during the development of its forced-regressive basic wedge (cf. Fig. 12). The successive diagrams depict highstand (**A**), falling-stage (**B**), lowstand (**C**) and transgressive systems tract (**D**)

ca. 30° out of the outcrop section. The FSST in its proximal part consists of a relatively thin (< 2 m) erosional blanket of gravelly alluvium that includes isolated deep (> 3 m) palaeochannels. The alluvial deposits indicate diversification of fluvial distributaries, with the formation of local deep channels accompanied by peak-flood activity of many shallow (0.5–1 m) ones, where discrete gravel sheets were deposited as longitudinal bars and covered with sand (Fig. 4, log interval 36.7–40.2 m). The fluvial system was then gradually reduced to a single trunk river, which formed an incised valley (Fig. 13B). The incision must have caused cessation of sediment dispersal across the delta plain whilst maximising its localised supply to the delta shoreline. The accretion of sediment to the coastline by waves and alongshore drift caused the delta front to prograde as a strandplain, with the local bathymetry promoting deposition of facies DF foreset (Figs. 3C and 13B) by beachface collapses, debrisflows and plunging storm rips. The fan delta front thus changed its "shoal-water profile" into a massflow-dominated "deep-water profile" (sensu Postma1990). An analogous development is shown by the FSST in the middle outer part of wedge G7, where it overstepped the convex-upward morphology of the underlying wedges (Fig. 3A, B). The development of progradational strandplain foresets of this type has been reported from forced-regressive shorelines (Trincardi and Field 1991; Massari 1996, 1997; Lønne et al. 2001), including fan deltaic (Lønne and Nemec 2003).

Lowstand systems tract (LST). The lowstand systems tract of wedge G3 in the proximal outcrop is represented by a unit of alluvium, 2–3 m thick, comprising sand-capped gravel sheets (facies AF.LB and AF.BC) deposited as longitudinal bars in shallow (≤ 0.8 m) multi-storey channels. The alluvium is overlain by a thin and laterally discontinuous sheet of bioturbated sandstones (facies MI.WW) marking the base of the transgressive systems tract (Fig. 4, log height 41.6 m). The alluvial unit thickens to more than 10 m over a basinward distance of *ca.* 4 km, where it passes into a succession of delta-front deposits (Fig. 12), whose lower part consists of progradational mouth-bar and shoreface facies and the upper part of chiefly aggradational beach and shoreface facies. In the distal log 1 km further basinwards, the LST is a coarsening-upward succession of gravel-bearing shoreface sandstones, 19 m thick, with a pinch-out unit of mouth-bar facies in the middle and an analogous pinch-out unit of beach deposits at the top (Fig. 10). The LST here is overlain by transgressive ravinement lag (facies MI.TL). As the sea level ceased to fall and began to rise slowly, the rate of shoreline progradation declined and aggradation predominated, with the delta front restoring its shoal-water profile and the shoreline trajectory rising and steepening (Fig. 12). Fluvial sediment dispersal was initially limited to a head-incised, narrow active sector, where shingled mouth bars formed at the delta front, heavily modified by waves (Fig. 13C). The gradual replacement of mouth-bar deposits by beach facies in this succession indicates that the aggrading fan delta front became increasingly dominated by waves, which was accompanied by minor shoreline shifts attributed to the lateral switching of fluvial activity and climatically-controlled fluctuations in sediment supply. The LST underwent very limited aggradation in the proximal part, and it was mainly the pre-existing incised valley and large delta-plain area that provided accommodation for alluvial deposits.

Transgressive systems tract (TST). The lower boundary of the transgressive systems tract in wedge G3 is the lowest recognisable surface of minor (5th-order) marine flooding, lined with deposits of facies MI and traceable over a distance of nearly 5 km landwards from the delta front (Fig. 12). The upper boundary is the major, 4th-order surface of maximum flooding (Fig. 12) that corresponds to a landward-thinning, transgressive blanket of shoreface sandstones (facies SF) covering the wave-scoured ravinement and overlain erosionally by the alluvium of next basic wedge (Fig. 4, log interval 53.3–57.3 m). This maximum-flooding surface corresponds to a unit of facies OT sandwiched between the transgressive and regressive shoreface sandstones in the medial to distal part of the outcrop section. The TST is thickest in its proximal part (Fig. 12), where the alluvium exceeds 12 m in thickness and consists of multilateral and multi-storey palaeochannels, mainly 1–2 m deep (Fig. 4, log interval 41.6–53.3 m). The alluvial succession is intercalated with a few thin horizons of transgressive facies MI, attributed to minor episodes of marine flooding. These isolated horizons are discontinuous, extensively erased by fluvial erosion, and no more than three or four can be traced laterally to the upper delta-plain reaches in the outcrop section. The alluvium is truncated basinwards by the ravinement surface and onlapped by the transgressive blanket of facies SF overlain by facies OT (Fig. 12). This fining-upward unit is thought to be a transgressive product of shoreface erosion, comprising sediment deposited seawards of the landward-migrating "wave razor". The TST indicates intense wave action during the drowning of the fan delta, with the alluvial plain aggrading and the transgressive ravinement surface climbing by more than 12 m over a landward distance of *ca.* 6 km. The ravinement surface is thus at the base of the TST in the distal outcrop. In its uppermost part in the proximal outcrop, separating the landward-thickening alluvium from the seaward-thickening, wave-worked transgressive marine deposits (Fig. 12). The fan's active sector was probably shifting, with mouth bars deposited laterally to shoreline stretches where intense marine reworking and beach sedimentation occurred (Fig. 13D). The lateral switching of fluvial activity, combined with the minor shoreline shifts and general transgression, rendered the delta front wave-dominated and preservation potential of mouth-bar deposits very low. The wave-worked shoreline was probably swept by alongshore currents, and the backshore and lower delta plain could be prone to tidal influence during the brief marine invasions (cf. Larsen et al. 2024b), even though no obvious tidal products have been recognised in the present case.

Possible associated turbidites. In the adjacent Köprü Basin, several isolated turbiditic palaeochannels, up to 10 m deep and more than 200 m wide, have been found in the offshore-transition succession basinwards of Serravallian fan deltaic complexes and linked to their FSSTs (Larsen et al. 2024b). The incised fluvial trunk channel of the forced-regressive tract, when extended to the edge of the nearshore shoal formed by vertically stacked fan deltaic wedges, is thought to have allowed the sediment-laden effluent to plunge erosively beneath the wave base, ignite and spread basinwards as a channelised underflow (see facies OT.TC in Larsen et al. 2024a).

No similar evidence of turbiditic sedimentation has been recognised in the Göktaş fan delta complex, where the coeval, basinward offshore-transition deposits are dipping to the southwest below the ground level and hence are little exposed. However, packages of sandstone beds interpreted to be turbiditic palaeochannels and associated lobes (Fig. 14) have been reported by Dreyer et al. (1998) from an outcrop section of the lowermost Karpuzçay Formation near Çardak, *ca.* 3 km to the west, on the other side of the adjacent tip zone of Kırkkavak Fault (Fig. 1C). It is possible that some turbidity currents were generated in the FSSTs at the earliest depositional stages of the Göktaş complex, when the fan delta was yet relatively small, a few kilometres in radius, and advancing over the nearshore platform of previous fan deltaic complex; the currents might have readily crossed the intrabasinal fault-tip monocline and spread southwards into the Çardak area. Alternatively, the turbidites near Çardak could have been derived from the inner Köprü Basin, where the corresponding part of basin-fill succession is not preserved. Hence, this possibility cannot be discounted.

6 Discussion of the Göktaş complex

The Göktaş fan delta complex, like the coeval adjacent ones (Fig. 2), owes its origin to a late Serravallian sea-level fall and related activation of local fluvial supply. The resulting alluvial fan advanced far in the basin and subsequently retreated, supplied with sediment from a large valley in the mountainous northern hinterland. The pre-existing valley, which previously sourced an early Serravallian fan delta

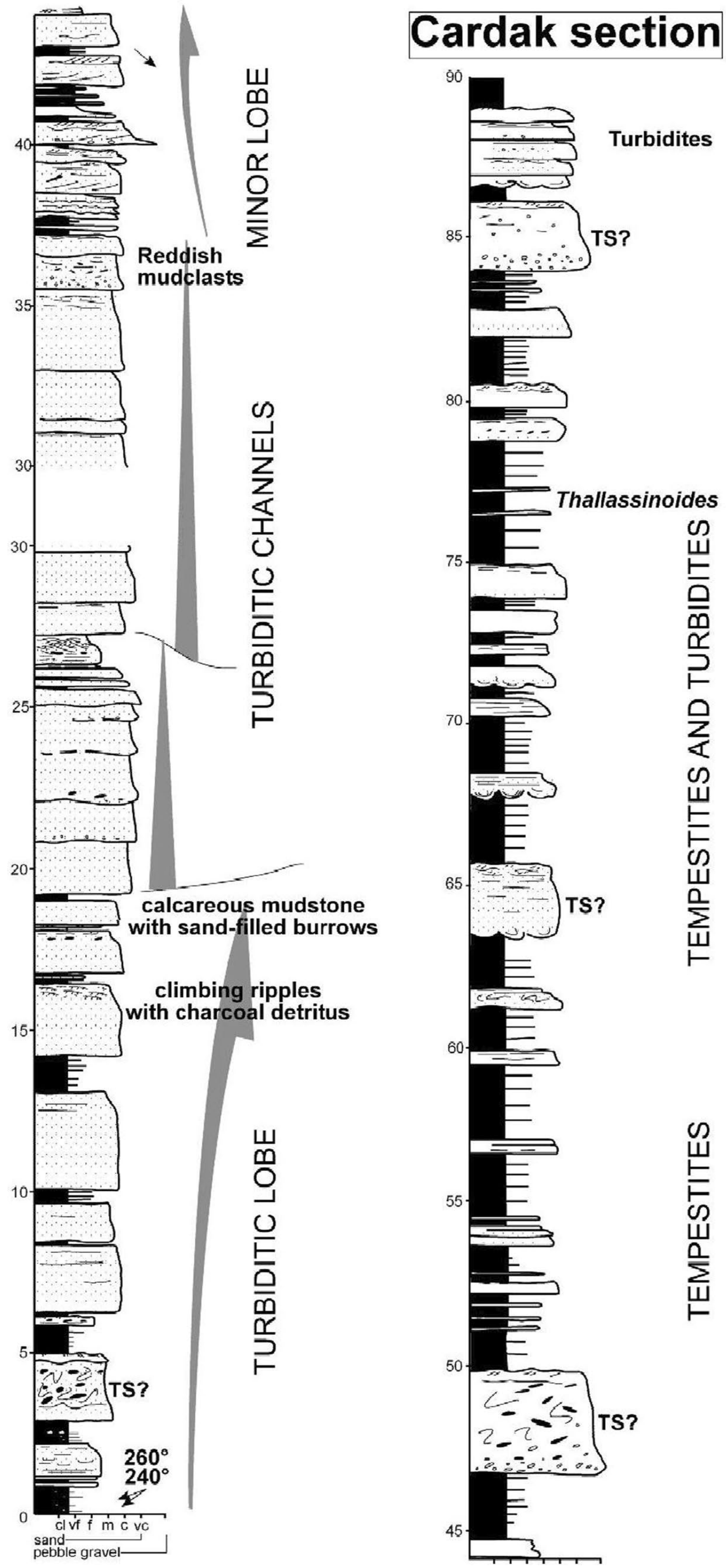

Fig. 14 Sedimentological log from the lowermost part of Karpuzçay Formation in the Çardak area, *ca.* 3 km west of the outcrop section of Göktaş complex (see locality in Fig. 1C), showing sandstone packages interpreted to be turbiditic lobes and palaeochannels embedded in offshore-transition facies succession (modified from Dreyer et al. 1998)

complex (the Beydiğin Mb. of Sağırın Fm., Figs. 1C and 2), was probably filled with sediment during the Serravallian sea-level highstand. Its reactivation would yield abundant sediment, whose supply was controlled by climatic conditions (runoff), basin tectonism and stream profile adjustments. The Miocene regional climate was humid, as indicated by powerful and perennial fluvial systems (see earlier facies association AF; Alçiçek et al. 2024; Larsen et al. 2024b; Wathne et al. 2024), but almost certainly fluctuated. The high sediment yield and streams supplying large volumes of sediment on a semi-continuous basis rendered this fan delta the largest and longest-active amongst the coeval fan deltaic systems in the Manavgat Basin (Fig. 2).

Based on the basinward extent and facies anatomy of its component wedges, the fan delta succession is recognised to consist of a set of three forward-stepping basic wedges (G1–G3), recording episodes of forced regression, overlain by a set of seven aggradational to backstepping wedges (G4–G10, Fig. 3A). In the latter set, wedge G6 overlapped the preceding wedge G5 by fan head entrenchment (sensu Wasson 1977), whereas wedge G7 overstepped both of them considerably, recording a late episode of forced regression. The basinward extent of the basic wedges varies between 13 and 18 km relative to the basin margin. The fan head was initially located at the margin (cf. Wathne et al. 2024) but had subsequently been incised (sensu Wasson 1977) and shifted basinwards, most profoundly with the advance of wedge G3, which significantly overstepped the previous forced-regressive wedges (Fig. 3A). The forward-stepping pattern of wedges G1–G3, with the first one already extending more than 13 km from the margin, suggests that the fan delta progradation most probably involved also some early shorter wedges, now removed with the whole landward part of the complex by Quaternary erosion. In other words, although wedge G1 is recognisably younger than the basal wedges of the adjacent fan deltaic complexes, it is likely that the Göktaş complex commenced its development concurrently with the others (Fig. 2) or perhaps even slightly earlier. Notably, the forward-stepping lower part of the adjacent Katırınemeği complex consists of as many as five basic wedges. However, this fan delta was considerably smaller and retrograded much faster, with only three aggradational to backstepping normal-regressive wedges observed in its proximal outcrop *ca.* 3 km from the basin margin (Wathne et al. 2024).

The basin accommodation was controlled by relative sea level changes, driven by tectonic subsidence and probably eustasy, but the shoreline trajectory itself depended strongly upon the basin-margin morphology and depositional seafloor topography. The shoreline, perched on the high-relief margin during the Serravallian highstand, is thought to have initially had a steep trajectory (cf. Wathne et al. 2024) when also the fan delta was yet small and barely covering the nearshore shoal formed by the previous fan delta complex. When reaching the shoal margin during forced advances, the incised trunk channels of FSSTs might have had the capacity to generate episodically turbidity currents even at the early developmental stages of the Göktaş complex (see discussion by Larsen et al. 2024b). Some turbidity currents could also be generated in the FSSTs of the later fan delta wedges, owing to the incision of fluvial valleys and the seafloor relief resulting from the vertical stacking of the successive wedges.

As the sea-level fall continued, the fan head became increasingly incised, and the fan delta began "telescoping" seawards, thus greatly extending its apparent radial length. High sediment supply, boosted by incision and combined with alongshore drift, rendered the fan delta front capable of overstepping the topography of previous wedges and developing a deep-water profile (sensu Postma 1990), with marine processes accumulating sediment along the beach and the latter advancing and collapsing. The resulting Massari-type foreset (Figs. 3C and 12) comprises deposits of beach-derived debrisflows and plunging storm rips, and local debrisflow mounds emplaced by floods of the incised, delta-cannibalising river. This morphodynamic state of delta-front progradation as a steep-faced strandplain would end once the falling sea level made the wave base meet the seafloor in the nearshore zone, restoring the delta shoal-water profile. The onset of relative sea level rise would then instigate aggradation, causing channel shifting, a decrease in sediment supply and an increase in marine reworking. The same morphodynamic pattern of sedimentation was repeated later by the development of wedge G7, though not shown by any of the normal-regressive wedges.

The fan deltaic succession studied was deposited in the latest Serravalian to late Tortonian time (Fig. 2), in *ca.* 4 Ma, implying that the average timespan of its individual basic wedges was about 400 ka. However, their sizes (volumes) and probably their timespans vary greatly. In the hierarchical time-scale of sequence stratigraphy, the development of the regressive-transgressive fan delta complex might correspond to the turnaround phase of 3rd-order eustatic cycles (i.e. the Serravalian/Tortonian transition of the regressive part of cycle 2.6 to the transgressive part of cycle 3.1 of Haq et al. 1988) or the corresponding turnaround of 2nd-order cycles (i.e. supercycles TB2 and TB3 of Haq et al. 1988). The time span of the fan delta basic wedges would render them comparable to 4th-order eustatic cycles (Haq et al. 1988; Vail et al. 1991) as well as to the astronomical 400-ka eccentricity cycles (Laskar et al. 1993). However, neither eustasy nor climatic changes alone can explain the origin of the wedges, whose principal formative mechanism is basin tectonics. The wedges, bounded by 4th-order maximum-flooding surfaces, also show evidence of 5th-order marine incursions in the form of isolated erosional horizons of facies MI, only some of which are probably preserved.

The fan deltas in the Manavgat and Köprü grabens were associated with active, main antithetic faults, and the thick sedimentary successions indicate rapid, incremental subsidence. The 4th-order cycles might thus be attributed to episodes of the basin floor downthrow by graben fault activity, marked by periodical increases in the frequency of discrete movements and subsidence rate, known as seismic cycles (McCalpin 1996; McCalpin and Nelson 1996; Sieh 2000). In an asymmetrical graben, a series of movements on the master fault would likely be followed by compensating movements on the antithetic one, both causing downthrow of the hangingwall block. Accordingly, the forward-stepping set of wedges might have formed during a 3rd-order sea-level fall punctuated by the episodes of basin floor downthrow and fan delta drowning. In contrast, the aggradational to backstepping set would have formed during a 3rd-order sea-level rise, countered by continuing sediment supply and punctuated by similar episodes of downthrow. Each episode of rapid subsidence would be responsible for a 4th-order marine flooding event.

Similarly, the 5th-order flooding events might be attributed to fault activity, as this would inevitably involve irregular and compensating movements of lesser magnitude. The sedimentary record of the brief marine incursions is sparsely preserved but suggests that relatively few reached the medial to the upper part of the fan delta plain (Fig. 4; see also wedge G3 in Fig. 12). The more common events of minor marine flooding are likely to have been inflicted by autocyclic lateral switching of fluvial activity (see earlier discussion of LST and TST) and climatic fluctuations. No apparent record of Milankovitch-type cyclicity is recognisable in the fan delta succession, but the Miocene regional climate is known to have fluctuated by astronomical forcing (Postma et al. 1993a, b; Krijgsman 1996; Postma and Ten Veen 1999; Steenbrink et al. 1999, 2000; Abdul Aziz et al. 2000). The diversified fluvial bars and their internal reactivation surfaces, varied texture and sandy cappings indicate considerable discharge fluctuations. Also, the TST deposits and the terminal LST deposits of the aggradational delta front commonly show evidence of minor shoreline shifts, apparently caused by fluctuations in stream discharges and/or wave energy levels, possibly reflecting climatic changes. These minor, 6th-order flooding events can be attributed to climatic fluctuations forced by precession cycles or 100-ka eccentricity cycles (Laskar et al. 1993), some of which were more pronounced than others (Krijgsman et al. 1995; Postma and Ten Veen 1999), with greater runoff during precession minima and smaller during maxima (Rohling and Hilgen 1991).

The Göktaş fan delta complex would thus appear to bear a high-resolution record of the late Serravallian-Tortonian history of the basin margin, including a signal of a wide range of factors that controlled coastal and nearshore sedimentation in the basin. Notably, no comparably detailed record can be deciphered from the coeval non-deltaic nearshore succession lateral to the fan delta complex (Wathne et al. 2024). The non-deltaic shoreline, perched on the steep margin by the Serravallian sea-level highstand, had a steep trajectory, whereby its shifting caused little facies change in the nearshore zone. This striking difference highlights the stratigraphic significance and unique importance of a fan deltaic complex in the basin-fill succession.

7 Towards a stratigraphic facies model

Studies of fan delta complexes in the Antalya Basin (Alçiçek et al. 2024; Larsen et al. 2024a; Wathne et al. 2024) and other shallow-marine basins (see cases in Nemec and Steel 1988; Chough and Orton 1995; Marzo and Steel 2000) have shown that the advances and retreats of fan deltaic system in a littoral environment produce prominent clastic wedges that consist of specific facies and can be classified hierarchically based on their timespan and anatomy. The various orders of stratigraphic cyclicity recognisable in fan deltaic successions have been attributed variously to changes in relative sea level caused by tectonics and eustasy, as well as to fluctuations in sediment supply (Blair and Bilodeau 1988; Pivnik 1990; Postma and Drinia 1993; Postma et al. 1993a, b; Dart et al. 1994; Postma 1995; Weltje et al. 1996; Leeder et al. 1998; López-Blanco et al. 2000a, b). Fan deltas are most common in tectonically active basins (Nemec and Steel 1988; Wescott and Ethridge 1990), where the subsidence, base level and alluvial sediment supply can vary on both temporal and spatial basis (Leeder et al. 1988; Gawthorpe and Colella 1990) and the resulting syntectonic successions commonly show considerable three-dimensional variation (Gawthorpe et al. 1994; Howell and Flint 1994; Gawthorpe and Leeder 2000; Ilgar and Nemec 2005). The exact mechanisms for a particular order of stratigraphic cyclicity are thus generally challenging to determine (Dart et al. 1994; Hardy et al. 1994; Molenaar and Martinius 1966; Weltje et al. 1996; Gawthorpe et al. 2003). The same pertains to the suggestions on cyclicity derived from the present case study, which may not necessarily be of broader significance.

The stratigraphic architecture and facies anatomy of a fan deltaic complex can be recognised in considerable detail from large outcrop sections, as has been demonstrated in the present study and many other papers (e.g. Fernández et al. 1988; Marzo and Anadón 1988; Robles et al. 1988; Flint et al. 1991; Fernández et al. 1993; López-Blanco et al. 2000a, b; Steel et al. 2000; Ilgar and Nemec 2005; Alçiçek et al. 2024; Larsen et al. 2024a; Wathne et al. 2024), but is far more difficult to identify based on seismic and drilling-core data (cf. Graue et al. 1987; Rossi and Rogledi 1988; Collier et al. 2000). An understanding of the relationships between the stratigraphic architecture of fan deltaic wedges and their facies anatomy may be an essential tool for the prediction of spatial-facies distribution in subsurface exploration targets of this type when recognised using seismic sections, even if not necessarily drilled. A reliable stratigraphic facies model may help to assess the quality of a petroleum reservoir, including its heterogeneity, geometry and possible outliers.

In the present section, some key aspects of the stratigraphic architecture and facies anatomy of fan deltaic complexes in the Antalya Basin are summarised based on six case studies (Alçiçek et al. 2024; Larsen et al. 2024a, b; Wathne et al. 2024). The discussion focuses on the geometry and dynamic stratigraphy of an evolving fan delta complex, emphasising the controlling factors, sedimentation processes and facies.

7.1 The development of the fan *delta* complex

Stratigraphic significance. The fan deltaic complexes in the Antalya Basin are composite clastic wedges formed by several advances and retreats and hence comprise a series of basic wedges representing these regressive-transgressive cycles. The basic wedges in a fan delta complex are typically organised into a forward-stepping set overlain by an aggradational to backstepping set. The fan delta complex as a whole is thus a composite regressive-transgressive wedge developed as the middle, culmination part of a sequence bounded by maximum-flooding surfaces, with the turnaround from regression to transgression recognisable from the stacking architecture and facies anatomy of the component basic wedges (see discussion by Wathne et al. 2024). The fan delta complexes have an approximate timespan of *ca.* 3–4 Ma and are thought to have formed at the transition, or regression-transgression turnaround, of 3rd-order eustatic cycles (Haq et al. 1988; Vail et al. 1991). The component basic wedges, bounded by 4th-order flooding surfaces, vary in volume, and their timespan may range between less than 200 ka and more than 400 ka. These 4th-order cycles are inferred to result from rapid tectonic subsidence and fan delta drowning episodes. Subordinate (5th-order) brief events of extensive flooding can similarly be attributed to irregularities in the pattern of tectonic subsidence. The more frequent (6th-order) minor shoreline shifts probably reflect autocyclic fluvial switching and astronomical climatic fluctuations.

The aggradational terminal part of the lowstand systems tract, where beach and shoreface deposits commonly alternate, and the alluvium of the transgressive systems tract interspersed with horizons of marine-incursion facies seem to be the only parts of a fan delta wedge where the signal of climatic changes can be recognisable. Changes in the frequency of sea storms may be recognisable in the surrounding offshore-transition facies succession, where the record of infrequent tsunami events is well preserved whilst being obscured in wave and fluvial activity areas.

Lateral correlation. The turnaround horizon of maximum regression separating the forward-stepping set of basic wedges from the aggradational to backstepping set is probably the best surface to correlate coeval fan deltaic complexes in a basin because their timespans may differ, and neither their first nor the last basic wedges may necessarily be correlative. Also, the earliest and the latest wedges are invariably the shortest and, hence, are not constantly exposed or preserved. The component wedges of coeval fan delta complexes along one basin margin can be assumed to be correlative and thus matched successively in their downward and upward stratigraphic order relative to the maximum regression surface. However, fan deltas formed on the opposing sides of a graben are unlikely to be correlative at this level. They should instead be regarded as an important basis for recognising and comparing the subsidence history of basin margins. As pointed out by Gawthorpe et al. (2003), coeval deltas formed in the footwall, hangingwall and fault-tip settings may show markedly different stratigraphic architectures.

The component wedges of a fan delta complex may correlate laterally with analogous regressive episodes recorded by the margin's coeval non-deltaic nearshore facies, provided that the shoreline trajectory outside the delta area was not too steep. Otherwise, the down-and-up shoreline shifts on a steep basin margin may result in little recognisable facies change in the nearshore to offshore zone and be hardly recognisable (see discussion by Wathne et al. 2024).

External and internal geometry. The component basic wedges are amalgamated and difficult to distinguish in the proximal, landward part of a fan delta complex, consisting of alluvium. The wedges are split by marine facies and thinning in a basinward direction, where their termini consist of sandy shoreface facies interfingering with offshore-transition heterolithic deposits. The basinward transition from thick gravelly deposits to compactable and relatively thin coeval heterolithic deposits results in a distinctive, basinward-tapering geometry of the whole fan deltaic complex. However, the longitudinal geometry of a single basic wedge is by no means perfectly wedge-shaped because its maximum thickness tends to be in the outer, middle part, around the seaward pinch out of delta-plain alluvium.

This internal geometry reflects the fan delta system's development towards morphodynamic equilibrium, with process-related local imbalances coming simultaneously into play. As the fan delta advances, the distributary fluvial system inevitably adjusts its profile. The surface inclination of the alluvial fan decreases as its radius grows. At the same time, stream entrenchment and net erosion occur in the fan head area, with increasingly more sediment bypassing this zone. At the other end of the distributary system, an aggradational stacking of delta-front deposits occurs when the sea-level rise begins, the fan delta reaches its maximum radius, and the frontal reworking by waves gradually predominates. The nearshore zone has the highest aggradation potential because the shoreline acts as a trap for sediment, and there are also physical limits for its seaward dispersal by storms. The waves thus keep combing sand and gravel shorewards until the landward expansion of transgressive ravinement begins.

These thicker nearshore portions of successive basic wedges (coastal prisms of Posamentier et al. 1992) tend to accumulate vertically in the fan delta complex, whose net thickness in this part is thus commonly greater unless younger ones considerably overstep the earlier wedge. The resulting composite wedge has a maximum positive relief at the top of its aggradational sequence set (e.g. see wedges G5–G7 in Fig. 3B; Larsen et al. 2024a), and this stratigraphic level is thus prone to fluvial incision in the event of subsequent forced regression (Talling 1998). Although an aggradational sequence set is typically formed during an overall rise of relative sea level, a minor eustatic fall may occasionally outpace basin-floor subsidence in a hanging-wall dip-slope setting (Gawthorpe et al. 2003), resulting in an episode of forced regression. This is thought to have been the case with the formation of forced-regressive wedges and incised valleys in the upper part of the aggradational sequence sets in the Altınkaya fan delta complex (Larsen et al. 2024a) and the Göktaş complex (wedge G7 in Fig. 3A).

Effects of substrate morphology. Depending on the rates of sea-level change and sediment supply, the topographic configuration of an evolving fan delta complex may profoundly impact the sedimentation pattern of the forced-regressive wedge. The vertical stacking of basic wedges creates a

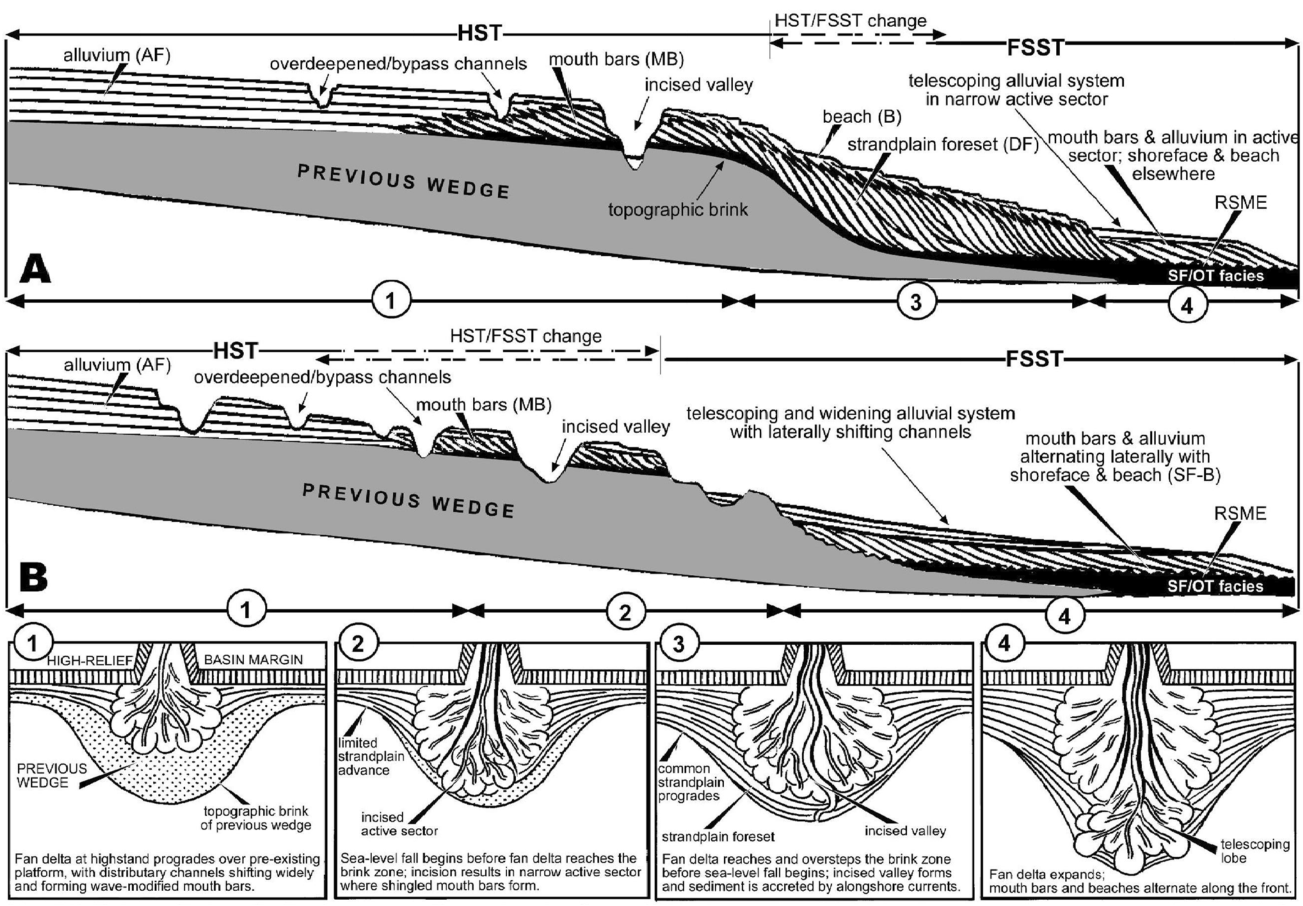

Fig. 15 Schematic longitudinal cross-sections showing two principal ways in which an advancing, forced-regressive fan delta wedge can overstep a previous wedge. **A** The relative sea-level fall begins after the delta front has overstepped the topographic brink of the previous wedge. This renders the shoreline trajectory diverging from the substrate profile through most of phase 3 and causes deposition of large strandplain foreset. **B** The relative sea level begins before the delta front oversteps the topographic brink, which renders the shoreline trajectory converging and the front maintaining a shoal-water profile. The plan-view diagrams 1–4 depict the successive phases of fan delta progradation

nearshore sedimentary platform, which may be covered or overstepped by subsequent wedges.

If the new fan delta wedge comes out to be no larger than the previous one, it merely adds to the platform relief. The sea-level fall will cause an incision of the fluvial valley, and this may be prone to generate turbidity currents during floods, particularly after an inland or coastal heavy rainstorm, when the peak flood may coincide with quiet sea conditions. The affluent in such a setting will likely be voluminous and robust, heavily charged with suspended sediment (Nemec 1990, 1995); the nearshore seafloor gradient will be sufficiently steep to allow density–current ignition (Parker 1982); and the effective wave base outside the shoreline will be well above the seafloor so that the hyperpycnal effluent can plunge quickly under and avoid being "mixed out" by ambient turbulence (Wright 1977). Such depositional conditions are thought to have characterised some of the forced-regressive component wedges of the Altınkaya fan delta complex (Larsen et al. 2024a) and possibly the earliest (unpreserved) forced-regressive wedges of the Göktaş complex, as discussed a previous section. Simple vertical stacking also characterised the development of aggradational and backstepping basic wedges, formed by episodic normal regressions under an overall sea-level rise, with the fan delta distributary channels branching, aggrading and shifting laterally, rather than being incised, and the sediment supply decreasing (Larsen et al. 2024a; Alçiçek et al. 2024; Wathne et al. 2024).

Alternatively, the advancing fan delta wedge may have the capacity to overstep significantly the previous one, whereby two possible situations can occur:

1. The relative sea level may begin after the fan delta front has overstepped the topographic brink of the previous wedge (Fig. 15A), in which case the shoreline trajectory temporarily diverges from the seafloor profile (Helland-Hansen and Gjelberg 1994; Helland-Hansen and Martinsen 1996) and a Massari-type strandplain foreset forms. The foreset progrades until the trajectory converges with the seafloor, the wave base encompasses the nearshore zone, and a shoal-water frontal profile is re-established by the "telescoping" fan delta lobe. Such depositional conditions characterised some of the forced-regressive basic wedges of the Göktaş fan delta complex, as discussed earlier in the text, and possibly also some component forced-regressive wedges of the Altınkaya and Beşkonak complexes (Larsen et al. 2024a), which are incompletely exposed.
2. The relative sea level fall may begin before the fan delta front has overstepped the topographic brink (Fig. 15B), in which case the shoreline trajectory converges with the substrate, headward incision confines fluvial activity to a narrow sector, and the delta front progrades whilst maintaining its shoal-water profile, laterally dominated by waves. Such depositional conditions characterised the forced-regressive basic wedges of the Ihtiyarlı, Katırınemeği and Asar fan deltaic complexes (Alçiçek et al. 2024; Wathne et al. 2024), most of the forced-regressive basic wedges of the Altınkaya and Beşkonak complexes (Larsen et al. 2024a), and the early component wedges (G1–G2) of the Göktaş complex.

Although the FSST in either case involves fluvial incision and may be capable of generating episodically turbidity currents (Fig. 15), the forced-regressive system's propensity for this phenomenon is probably much higher when no wedge overstepping occurs, and the robust effluent takes direct advantage of the platform-margin morphology (as discussed in a previous paragraph).

Role of basin-margin conditions. The basinward extent of basic wedges and the whole fan delta complex reflects the combined effect of sediment supply and nearshore accommodation. The fluvial supply was controlled by climate, particularly precipitation, but depended strongly on the catchment size and type. Fan-delta complexes sourced from contemporaneously formed bedrock canyons were comparatively small, no more than 3–5 km in radial length (Ihtiyarlı, Katırınemeği and Asar complexes), whereas those sourced from pre-existing, sediment-filled large valleys were up to 15–18 km in length (Beşkonak, Altınkaya and Göktaş complexes).

The trajectory of shoreline migration on the small, canyon-fed alluvial fans would be considerably steeper than on the large, valley-fed ones. This factor would necessarily restrict the landward extent of marine incursions and favour vertical stacking of wedges in the former case whilst promoting major basinward offset and "telescoping" of wedges and allowing extensive inundation and valley drowning in the latter case.

7.2 Internal characteristics of basic wedges

The relative basinward extent, geometry and internal facies architecture of the normal- and forced-regressive basic wedges are generally different. The basic wedges formed by normal-regressive to transgressive cycles are shorter and commonly shortening upwards, and each consists of a highstand (HST) and a transgressive systems tract (TST). In contrast, those formed by forced-regressive to transgressive cycles are longer and lengthening-upwards, quite profoundly in some cases, and each can be divided into four systems tracts (Hunt and Tucker 1992, 1995; Helland-Hansen and Gjelberg 1994; Plint and Nummedal 2000), namely a highstand (HST), falling-stage (FSST), lowstand (LST) and transgressive system tract (TST). The general facies architecture of the individual systems tracts is discussed below.

HST. The fan delta under the highstand has a relatively short radius, whereby the specific deposition rate (i.e. sediment accumulation per unit area) is high, and the delta gradually progrades and aggrades as the relative sea level continues slowly to rise. The rise provides some accommodation for the alluvial fan aggradation, but large amounts of sediment are bypassing the delta plain and being deposited at the shoreline on the coasts, causing delta-front progradation. In other words, the delta plain's accommodation is lower than the rate of sediment supply. It is probably much lower during the early highstand when the fan radius is at its minimum and possibly during the late highstand if followed by a relative sea-level fall.

Though limited, the aggradation allows the distributary channels to shift laterally, adjust their profile, and, in the long term, supply sediment more or less evenly to the entire delta front as the fluvial system switches its activity from one fan sector to another. However, the short fan radius and limited accommodation render the "bypass" channels deep, whereby the sediment supply to the shoreline surpasses marine reworking and mouth bars are formed. As the active sector shifts laterally and the fan delta advances, facies successions SF-MB-AF and SF-B are deposited alternatingly at the delta front (facies symbols as in Table 1). The relative abundance of the two succession types reflects the intensity of the delta front reworking by waves. The intensity is high during an early highstand and decreases as the delta-front progradation rate increases, reaching a minimum during the HST transition to FSST or increasing rapidly again around the HST turnaround to TST. When the fluvial sediment supply to the fan delta front predominates, the progradation rate is higher, and waves have less time for reworking (Marzo and Anadón 1988). However, the energy of marine processes may vary from basin to basin and considerably fluctuate.

FSST. During the falling stage of the sea-level cycle, the fluvial distributary network evolves into fewer and deeper channels and eventually into one or more trunk channels, which may form incised valleys (Ritchie et al. 1999). For a significant incision to occur, the shoreline trajectory must be falling seawards at an angle steeper than the surface inclination of the distal alluvial plain (Helland-Hansen and Martinsen 1996, Fig. 6), and the incision will be deepest where the channel crosses the convex-upward topography of the fan delta (i.e. the coastal prism of Posamentier et al. 1992; Talling 1998, Fig. 2A). The sediment supply to the fan delta front is thus maximised by incision whilst being simultaneously reduced to little more than one or two fixed outlets. A multi-lobate shoreline may tend to develop (Ritchie et al. 1999; Gawthorpe et al. 2003; Fig. 3B), but not in an open-marine coastal setting where the shoreline is subject to long-fetch waves, as was the case in the Manavgat Basin and still is along the modern coast (Larsen et al. 2024b). Instead, wave action and alongshore currents distribute the river-derived sediment along the delta front, causing intense shoreline accretion. The fan delta effectively continues to prograde as an arcuate strandplain. It may have the capacity to overstep considerably the morphology of the previous wedges, in which case a Massari-type foreset of facies DF is deposited, with local intercalations of facies MB.DF and a topset of facies B. The strandplain foreset succession DF-B is replaced seawards by delta-front facies succession SF-MB-AF as the FSST turns gradually to LST and aggradation predominates (Fig. 12).

If the advancing fan delta lacks the capacity overstep the previous wedges, no strandplain foreset develops, and the incised trunk river may instead be capable of generating hyperpycnal currents during floods. These episodic, sustained-type turbidity currents tend to be channelised and deposit sand lobes in the offshore zone (Larsen et al. 2024a, b).

LST. During the sea-level lowstand, the fan delta gradually reaches its maximum radius whilst aggrading as the sea level rises slowly. The large area of the delta plain renders the specific rate of alluvial deposition low, but as the accommodation of the expanding delta plain increases (Muto and Steel 1997), so does the accumulation potential of alluvium. The aggrading stream channels are relatively shallow, and the fan surface acquires smoother morphology. The rate of sediment supply to the shoreline consequently decreases, and the rate of delta-front progradation declines, causing marine reworking to prevail. The facies succession SF-MB-AF is replaced by an aggradational succession SF-B-AF (Fig. 12). The alternation of facies SF and B in the delta-front succession indicates minor shoreline shifts, apparently caused by fluctuations in stream discharges and/or wave energy and hence possibly reflecting regional climatic changes.

TST. The accommodation in the delta-plain area during transgression is higher than the sediment supply rate, and storing sediment in the alluvial plain results in shoreline starvation and retreat ("delta auto retreat" of Muto and Steel 1997). As pointed out by Marzo and Anadón (1988), frontal marine reworking prevails over fluvial supply at the turnaround from regression to transgression in the development of a basic fan delta wedge (see also Larsen et al. 2024a; Wathne et al. 2024). Significant discharge fluctuations might render the fan delta front more vulnerable to reworking.

The fan delta under a 4th-order transgression (wedge-drowning stage) may retreat in a punctuated manner by forming a set of backstepping parasequences, provided that the wave action is not excessive (e.g. Ilgar and Nemec 2005; Larsen et al. 2024a). In such a case, the lateral switching of the active fan sector plays the same role as the autocyclic mechanism of lobe shifting in river deltas, which is responsible for generating backstepping deltaic parasequences. Marine incursions occur preferentially in fan plain areas lateral to its active sector (Fig. 13D), which meanwhile aggrades and eventually shifts laterally to such a low-lying zone, where progradation is then renewed. The transgressive marine deposits (facies MI or SF) are covered by alluvial facies AF or a delta-front facies sequence SF-B-AF. Depending on the accommodation, the transgressive blanket of shoreface deposits may be thin (e.g. Alçiçek et al. 2024; Wathne et al. 2024) or relatively thick, aggradational (e.g. Larsen et al. 2024a). As recognised in the upper part of the Altınkaya complex (Larsen et al. 2024a), the transgressive marine deposits in a drowned incised valley or a sheltered fan surface depression may show tidal influence or may include carbonate facies (micritic, bioclastic and patch-reef limestones) in association with a 4th-order surface of maximum flooding, particularly at the top of the fan delta complex (Monstad 2000; Karabıyıkoğlu et al. 2005). The process of marine flooding and renewed advance may repeat several times during a 4th-order transgression (Siggerud et al. 2000), whilst the whole proximal, alluvial part of the fan delta aggrades (Fig. 12).

The distributary channels at that stage are far extended and relatively shallow (e.g. see log interval 41.6–53.2 m in Fig. 4), initially around 1 m deep and dominated by longitudinal bars (facies AF.LB and AF.BC), though later 1.5–2 m deep and filled by steep-fronted bars (facies AF.CL and AF.TB), which reflects the increasing rate of aggradation and decreasing fan radius. Shallow channels shift more often and promote unconfined floods (facies AF.BC sheets); hence, the fan surface in TST remains comparatively smooth.

8 Conclusions

The Göktaş fan delta complex is a regressive–transgressive composite wedge deposited in the late Serravallian to late Tortonian in the western part of the Manavgat Graben, near its junction with the adjacent Köprü Graben. The wave-dominated, shoal-water fan delta formed as a dip-slope coastal system associated with the hangingwall antithetic faultline of the asymmetrical graben, whose footwall was submerged. The gravelly fan delta was sourced by a fluvial system from a pre-existing large valley in the basin's mountainous northern hinterland.

The composite wedge is more than 230 m thick and consists of a series of regressive–transgressive basic wedges stacked upon one another and extending up to 18 km from the basin margin. The proximal outcrop section, separated from the margin by a modern valley, shows ten such component wedges. Still, the fan delta complex is inferred to have included at least two or three earlier short wedges and possibly a couple of short later wedges, presently not preserved. The succession comprises a forward-stepping set of forced-regressive basic wedges overlain by an aggradational to a backstepping set of normal-regressive wedges, split by a forced-regressive wedge in the middle. The basic wedges consist of erosional alluvial-fan facies underlain and passing basinwards into mouth-bar, beach and shoreface facies and also overlain transgressively by the last two. The occurrence of mouth-bar deposits is limited to forced-regressive wedges, whose fluvial channels also tend to be deeper. The forced-regressive wedges, where overstepping the morphology of previous ones, tended to involve incised valleys and advance basinwards as a strandplain with an avalanching steep subaqueous face, forming a large gravelly foreset of debrisflow and rip-current deposits overlain by a topset of beach deposits. The advance of the earliest forced-regressive wedges may have led to an episodic generation of channelised hyperpycnal currents and turbiditic sedimentation in the offshore-transition zone.

The fan delta complex has an estimated timespan of *ca.* 4 Ma. It is thought to have formed in the turnaround, fall-rise transitional phase of two successive 3rd-order eustatic cycles, punctuated by rapid tectonic subsidence and fan delta drowning (4th-order flooding demarcating the basic wedges). Sporadic 5th-order events of brief flooding, recorded as intercalations in delta-plain alluvium below the TST ravinement, can also be attributed to tectonics. Minor shoreline shifts of the 6th order, recognisable above the ravinement and in the aggradational deposits of late LST, are probably due to climatic fluctuations and autocyclic lateral switching of fluvial activity.

The Göktaş complex shows some individual features, like the formation of strandplain foresets and the impressive basinward advance of "telescoping" wedges. Otherwise, it combines characteristics of the other fan deltaic complexes in the Manavgat and Köprü grabens. Based on these case studies, a dynamic stratigraphic model has been suggested for the depositional architecture and facies anatomy of wave-dominated, shoal-water fan deltaic complexes, emphasising their sedimentation processes and response to relative sea-level changes. In the hierarchical organisation of a composite fan delta wedge, the normal-regressive component wedges consist of HST and TST. In contrast, the forced-regressive ones consist of HST, FSST, LST and TST. The systems tracts differ in their spatial partitioning of facies. The HST has a moderately thick, short-radius alluvium with relatively deep palaeochannels, extending basinwards over progradational mouth-bar facies underlain and passing into a narrow belt of wave-worked shoreface facies and further into tempestitic offshore-transition deposits. The FSST has a thin and poorly preserved alluvium, including basal deposits of overdeepend bypass channels and incised valleys, passing basinwards into progradational delta-front deposits developed as either mouth-bar facies underlain by shoreface facies (possibly with offshoot turbiditic channels and lobes in offshore-transition zone) or a large strandplain foreset overlying offshore-transition facies. The LST has a relatively thin, basinward-thickening alluvium with moderately deep to shallow palaeochannels, which overlies mouth-bar facies and passes basinwards into an aggradational delta-front succession of alternating beach and shoreface deposits, the latter far-extended in their passage to tempestitic offshore-transition deposits. The TST has the thickest alluvium, with shallow to moderately deep palaeochannels, but truncated by a landward-rising transgressive ravinement and thinning rapidly basinwards; the ravinement surface is overlain by a blanket of alternating upper/lower shoreface facies, passing landwards into beach facies and seawards into offshore-transition deposits.

The stratigraphic model may serve as a useful tool for predicting facies distribution in fan deltaic littoral clastic wedges and assess reservoir quality in subsurface petroleum exploration, including heterogeneity, geometry, and possible sand-prone outliers.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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