Development of Gilbert-type deltas:

sedimentological case studies from the Plio-Pleistocene of Corinth Rift, Greece

Katarina Gobo

Dissertation for the degree of Philosophiae Doctor (Ph.D.)

Faculty of Mathematics and Natural Sciences

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Do not go where the path may lead,
go instead where there is no path and leave a trail.

– Ralph Waldo Emerson

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1. **Gobo, K., Ghinassi, M., Nemec, W.** and **Sjursen, E.**
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   Sedimentology, doi: 10.1111/sed.12089, in press, 2014.

2. **Gobo, K., Ghinassi, M.** and **Nemec, W.**
   Gilbert-type deltas recording short-term relative base-level changes: delta-brink morphodynamics and related foreset facies.
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3. **Gobo, K., Ghinassi, M.** and **Nemec, W.**
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   Journal of Sedimentary Research (MS in review).

Preface

This thesis has been submitted for the degree of Philosophiae Doctor (Ph.D.) at the Department of Earth Science, University of Bergen. The research presented herein was carried out at the University of Bergen, under the principal supervision of Prof. Wojciech Nemec, co-supervision of Prof. Robert Gawthorpe and external co-supervision of Dr. Massimiliano Ghinassi (Univeristy of Padova). The project was funded through a Bergen University 4-year scholarship that commenced in January 2010. Additional financial support was kindly provided by the University of Bergen, University of Padova, the International Association of Sedimentologists (IAS) and Statoil (through the Akademia agreement on mobility funds) for covering fieldwork expenses, laboratory analyses and participation in conferences abroad.

The thesis is structured according to the Norwegian guidelines for doctoral dissertations in natural sciences, where the main part of the thesis consists of research papers either published, submitted or about to be submitted to international peer-reviewed journals. The present thesis comprises three papers: Paper 1 has already been published in the journal *Sedimentology*; Paper 2 is in review in the same journal; and Paper 3 has been submitted to the *Journal of Sedimentary Research.* Their text format and written English (UK vs. USA) are thus inconsistent, as is also the format of their lists of references. The three research papers are preceded by a general introduction that gives the project background and aims, synthesizes its outcome, and outlines prospects for future progress in the explored research field. An authorship statement provides an overview of the contribution of each author to this collaborative research work.

Katarina Gobo

Bergen, 27 March 2014

Acknowledgements

First of all, I would like to express my immense gratitude to Prof. Wojciech Nemec and Dr. Massimiliano (Gino) Ghinassi for their designing of the project, their dedication and invaluable help in fieldwork, and their enthusiasm and encouraging attitude offered throughout these 4 years. It was a privilege to work with you and learn from you! Thank you for all your scientific input, invaluable advice and for being so patient with my work progress. A special *dziękuję* to Wojtek for all the time and effort he has spent on editing my consecutive manuscripts, and a special *grazie* to Gino for all his moral (and often also physical on outcrop cliffs!) support and for his ability to find the right consoling words in all circumstances. Prof. Rob Gawthorpe is kindly thanked for the useful discussions and practical advice, and for his comments on my research ideas and one of the paper drafts. Rob's knowledge of the study area was very helpful, as was also his ability to view my local case studies from a wider regional perspective.

My special thanks go to the Department of Earth Science, University of Bergen, for funding my research and for providing me with a pleasant, friendly and comfortable work environment. I am grateful to Prof. William Helland-Hansen and Dr. Gunnar Sælen for giving me the opportunity to combine duty and pleasure through our teaching collaboration in the course *Introduction to Sedimentology* and the four memorable related fieldtrips to Spain that will certainly stay among the most enjoyable events for me in these past few years.

I thank also Valeria Bianchi for her good-humoured support during my PhD study period and her comments on an early draft of one of my papers, and most particularly for her generous hospitality during my research stay in Padova, Italy.

As a newcomer to Bergen, I was lucky to become immediately a member of a cheerful and friendly group of fellow PhD students and postdocs. In the meantime some of them moved away, some of them stayed and some new people arrived; I wish to thank them all for their support, especially in these last hectic months, and for all the interesting and hilarious discussions at lunch time and on other social occasions. An attempt of naming them all individually would just increase the chance of involuntary omissions; therefore I thank simply the *lunch group*, the *board-game group*, the *Earthcake club*, the *Geo-sport* enthusiasts, my former and current flatmate(s) and also all the 'non-grouped' nice people that I have met in Bergen over these few years. With you around, my friends, Bergen doesn't seem to be that much rainy after all!

Finally, I wish to thank my family and friends in Croatia for their long-distance encouragement, for always having their time for me during my short visits in my native country, and for their constant concern as to whether I am not freezing at these high latitudes. No worries, folks, I have acclimatized!

— Katarina Gobo

Abstract: what's this thesis about

Gilbert-type deltas form where a river system debouches into a relatively deep marine or lacustrine basin, whereby the subaqueous delta slope is steep and fully dominated by sediment gravity-transport processes. These deltas occur in various tectono-geomorphic settings and have attracted considerable research interest in the last three decades or so, although mainly from the viewpoint of their large-scale architecture, spatial-stratigraphic stacking pattern and relationship to basin-margin faults. Side-scan sonar studies of a number of such modern deltas provided highly instructive 'snapshots', but lacked the stratigraphic perspective of a deltaic system evolution with time. More recent detailed sedimentological studies of several ancient Gilbert-type deltas have meanwhile indicated that these sedimentary systems are some of the most valuable archives for the stratigraphic record of various allogenic and autogenic factors, most notably the record of relative base-level changes.

The present series of case studies from the Plio–Pleistocene deltas in the Corinth Rift, Greece, elucidates further this conceptual notion by focusing on such key issues as: the 'birth' and subsequent evolution of Gilbert-type delta as a valley-fill bayhead system (Paper 1); the relationship between the delta-brink morphodynamics controlled by base-level behaviour and the mode of the subaqueous delta-slope processes of sediment dispersal (Paper 2); and the impact of these brink-to-slope temporal changes on the sedimentation pattern in the delta-foot zone (Paper 3). The application of detailed facies analysis has proven to be of crucial importance in unravelling the system formative conditions. The case studies highlight the significant role of the rift-margin tectonics, while revealing further the spatio-temporal patterns of the deltaic system's own responses to tectonically-induced perturbations.

This series of case studies from the Corinth Rift contributes to a better understanding of the morphodynamics of evolving Gilbert-type deltaic systems and their pattern of responses to both long- and short-term changes in base level. The studies contribute also to a better understanding of the Plio–Pleistocene tectonic development history of this youngest European rift basin.

Authorship statement

This dissertation consists of three research papers, with the Ph.D. candidate Katarina Gobo as the first author of all of them and the sole author of the thesis *Introduction* chapter. The papers are a result of collaborative fieldwork and the relative contribution of their authors is specified below.

Paper 1: *Development of an incised valley-fill at an evolving rift margin: Pleistocene eustasy and tectonics on the southern side of the Gulf of Corinth, Greece* by **K. Gobo, M. Ghinassi, W. Nemec, W.** and **E. Sjursen**

All four authors were actively involved in the collection of field data and their preliminary interpretation. **KG** subsequently analysed the data in detail, developed a palaeogeographic and chronostratigraphic scenario for the valley-fill depositional system, wrote the manuscript and drafted most of the figures. **MG** drafted Fig. 9, designed Fig. 8A and contributed to the paper's Introduction. **ES** drafted Fig. 10 and participated in the joint discussions of results. **WN** designed the general concept of the paper, inspired discussions, offered practical advice and edited the final manuscript.

Paper 2: *Gilbert-type deltas recording short-term relative base-level changes: delta-brink morphodynamics and related foreset facies* by **K. Gobo, M. Ghinassi and W. Nemec**

All three authors were actively involved in the collection of field data and their preliminary discussion and interpretation. **KG** subsequently analysed and interpreted the data in more detail, wrote the manuscript and drafted all the figures. **MG** contributed to the design of figures 1 and 8. **WN** designed the general concept of the paper, instigated crucial discussions, offered practical advice and edited the final manuscript.

Paper 3: *Reciprocal changes in foreset to bottomset facies in a Gilbert-type delta: response to short-term changes in base level* by **K. Gobo, M. Ghinassi and W. Nemec**

All three authors were actively involved in the collection of field data and their preliminary discussion and interpretation. **KG** subsequently analysed and interpreted the data in more detail, wrote the manuscript and drafted all the figures. **MG** and **WN** offered stimulating discussions and practical advice. **MG** gave helpful comments on the manuscript, and **WN** edited its final version.

Introduction

Sedimentology of Gilbert-type deltas

Gilbert-type deltas – first described by Gilbert (1885) and afterwards named after him – are a variety of deltaic systems that form where river debouches into a body of standing water that is considerably deeper than the fluvial feeder channel. These deltas comprise a steeply inclined *foreset* of subaqueous delta-slope deposits passing down-dip into subhorizontal *bottomset* of prodelta deposits and overlain by a subhorizontal *topset* of fluvial delta-plain deposits (Fig. 1). These characteristic units were defined by Barrell (1912), with the term *toeset* commonly used to describe the tangential transition from foreset to bottomset (e.g., Massari 1996; Sohn et al. 1997; Breda et al. 2007). The delta thickness and bulk volume are determined by the host-water depth and river sediment supply, respectively.

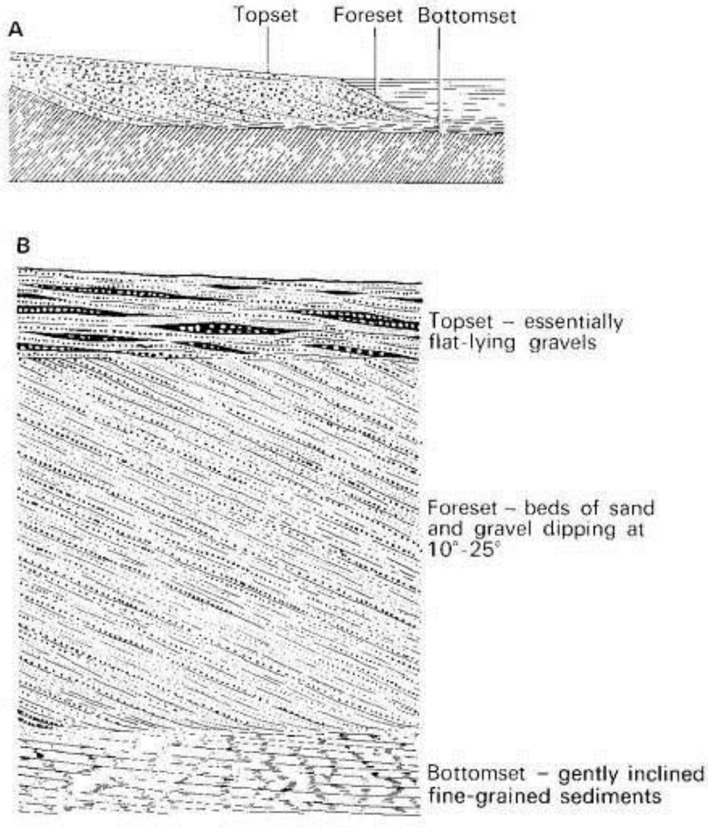

Fig. 1. (A) Section through a Gilbert-type delta. **(B)** Vertical facies sequence produced by delta progradation (after Gilbert 1885; Barrell 1912). Note that delta architecture is portrayed rather simplistically.

The mode of sediment transfer from the subaerial delta plain to the subaqueous delta slope depends on the type and amount of sediment delivered by the fluvial system and the density contrast between the sediment-laden river outflow and the basin water (Bates 1953). Hypopycnal outflow results in a buoyant plume of fine-grained sediment suspension (Fig. 2) that spreads away from the delta and gradually settles in its distal realm (Nemec 1995). Homopycnal outflow involves rapid mixing of river and basin water, which causes sediment deposition close to the river mouth (Colella et al. 1987). Hyperpycnal outflows plunge down on the steep delta slope, depositing there their sediment load (Fig. 2A). The latter two types of river outflow conditions thus favour delta build-out, with most of the sediment deposited beneath the wave base and transported by gravitational processes.

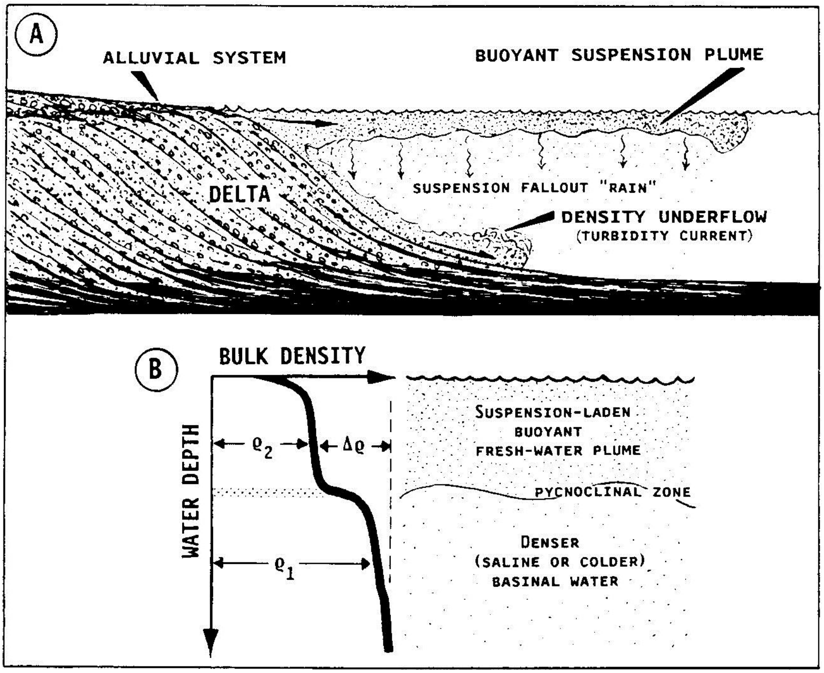

Fig. 2. (A) Schematic diagram showing deltaic buoyant hypopycnal plume and hyperpycnal underflow. **(B)** The density layering of water column associated with a hypopycnal plume. (From Nemec 1995).

Gilbert-type deltas were initially considered to be exclusively lacustrine features, but field studies since the 1980s have documented their common occurrence in marine settings (e.g., Postma 1984; Postma & Roep 1985; Massari & Parea 1990; Dorsey et al. 1995; Massari 1996; Sohn et al. 1997; Mortimer et al. 2005; Longhitano 2008), particularly as bayhead systems in fjords (Prior et al. 1981; Kostaschuk & McCann 1987; Prior & Bornhold 1988, 1990) and estuarine incised valleys (e.g., Postma 1984; Li et al. 2006; Breda et al. 2007, 2009; **Paper 1**). They form not only in tectonically active areas (Massari & Colella 1988; Gawthorpe & Colella 1990; Ford et al. 2007; Backert et al. 2010;

Paper 1), but also in proglacial settings (Nemec et al. 1999; Lønne et al. 2001; Lønne & Nemec 2004) and in natural and artificial lakes (Grover & Howard 1937; Fan & Morris 1992; Morris & Fan 1997), and have even been reported from extra-terrestrial settings (Ori et al. 2000; Mangold & Ansan 2006). The growth, geometry and stacking pattern of Gilbert-type deltas were studied by means of laboratory experiments (e.g., Jopling 1963; Kostic & Parker 2003b; Kleinhans 2005; Lai & Capart 2007; Rohais et al. 2011; Bijkerk et al. 2013) and numerical modelling (e.g., Muto & Steel 1992; Syvitski & Daughney 1992; Hardy et al. 1994; Hardy & Gawthorpe 1998; Uličný et al. 2002; Kostic & Parker 2003a). This considerable research interest in Gilbert-type deltas stems partly from their economic significance as stratigraphic traps for hydrocarbons (Graue et al., 1987; Muto & Steel, 1997) and sites of mineral placers, but mainly from their sensitivity to relative base-level changes, making them play an important role in basin analysis (Gawthorpe & Colella 1990).

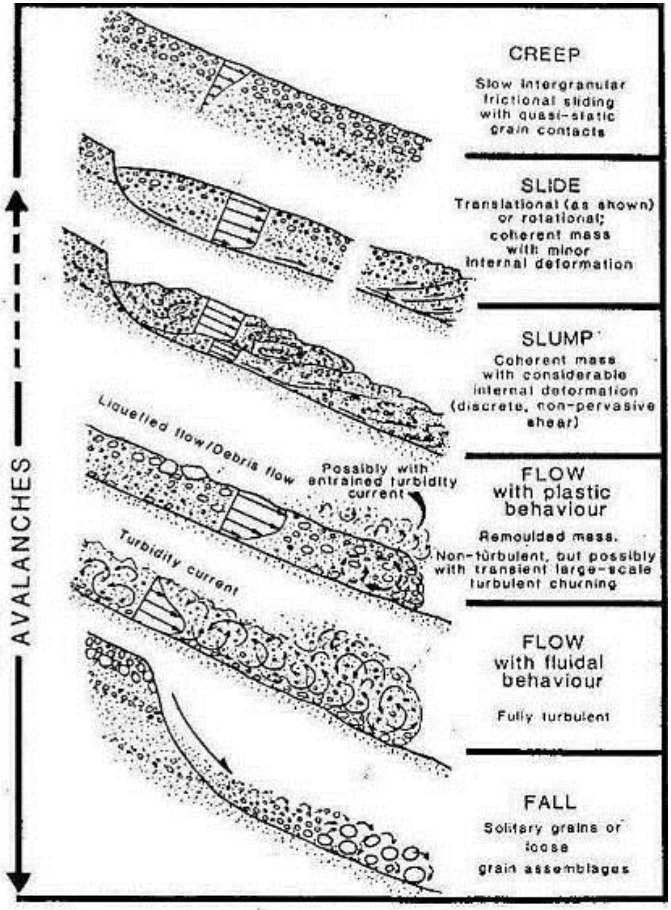

Fig. 3. Depositional processes on the steep slope of Gilbert-type deltas and the resulting foreset facies (from review by Nemec 1990).

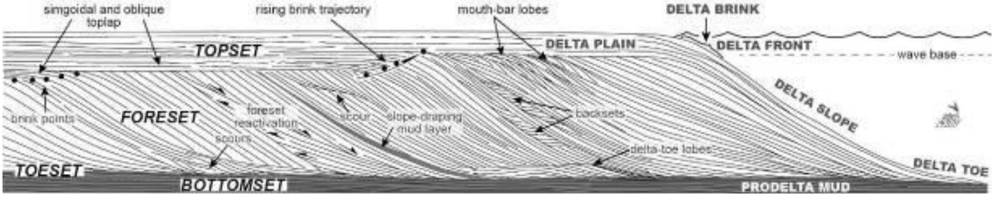

Fig. 4. Schematic review of various architectural elements recognized in Gilbert-type deltas. No scale is given, as the delta thickness depends on the host-basin depth and may range from a few metres to a few hundred metres.

These steep-faced deltas were initially portrayed rather simplistically (Fig. 1), both in terms of depositional architecture and subaqueous depositional processes. The latter were traditionally lumped under the label of 'slope avalanches', but studies of modern and ancient deltas over the last three decades have revealed a whole range of delta-slope depositional processes (Fig. 3), including debrisflows, debrisfalls and both sustained (hyperpycnal) and surge-type turbidity currents of high to low density (*sensu* Lowe 1982). A considerable variation in Gilbert-type delta architecture has also been recognized (Fig. 4):

- The delta brink during delta progradation may have a horizontal, falling or rising trajectory (*sensu* Helland-Hansen & Martinsen 1996), which is considered to be an important high-resolution record of relative base-level changes during the delta life-span;
- The topset–foreset contact may be either transitional (sigmoidal) or erosional (oblique), which is attributed to accommodation space formation or subtraction, respectively (Massari 1996);
- The topset-foreset contact may display scoop-shaped 'destructional' scours and/or 'constructional' mounds (Fig.5) (Postma & Cruickshank 1988; Nemec et al. 1999; Lønne & Nemec 2004);
- The foreset unit may contain slope-draping mud layers, followed by an onlapping or downlapping foreset reactivation (Nemec et al. 1999; Lønne & Nemec 2004), commonly at a reduced angle (Kostic et al. 2002);
- Delta slopes show the occurrence of ridges and chutes, which are respectively attributed to subaqueous high-viscosity mass-movement processes and turbidity currents (Prior et al. 1981; Kostaschuk & McCann 1987; Postma 1984);
- The delta-slope and delta-toe bedding may include 'backsets' of upslope-dipping cross-strata filling a chute and/or abutting against a downslope obstacle; their origin is attributed to turbidity currents that underwent hydraulic jump (Fig. 6) (Postma 1984; Nemec 1990; Massari 1996; Nemec et al. 2007);
- The foreset-bottomset transition may be smoothly tangential (Gilbert 1885; Nemec et al. 1999) or sharply angular (Colella 1988b; Zelilidis & Kontopoulos 1996); and may be characterized by offset-stacked depositional lobes or hummock-shaped

- ‘splays’ (Postma & Roep 1985; Postma & Cruickshank 1988; Prior & Bornhold 1988; Nemec et al. 1999; Lønne & Nemec 2004);
- The delta toe may show scoop-shaped scour-and-fill features referred to as ‘spoon-shaped depressions’ (Massari & Parea 1990; Breda et al. 2007), ‘arcuate scarps’ (Prior & Bornhold 1988) or ‘large flutes’ (Bornhold & Prior 1990), and attributed to turbidity currents that underwent hydraulic jump at the break in slope (Fig. 7).

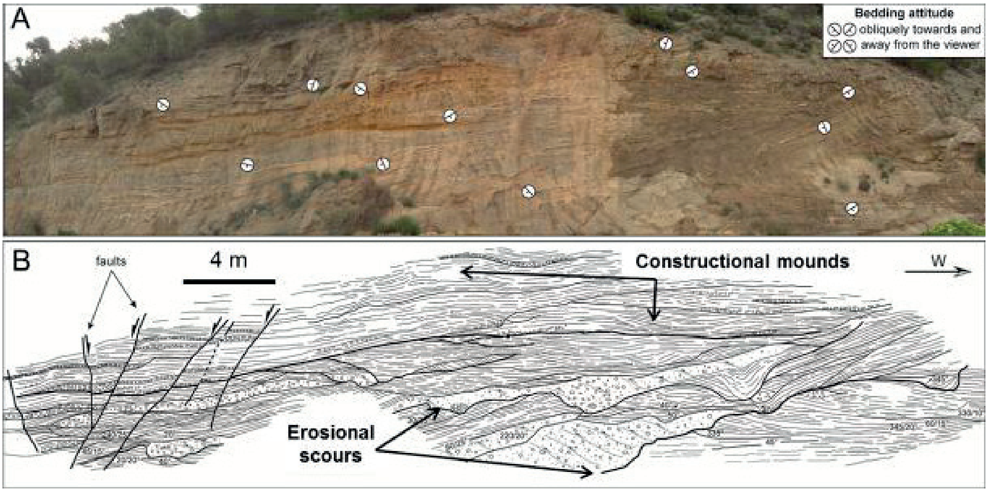

Fig. 5. (A) Panoramic view and **(B)** overlay sketch of a sigmoidal brink-zone geometry in transverse section; note the erosional scours in the lower part and the overlying mounds stacked in a compensational manner, attributed to mouth-bar progradation (see **Paper 2**).

Fig. 6. Large backset (set of upslope-dipping cross-strata) within the foreset of Gilbert-type Espirito Santo delta (Postma & Roep 1985); photograph courtesy of G. Postma.

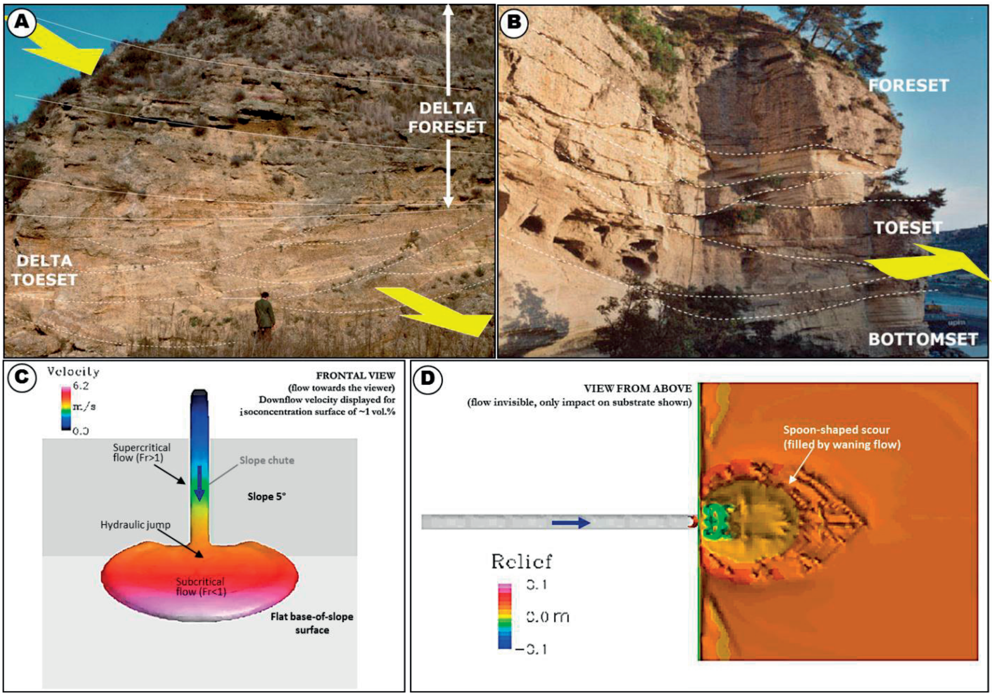

Fig. 7. Spoon-shaped multiple scour-and-fill features at the toe of Gilbert-type delta in **(A)** Bradano and **(B)** Ventimiglia, Italy (Breda et al. 2007), with yellow arrows indicating the flow direction; photographs courtesy of F. Massari. **(C, D)** Snapshot images of a numerical CFD simulation showing the formation of spoon-shaped scour at the toe of slope chute channel; the flow in D was made invisible in order to see its scouring effect, with the scour being subsequently filled in and smoothed out during the waning phase of the flow; images courtesy of W. Nemec.

Gilbert-type deltas recording relative base-level changes

Gilbert-type deltas are sensitive coastal recorders of relative base-level changes. In zones of active tectonics in particular, the combined effect of eustasy and tectonic uplift/subsidence gives rise to diverse delta architecture. Large changes in relative base level may lead to axial dissection of delta by an incised valley and its subsequent drowning with the progradation of a younger bayhead delta (Ford et al. 2007; Backert et al. 2010; **Paper 1**), or result in vertical stacking of successive deltas (Colella 1988a, 1988b; Breda et al. 2007, 2009). Low-magnitude short-term changes are recorded in the delta brink-zone, with the relative base-level rise reflected in a sigmoidal geometry and the relative base-level fall or stillstand in an oblique geometry (Fig. 4). As the brink zone tends to be eroded by fluvial system and waves, the foreset and toeset/bottomset deposits are the most valuable archives of allogenic and autogenic changes affecting the delta front and its fluvial feeder system. However, the detailed facies anatomy of these subaqueous deposits has been little studied. A systematic, bed-by-bed study has thus far been used in the facies analysis of colluvial-cone deltas (Blikra & Nemec 1998) and fjord-hosted proglacial Gilbert-type deltas (Nemec et al. 1999; Lønne et al. 2001; Lønne & Nemec 2004). Yet no attempt has, until now, been made to study the relationship between the observed brink geometries and coeval subaqueous depositional processes. The relative frequency, spatio-temporal association and time-sequence of changes of these processes may vary from one delta to another and also within a single delta, thus potentially reflecting the variable impact of particular controlling factors. Therefore, the present study attempted to shed more light on this particular issue through detailed facies analysis of some well-exposed deltas. The Gilbert-type deltas uplifted on the southern side of the Corinth Rift have a well-studied structural, stratigraphic and palaeogeographic framework, which allows various aspects of delta development to be assessed.

Gilbert-type deltas in the Gulf of Corinth

The Gulf of Corinth in central Greece is the submerged part of a rapidly extending rift that was initiated in Pliocene times (Ori 1989; Briole et al. 2000; Leeder et al. 2008). This area has been extensively studied, with a main focus on its tectono-sedimentary evolution and spatial-stratigraphic stacking pattern of the large Gilbert-type deltas uplifted along the gulf's southern coast (Ori 1989; Seger & Alexander 1993; Dart et al. 1994; Collier & Gawthorpe 1995; Ford et al. 2007; Rohais et al. 2007a, 2007b, 2008; Backert et al. 2010; Ford et al. 2013).

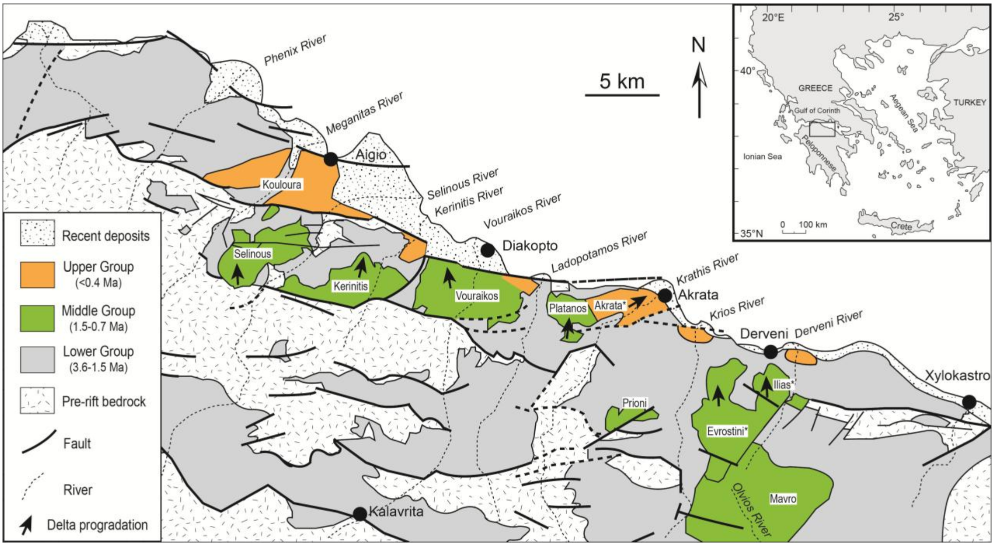

Fig. 8. Map of the southern coast of the Gulf of Corinth showing the main onshore faults and the distribution of the pre-rift and syn-rift units; modified from Ford et al. (2007) and Backert (2009). The large Gilbert-type deltas are labelled and the ones analysed in this study are marked with an asterisk; note delta distribution in the fault blocks and their progressive northward migration over time. The inset frame shows the location of the Gulf of Corinth in the Aegean region.

These footwall-derived gravelly deltas developed concurrently with the evolution and northward migration of the rift-margin system of normal faults (Fig. 8), with some of the younger deltas inset in older ones as the infill of axially incised valleys (McMurray & Gawthorpe 2000; Ford et al. 2007; **Paper 1**). The deltas were referred to as *fan deltas*, which means formed by alluvial fans, although no evidence has been given in support of this notion. It is more likely that these deltas were fed by antecedent and juvenile fluvial systems, similarly to their modern counterparts built along the gulf's southern coast (Seger & Alexander 1993; Ford et al. 2013). The deltas reach several hundred metres in thickness in their spectacular, seismic-scale 3D outcrops (Fig. 9). Depositional architecture and sequence stratigraphy of four deltas have been studied (Dart et al. 1994; Ford et al. 2007; Rohais et al. 2008; Backert et al. 2010), but without a high-resolution analysis of depositional processes. Consequently, no link between the observed changes in delta architecture and coeval changes in delta-slope processes has been established, leaving a wide range of unexplored aspects of deltaic system development (here addressed by **Papers 1–3**).

Fig. 9. The Gilbert-type Evrostini delta in the Corinth Rift. The delta foreset is ~400 m thick and its dip direction is to the north.

The present-study objectives

This study focused on the detailed facies anatomy and depositional architecture of a number of Corinth deltas to recognize which subaqueous processes were involved in their development at different stages of delta progradation. More specifically, the project objectives were to:

- Provide a high-resolution sedimentological and sequence-stratigraphic analysis of a previously unstudied, relatively young valley-fill deltaic system (**Paper 1**).
- Link the morphodynamic changes in delta-brink architecture with coeval changes in the delta foreset facies (**Paper 2**).
- Link changes in foreset facies with the changes in depositional architecture and facies in the corresponding toeset/bottomset deposits (**Paper 3**).

- Assess the deltaic system's formative conditions and link the morphodynamic and architectural changes to allogenic or autogenic factors (**Papers 1–3**).

Another initial objective was to assess the geological rate of the morphodynamic and facies changes by means of microfossil dating. However, this could not be achieved because of two limiting factors: (i) the delta deposits are mostly coarse-grained and unsuitable for the preservation of microfossils; and (ii) the sampled fine-grained interbeds were barren or yielded non-satisfactory results for high-resolution biostratigraphy.

The research outcome of this study — presented in **papers 1–3** — is summarized in the following chapter.

Summary of papers

Paper 1

Gobo, K., Ghinassi, M., Nemec, W. and **Sjursen, E.**
Development of an incised valley-fill at an evolving rift margin: Pleistocene eustasy and tectonics on the southern side of the Gulf of Corinth, Greece.
Sedimentology, doi: 10.1111/sed.12089, in press, 2014.

This paper presents a detailed sequence-stratigraphic and facies analysis of an incised valley-fill fluvio-deltaic succession whose development was controlled by the interplay of syn-depositional rift-margin tectonics and eustatic changes. The study combines facies analysis from outcrop data with previously published and re-evaluated U/Th dates of coral-bearing deposits to identify the relative role of tectonic subsidence/uplift, eustasy and regional climatic changes in the development of the valley-fill system.

The palaeovalley was incised in older rift-margin deltaic deposits due to tectonic uplift accompanied by glacio-eustatic sea-level falls and was subsequently filled in 100 ka with gravelly fluvio-deltaic deposits. Syn-depositional flexure of a valley-parallel relay ramp contributed to valley segmentation and strongly influenced the stratigraphic architecture and facies distribution of the valley-fill. The valley segment upstream from the ramp crest accumulated monotonous gravelly alluvium, whereas fluvio-deltaic deposits filled the downstream valley segment. Three consecutive bayhead deltaic systems – separated by transgressive lags – developed on top of one another, indicating that the ramp crest delimited the landward extent of marine invasions and pinned down the nucleation point of the bayhead systems. The ultimate growth of a thick Gilbert-type delta resulted from the inherited bathymetry produced by the slope of the two preceding shoal-water deltas. It is inferred that the coral-bearing deposits found directly outside the palaeovalley outlet mark the early flooding of the valley, whereas the Gilbert-type delta topset represents the ultimate stage of valley drowning.

This incised valley-fill succession differs from the existing facies models for such depositional systems because it comprises gravelly shoal-water and Gilbert-type deltaic deposits, shows strong wave influence and lacks evidence of tidal activity. The four end-member models for incised valley-fill suggested in literature are discussed in terms of the rates of sediment supply and accommodation development. It is pointed out that the departures of particular field cases from these conceptual models may reveal important information on the system's own specific formative conditions. The valley-fill case described in the paper represents conditions of high sediment supply and a rapid, but stepwise, development of accommodation controlled by the spatio-temporal evolution of normal faults at the rift margin, which overprinted the eustatic signal. Overall, the study adds to a better understanding of the Pleistocene tectonics and palaeogeography of the Corinth Rift margin, and to the spectrum of conceptual models for incised valley-fill architecture.

Paper 2

Gobo, K., Ghinassi, M. and **Nemec, W.**
Gilbert-type deltas recording short-term relative base-level changes: delta-brink morphodynamics and related foreset facies.
Sedimentology (MS in review)

This paper focuses on detailed facies anatomy of the foreset deposits of Gilbert-type deltas to evaluate whether the morphodynamics of delta-brink zone bear on the delta-slope depositional processes. Detailed sedimentological logging was carried out in three Corinthian deltas of different age, size and development stage.

In all these systems, the delta-slope facies abound in deposits of turbidity currents (whether slope collapse-generated brief surges or longer-duration, sustained hyperpycnal flows) and cohesionless debrisflows. Subordinate facies include debrisfall gravel, backset beds and minor tidal deposits. The facies are commonly organized in two distinct assemblages – one dominated by debrisflows (DFA) and the other by turbidites (TFA) – and their occurrence seems to be directly related to the type of brink-zone geometry. DFA assemblages tend to be associated with a sigmoidal brink geometry and are considered to form during relative base-level rise, when the aggrading delta front undergoes frequent collapses due to excessive sediment storage and over-steepening. TFA assemblages are linked to oblique brink geometry and are attributed to intense sediment bypass during a relative base-level fall or stillstand. Such generic link between the delta-front morphodynamic responses to relative base-level changes and the delta-slope sedimentation processes occurs at an advanced stage of delta development. An early-stage bayhead delta appears to be dominated by hyperpycnal flows irrespectively of the short-term low-magnitude relative base-level changes.

The study suggests that the foreset deposits alone may possibly be used to decipher the record of relative base-level changes when the topset-foreset contact is poorly exposed or when the sigmoidal evidence of relative base-level rise was obliterated by fluvial erosion.

Paper 3

Gobo, K., Ghinassi, M. and **Nemec, W.**
Reciprocal changes in foreset to bottomset facies in a Gilbert-type delta: response to short-term changes in base level
Journal of Sedimentary Research (MS in review)

The topic of this paper is a direct sequel of **Paper 2**, with the main focus on depositional processes at the foreset–bottomset transition and their relation to changes in the delta slope regime and brink-zone morphodynamics. This study of the Gilbert-type Ilias delta at the Corinth Rift margin combines observations from two outcrop sections, where the topset–foreset contact and foreset–bottomset transition are conveniently exposed. Outcrop photomosaics and marker bedding surfaces were used to correlate packages of foreset deposits with coeval toeset and bottomset deposits.

Both foreset and toeset-bottomset deposits tend to be organized into debrisflow-dominated (DFA) and turbidite-dominated assemblages (TFA), but show a reverse pattern of reciprocal changes. The DFA assemblages of delta foreset deposits tend to pass downdip into TFA assemblages of delta-foot deposits, whereas foreset TFA assemblages pass downdip into delta-foot DFA assemblages. The bottomset deposits show marked textural bimodality, with alternating fine-grained turbiditic sandstones and mainly clast-supported debrisflow conglomerates. The latter facies dominates in the bottomset DFA assemblages, while also filling chutes extending from the delta slope to its foot zone. The downdip changes from DFA to TFA assemblage are linked to delta-brink sigmoidal architecture, whereas the downdip changes from DFA to TFA are linked to the delta-brink oblique architecture. It is suggested that the excess brink-zone aggradation during base-level rise spawns frequent small debrisflows that 'freeze' mainly on the delta slope (foreset DFA), while predominantly turbidity currents are reaching the delta-foot zone (toeset–bottomset TFA). The relative fall or stillstand of base level intensifies deposition from hyperpycnal flows on the delta slope (foreset TFA), while slope chutes formed by large river floods allow the subsequent transfer to brink- and chute wall-derived debrisflows to the delta-foot zone (toeset–bottomset DFA). The observations indicate that the delta-brink morphodynamic response to short-term changes in relative base level has a major impact on the subaqueous pattern of delta sedimentation processes. The deltaic system's autogenic variability and regional climatic fluctuations inevitably add 'noise' to the facies record of these changes. The study suggests that the reciprocal alternation of TFA and DFA assemblages in delta foreset and toeset–bottomset deposits may potentially be used to decipher the hidden record of short-term relative base-level changes that occurred over the life-span of an ancient delta.

Conclusions and perspective

The research presented in this thesis provides important new insights in the morphodynamic development of Gilbert-type deltas, from the system's bayhead nucleation stage in a tectonically-controlled incised valley (**Paper 1**) to the pattern of its subaqueous depositional processes and facies partitioning during subsequent progradation influenced by relative base-level changes (**Papers 2 & 3**). The main novelty is the recognition of a generic link between the morphodynamics of the delta-brink zone — controlled by the base-level behaviour and reflected in delta-front architecture — and the coeval changes in sedimentary facies of the delta slope, toe and prodelta zone (Fig. 10). The primary signal of system changes deciphered in these Plio–Pleistocene Corinthian deltas is due to the changes in base level, with an inevitable superimposed 'noise' from the secondary signal of delta autogenic variation and probably the allogenic signal of climate seasonality and regional climatic fluctuations.

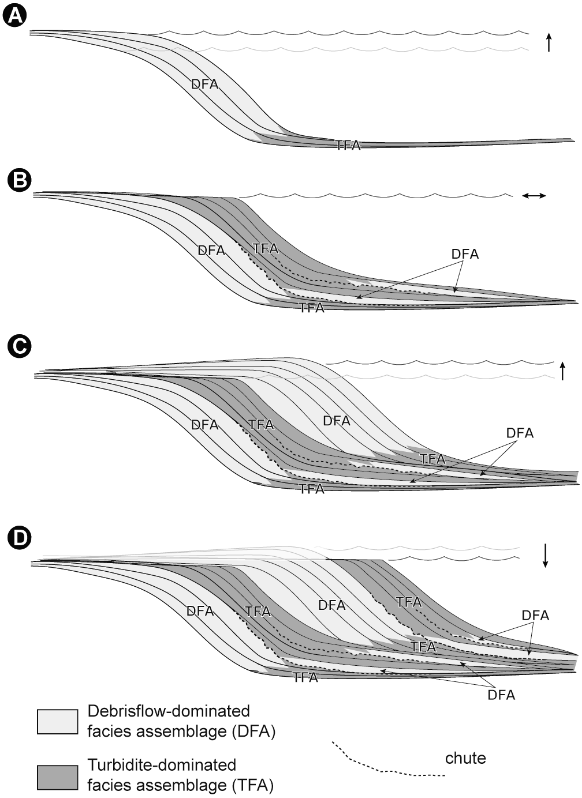

Fig. 10. Schematic cartoon showing the generic link between the morphodynamic responses of delta-brink zone to short-term relative base-level changes and the coeval depositional processes on the delta slope and in its foot zone. See **Papers 2 & 3** for further explanation.

The delta-brink architecture reflects relative base-level changes, but tends to be erased by subsequent incision of the delta-plain fluvial system or is often non-preserved in outcrop sections. The present study points to an attractive possibility for the recognition of such a 'hidden' record of relative base-level changes on the basis of the delta foreset and/or toeset–bottomset facies. The interpretive model suggested by this study thus bears important implications for basin analysis and may serve as a powerful tool for the spatial facies prediction and assessment of heterogeneities in a Gilbert-type deltaic hydrocarbon reservoir (such as the mid-Jurassic Oseberg Fm. in the northern North Sea; Graue et al., 1987).

However, the postulated facies model is tentative and needs to be verified on a wider data basis. Although the evidence of a generic link between the delta-brink architecture (oblique vs. sigmoidal) and coeval foreset facies (TFA vs. DFA assemblages) in the present study is dawn from both valley-confined and open-coast deltaic systems, the number of the cases analysed is very small (**Paper 2**). Likewise, the evidence of reciprocal facies changes in the foreset and toeset-bottomset TFA and DFA assemblages comes from a single case study (**Paper 3**). The research project's results are interesting and highly promising, but obviously require verification and thus invite a new wave of worldwide detailed sedimentological studies of Gilbert-type deltas.

The future high-resolution sedimentological studies should also focus on the distinction of the primary signal of base-level changes from the secondary signal of the delta's own autogenic variability and the allogenic signal of possible climatic fluctuations. This research issue is a challenging task, but is not infeasible in terms of a detailed facies analysis combined with studies of modern Gilbert-type deltas.

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