which were transported via turbiditic and sandy debris flows through fixed feeders across the fault-bounded, conglomerate-lined shelf into the narrow deep SE-NW trending syncline.

Sediments were further funnelled into the basin by a broad, shallow distributary system where the bulk of the sand-grade material was deposited in sheet-like lobe and fringe deposits. Distinct fan geometry and morphology are poorly established and a rather complex superimposition and lateral coalescence of lithofacies and fan components exists. The sediment accumulation pattern varies considerably spatially and temporally with an overall northward shift in depositional locus. Intrabasinal depressions captured turbiditic flows resulting in a locally confined, aggradational depositional style. Minor sediment contributions off the fault-scarp and/or directly off the shelf and/or the Claymore High complexly interfingering with the main turbidite system while the Claymore High represents a barrier on which turbidites onlap, pond or are axially deflected. Lateral migration and local retrogradation of the system is in response to locally decreasing sediment supply and shifting sources caused by differential uplift of the source area while intrabasinal tectonism resulted in localised erosion and sediment-remobilisation.

The S10 interval is best represented by the sand/mud-rich to sand-rich submarine ramp system *sensu* Reading & Richards (1994).

4 RESERVOIR CHARACTERISATION

As most sands in almost all submarine fan environments are originally porous and permeable, sandy depositional lobes *sensu* Mutti & Normark (1987) and related sheet-like sandy deposits provide excellent reservoirs if contiguous with adequate source beds (e.g. Normark *et al.* 1983; Richards & Bowman 1998). They are of great areal extent, tend to have a low percentage of total intergranular matrix and probably have some of the highest initial porosity (28 - 35 %) and permeability (200 - 4000 md) (McLean 1981; Risch *et al.* 1996).

Lobe and related sheet-like deposits do not form homogeneous reservoirs as different studies have shown (e.g. Schuppers 1995; Garland *et al.* 1999). Shales occurring at various scales within reservoirs constitute important barriers or baffles to fluid flow. Thus, for successful reservoir characterisation and hydrocarbon production, it is imperative to possess a detailed knowledge of the distribution of reservoir rocks and especially of their heterogeneities as well as their vertical and lateral geological variations. Much of the lobe character ultimately depends on the availability of sand and shale to a system. A combination of complex processes such as frequency of flow, composition, erosion, burial, compaction and diagenesis that occurred over millions of years fundamentally affect the reservoir, while, in particular, basin floor topography enacts one of the basic controls shaping lobe geometry and stacking pattern (e.g. Reading & Richards 1994).

The qualification of the geological variation of lobe deposits is typically undertaken at different scales, for example, the 3 scales of Mijnssen *et al.*(1993):

i) *large-scale* variation between genetic units, for example lobes, is mainly concerned with geometries and internal configuration of sedimentary environments
ii) *medium-scale* variation within genetic units is concerned with geometries and internal configuration of genetic units (e.g. width/depth ratios of genetic units, and sizes of baffles to flow).
iii) *small-scale* variation due to compositional feature of the rocks is concerned with variation in rock properties caused by texture and composition of rocks, mainly porosity and permeability trends. Cementation and matrix content, for example, play an important role in reservoir reduction. The behaviour of density currents depositing turbidites can impart textural variations and sedimentary structures which contributed to permeability heterogeneity at probe permeameter, core plug and bed-scale.

Each reservoir scale is characterised by specific, intrinsic heterogeneities (Weber 1986). Hydrocarbon recovery greatly depends on good connectivity and interconnectedness, especially in thin reservoirs (Guerillot *et al.* (1992) and thus the classification and quantification of reservoir heterogeneities plays an important role in the quality of production forecast. The scale and orientation of shales as i) boundary shales (the surfaces between zones), ii) intrazone shales (heterogeneities within the zone) and iii) permeable/non-permeable lithotypes form the most important heterogeneities (e.g. Geehan & Underwood 1993).

Furthermore, the production potential may be influenced by faults which can compartmentalize reservoirs and modify depositional continuity (Bryant & Flint 1993), the timing of petroleum migration and burial depth (McLean 1981).

The quantification of geological variations within reservoirs depends on adequate sampling. Clearly, outcrops have the advantage of providing some lateral control allowing for a more thorough analysis of geological variations, but they are lacking the third dimension in horizontal direction. On the other hand, core data present only a billionth of the total reservoir volume, but in combination with seismic data a densely drilled field may provide some 3 D information on the distribution and geometry of the genetic units and heterogeneities (Matheron *et al.* 1987; Fox 1992; Mjinssen *et al.* 1993).

4.1 Lobe deposits of E-Fan, Cingöz Formation

The Cingöz Formation is characterised by a high net sand content, good 4-way stratigraphic and structural closures with the basinal Güvenç shales as proven hydrocarbon source (Satur 1999). The thick sandy lobe successions of the E-Fan provide good reservoir rocks, however, lenticular shale-rich debrites at different stratigraphic level form important barriers to vertical flow. Post depositional faulting further compartmentalizes this reservoir into kilometre-scale blocks. It thus possesses all the qualities of a potentially good hydrocarbon play.

The E-Fan lobe deposits (Lobes A, B, C) are analysed individually under the following aspects:

- small to large-scale reservoir potential excluding microscopic and poro/perm analysis
- small to large-scale heterogeneities
- production aspects

4.1.1 Lobe A

Reservoir and heterogeneities (fig. 4.1):

SCALE	***RESERVOIR***	***HETEROGENEITIES***
SMALL	• vcs to cs sandstone and pebbly sandstone • poorly to moderately sorted • S$_{1-3}$, rare R$_{1-3}$ (Lowe 1982), DWMS, sandy debris flows (*sensu* Shanmugam 1996) • ~ 95 % net sand • 0.6 to 3.0 m thick x > 0.3 km • amalgamated, no shale partings	• localised accumulations of pebble to small cobble-sized clasts, associated with erosive beds
MEDIUM	• 5 – 33 m thick, 600 – 1200 m wide • 96 % net sand • elongate, sheet-like bodies • crude fining-upward	• 1% shale content • rare, inextensive shale beds (0.15 thick x >10 m wide), erosionally cut off • lobes may pass into channeling
LARGE	• mixed shingled-compensational stacking • highly amalgamated • 150 m thick / max width 1200 m, widening downflow • 84 % net sand, 15% conglomerates • crude fining upward	• lateral thinning & increasing shale content • occasional shale-rich debrites along margins • channeling with shale-clast-rich conglomerate

Production aspect:

The sandy, highly amalgamated Lobe A deposits may essentially be regarded as one large flow unit♣ with excellent vertical and horizontal connectivity. No CLTZ-wide barriers to flow developed and only few local

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♣ flow unit are assumed to be laterally and vertically continuous sharing i) similar porosity; ii) similar permeability; iii) similar bedding characteristics (Hearn *et al.* 1984), basically combining sedimentological and petrophysical reservoir characteristics barriers exist. The distribution of reservoir rocks and flow barriers indicates (fig. 4.1) that the best production area would be the central depositional area where only rare linear shale-matrix rich or shale clast-rich conglomerates within the channeling component may form baffles to flow. Towards the lateral margins, reservoir quality becomes relatively poorer due to the development of localised wedge-shaped shale-rich debrites, and thin shale beds. However, their erosional cut-off by succeeding flows and the subsequent amalgamation of sandstone beds ensures good vertical connectivity. The essentially unorganised vertical development throughout especially the lower 80 m suggests good reservoir quality while the gradual fining- and shaling upward into more classical lobe deposits overlying the CLTZ (*see* chapter 2.2) points to overall reservoir reduction. Equally reduced reservoir quality is anticipated in a downcurrent direction where grain size decrease and shale increase probably lead to a higher frequency of laterally persistent shale-rich intervals.

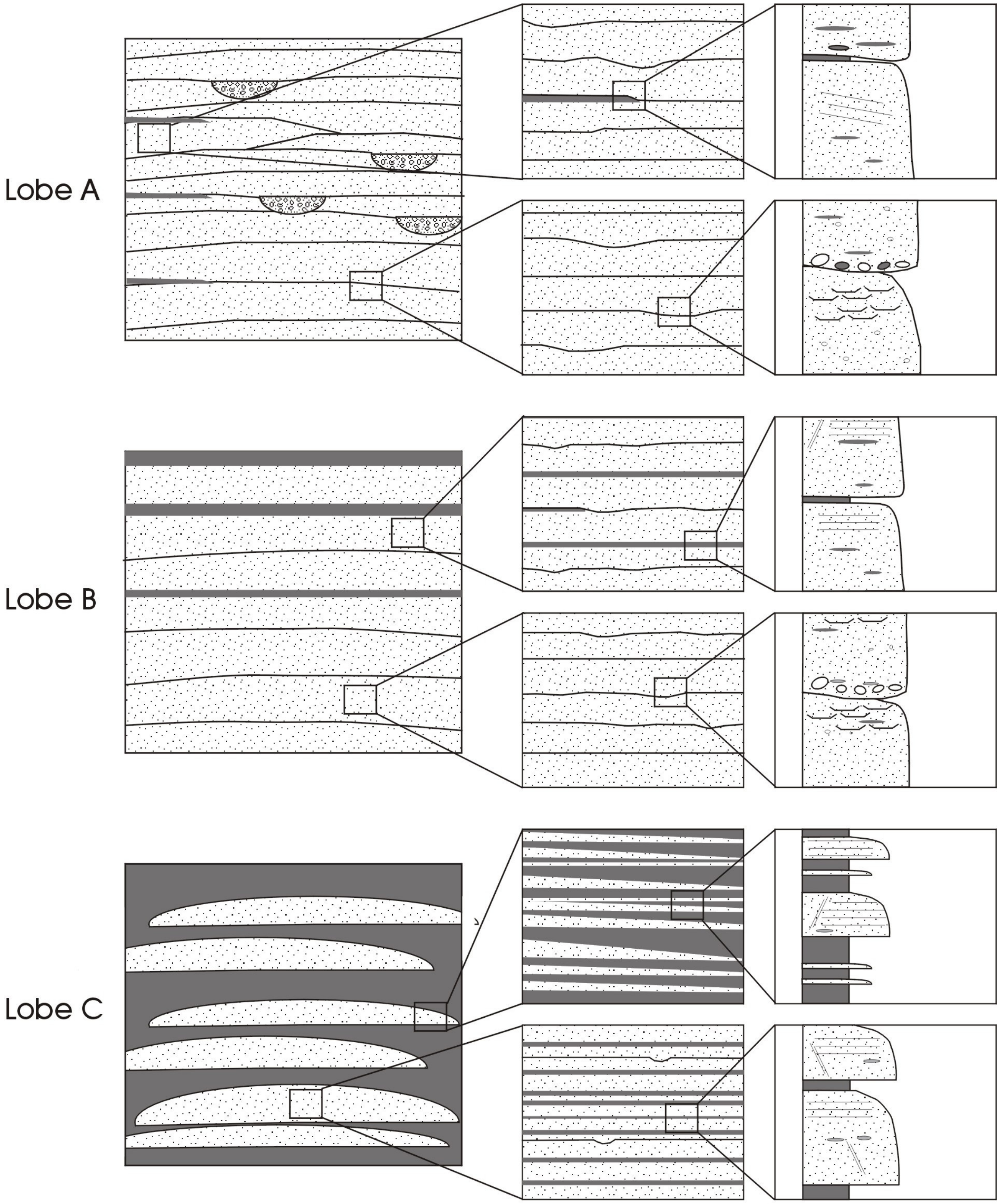


Figure 4.1: Reservoir characterisation of Cingöz lobe deposits at lobe complex-, lobe- and bed-scale.

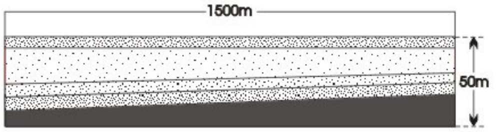
Strong reservoir layering akin to the layer-cake model (fig. 4.2; 70 % Lobe A deposits) with interspersed elements akin to channel-fill or jigsaw model (30 % channeling components) characterises the CLTZ. Potential reservoir compartmentalisation through faulting is probably negligible in this sand-rich environment.

4.1.2 Lobes B

Reservoir and heterogeneities (fig. 4.1):

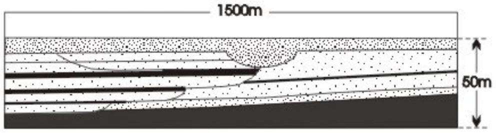
SCALE	*RESERVOIR*	*HETEROGENEITIES*
SMALL	• cs sandstone & pebbly sandstone • moderately sorted • R_3,S_{1-3} (Lowe 1982), DWMS, sandy debris flows (*sensu* Shanmugam 1996) • ~ 95 % net sand • 0.4 - 1.2 m thick / > 1.2 km width • 3-4 m thick composite beds • vertical burrowing	• randomly located clustered shale rip-up clasts • rare, inextensive (0.5 – 2/7 m) mud-lined amalgamation surfaces • discrete shale-clast horizons (> 1 – 10s m) at various levels within beds
MEDIUM	• 8 – 50 m thick, > 1200 m width, > 2.4 – > 4.8 km downcurrent extent • > 95 % net sand • highly amalgamated • elongate, sheet-like bodies • crude fining/thinning-upward	• rare thin (0.5 – 4 cm) shale partings, laterally extensive [absent in lower lobes, towards top increasingly abundant] • overall lateral thinning/fining, shale increase, mostly passing into lobe fringe
LARGE	• 300 m thick, > 3 km width • 100 % net sand [lower part] upward decrease to 95 % • mixed shingled-compensational stacking • lower part, highly amalgamated • crude fining/thinning upward	• upward increase in shale content • upward increase in thickness (2 - 6 m) and abundance of laterally extensive lobe fringe deposits (75 % net sand) • cut by rare, linear distributary channels (80 % net sand, distinct shale partings)

A) LAYER-CAKE RESERVOIR TYPE



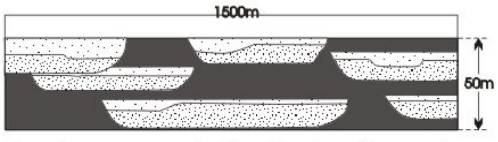
Distinct layering with marked continuity and gradual thickness variation.

B) LAYER-CAKE RESERVOIR TYPE



Different sand bodies fitting together without major gaps. Occasional low permeable zones can occur locally between adjacent or superimposed sand bodies.

C) LABYRINTH RESERVOIR TYPE



Complex arrangements of sand pods and lenses often appearing discontinuous in sections.

Figure 4.2: Basic reservoir types from Weber & Van Geuns (1990).

Production aspect:

The best quality reservoir rock of the sand-rich, stacked proximal Lobe B are formed by the lower, highly amalgamated lobe deposits. The high degree of amalgamation is responsible for creating thick flow units of excellent reservoir properties due to i) the thick, sand-rich homogeneous beds, ii) the general lack of interbedded shales and iii) the great lateral extent of individual beds, composite sandstone units and the individual lobes themselves. The sharp contrast in bed thickness between the sandstone units and the thin-bedded, shale-rich intervals allows for a straightforward zonation. The whole of the lower Lobe B deposits can essentially be regarded as one thick flow unit, while in the middle and upper part, increasingly frequent and laterally extensive lobe fringe and individual shale beds compartementalise at inter- (between) and intra- (within) lobe level (fig. 4.1). The lower net sand lobe fringe deposits due to their finer grain size will result in a lower "plug" permeability while the interbedded shale layers reduce the overall effective vertical permeability (K_{VE}). Bioturbation is not abundant, it may however locally increase the permeability of shale partings and beds. The resultant large-scale layering will effectively confine fluid flow to layer-parallel reservoir zones of sheet-like high net-to-gross units.

The proximal Lobe B complex is akin to a layer-cake reservoir (fig. 4.1), with some isolated, linear distributary channels forming localised baffles to flow with their partially shale-rich deposits. Individual Lobe B bodies and the larger complex are marked by moderately-defined vertical organisation allowing a reasonable prediction of the distribution of high-quality reservoir rocks. The overall thinning-upward trend combined with an upward decrease in amalgamation results in a vertical increase in reservoir compartmentalisation and a pronounced thinning of flow units. In an upstream direction, the Lobe B are probably connected to coarser-grained CLTZ deposits while in a downstream direction, increasing shale breaks between the massive sandstone units and decreasing amalgamation and grain size are expected resulting in an overall thinning of flow units.

Faulting is common in the proximal lobe zone. If non-sealing, they may in fact enhance the reservoir quality by offsetting thin impermeable shales against thick sands thus allowing for greater connectivity within the reservoir (fig. 4.3). Large (> 2 km) well-spacing within the excellent Lobe B reservoir may still ensure good recovery. Localised, wedge-shaped debris flows as observed further to the west of the study area, may potentially form localised barriers to flow.

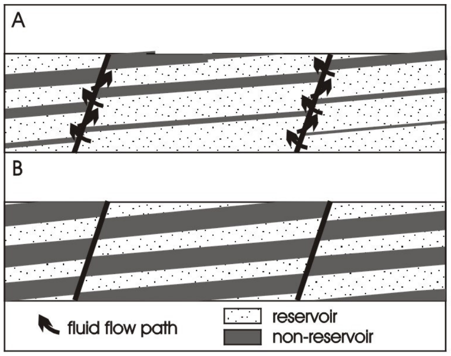


Figure 4.3: Schematic representation of reservoir changes as a result of non-sealing faulting. A: reservoir enhancement due to improved connectivity, e.g. Lobe B deposits. B: reservoir reduction due to reduced connectivity or isolation of reservoir bodies, e.g. Lobe C deposits.

4.1.3 Lobe C

Reservoir and heterogeneities (fig. 4.1):

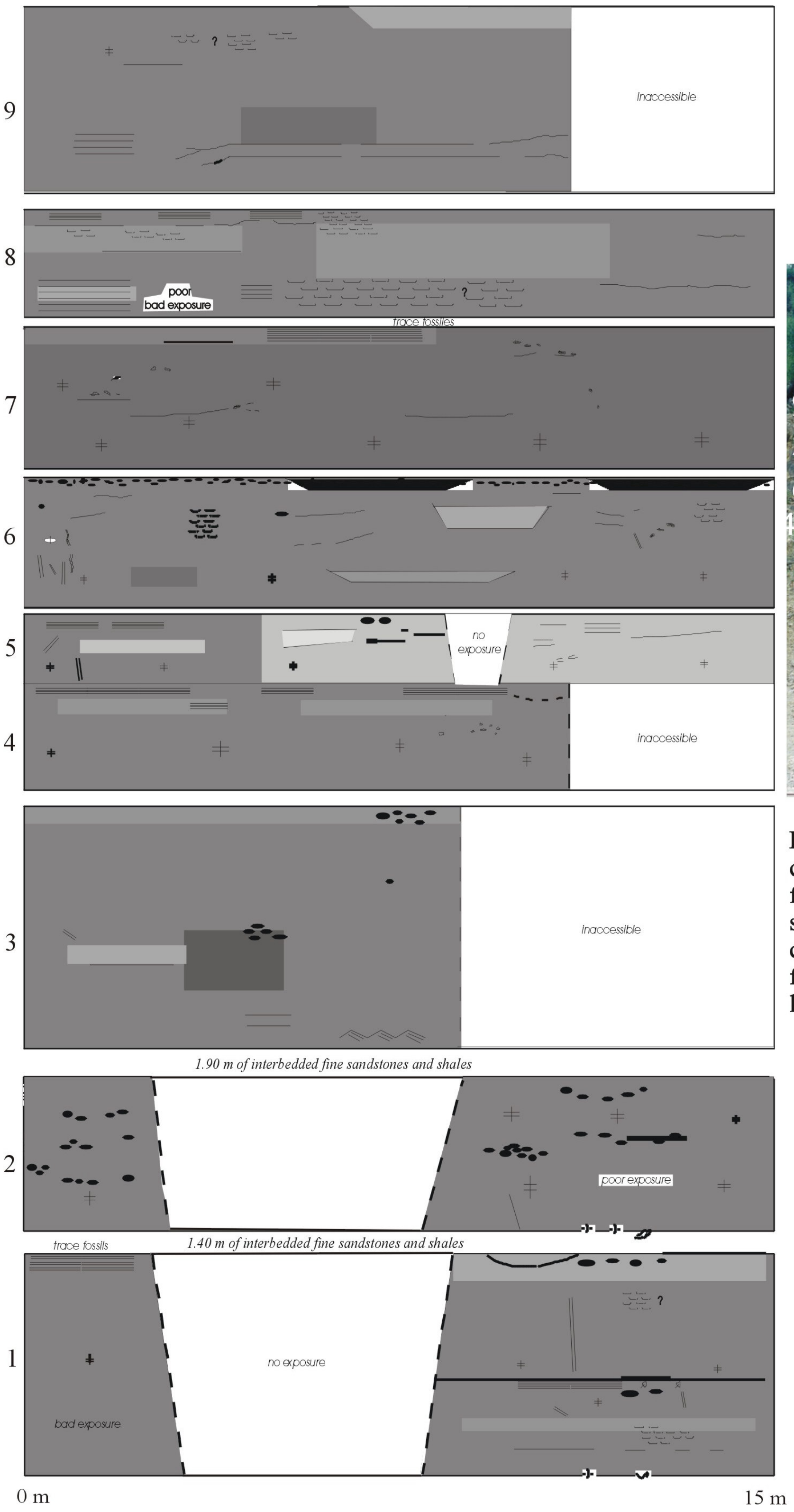
SCALE	***RESERVOIR***	***HETEROGENEITIES***
SMALL	• ms - cs sandstone • moderately - well sorted • S_{1-3} (Lowe 1982), $T_{a-c(d)}$ (Bouma 1962), rare sandy debris flows (*sensu* Shanmugam 1996) • 90 - 100 % net sand • 0.6 - 1.2 m thick / > 0.3 km width • up to 2.5 m thick composite beds • sheet-like • abundant bioturbation	• shale-clast lined amalgamation surfaces or discrete horizons [2-8 cm x >10s m] • inextensive (0.5 - 15 m), shale-lined amalgamation surfaces • localised, clustered shale rip-up clasts [few m^2] • rare mud-lined internal scours
MEDIUM	• 4 – 35 m thick, > 0.3 km width • > 60 to 70 % net sand, max 95 % sand • rare lobe amalgamation • sheet-like, some lobate geometry • well developed asymmetric sequences • lateral thinning/fining	• laterally extensive, thin (2 – 15 cm) shale / fine sand alternations separating sandstones bodies • rare slumped units (max. 1.2 m thick) • lateral shale increase, passing into lobe fringe • vertical separation by lobe fringe and/or interlobe deposits
LARGE	• 800 m thick, > 0.3 km width (outcrop limit) • isolated lobes (marginal/basinward) • some mixed shingled-compensational stacking (central depot area) • net sand < 80 - 95 % (margin – centre) • fining/thinning & shale increase towards margin and basin	• lobes/stacked lobes separated by laterally extensive lobe fringe (60 % net sand) or lenticular interlobe (<50 % net sand) deposits • upward/basinward increase in shale content • localised shale-rich debrites (?) • marginal areas with either onlap, debrites or slumps up to 10s of m thick. • overall fining upward to basin plain deposits

Production aspect:

Individual sandstone beds or amalgamated beds can be regarded as flow units separated by near impermeable fine sand / shale alterations. Internally, little variation in thickness, net sand content and/or sedimentary structures was recorded, which, however, may locally affect vertical fluid flow (fig. 4.4):

i) Thickness variations are largely a function of the size and depth of occasional, shallow scouring.
ii) Scours are shallow and do not erode through shales into underlying sandstone body (e.g. fig. 4.4c)
iii) Grain size profiling shows that most trends are persistent throughout beds, being either normally graded or more often marked by abrupt grain size breaks and rapid fining at top. However, grain sizes may vary laterally with small patches of different grain sizes developing locally (figs. 4.4a: bed 8; 4.4c: bed 2). Subtle amalgamation surfaces indicate that succeeding flows possessed the capacity to erode into predeposited sandstones. Thus individual sandstone beds may be the result of one or more flows.
iv) Dish structures, typically confined to 0.25 to 4 m^2, vary laterally in type, amount and presence, although the reason for this is not fully understood (Stow & Johansson 2000; e.g. figs. 4.4a: beds, 1,8,9; 4.4b: bed 2). They result from pore fluid movement (Nichols *et al.* 1994) and their absence may be due to the final depositional mechanism in high-density turbidites or sandy debris flows or by the rate of sediment supply to and through the basal layer or a combination of these factors. These horizons may be zones of low vertical permeability because clay mineral coatings can effectively plug pore throats while the porosity remains almost unaffected (Hurst & Buller 1984).
v) Highly bioturbated tops and frequent, but irregular spaced burrowing persists. The type and infill of the burrows varies considerably throughout individual beds, however, clay-lined walls and relatively coarser sediment infill are the most common type of infill.
vi) Amalgamation surfaces are subtle. Clay-draped amalgamation surfaces appear to be inextensive (0.5 to 15 m; e.g. fig. 4.4b).
vii) Clustered or discrete, laterally extensive shale clast horizons appear at various, though never basal, levels throughout turbidite beds (figs. 4.4a: beds 2,6; 4.4b: beds 1,3). They mark distinct rheological interfacies within the flow (Postma *et al.* 1988) resulting from freezing or thickening of the inertia flow layer which forces the gliding clast to a progressively higher level within the flow leaving the clasts trapped "suspended" above the base of the resulting turbidite. These fine-grained rip-up clasts and/or low density outsized clasts can complicate the patterns of fluid flow through reservoir rocks (Hughes *et al.* 1995).
viii) Lateral and vertical net-to-gross are largely a function of presence and abundance of shale clasts or shale partings (fig. 4.5)

The laterally extensive shale/fine sand alternations separating individual beds (flow units) result in a strongly layered, laterally extensive, sheet-like reservoir with good horizontal permeabilities but poor to no vertical permeability. Lobe C deposits and the related environments are strongly bioturbated. This may locally lead to enhanced vertical permeability by breaking down shale barriers, however, this has not been observed at outcrop scale. Neither were sand dykes nor scouring of sufficient downward extent to connect with underlying sandstone beds. The central Lobes C possess good overall reservoir quality (larger grain size, higher sand content, high connectivity due to intense burrowing, little interbedded shales). Their well predictable stacking pattern and vertical and lateral trends in grain size and thickness development, point to the thickest, coarsest sandstone beds with fewest shales interbedded in the central depositional area. In a basinward and marginal direction the reservoir quality decreases. These marginal lobes and/or lobe margins possess reasonably good but variable reservoir quality due to smaller grain sizes, lower sand content, thicker interbedded shales. Reservoir quality of the various slope contact relationships are qualified by the change in net sand content. Thus, pinch-out where grain size does not change infers good reservoir quality almost right to the pinch-out limit of sand units (Hurst *et al.* 1999), while onlap (gradual grain size and thickness reduction) and slumping (deformed and chaotic structures) result in declining reservoir potential.



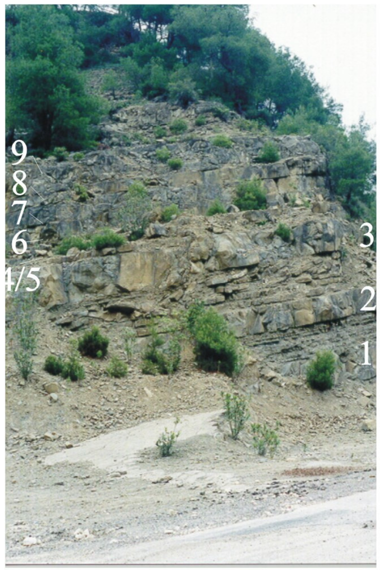
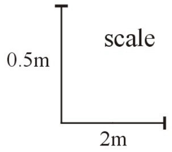


Figure 4.4a: lateral log within central lobe C deposits (m 0.4-13 of fig 2.33/(1) of fig. 2.32). Photograph showing lateral log meters 5-13 of corresponding beds. Interbedded fines are not represented in lateral log. For legend see fig. 4.4b,c.



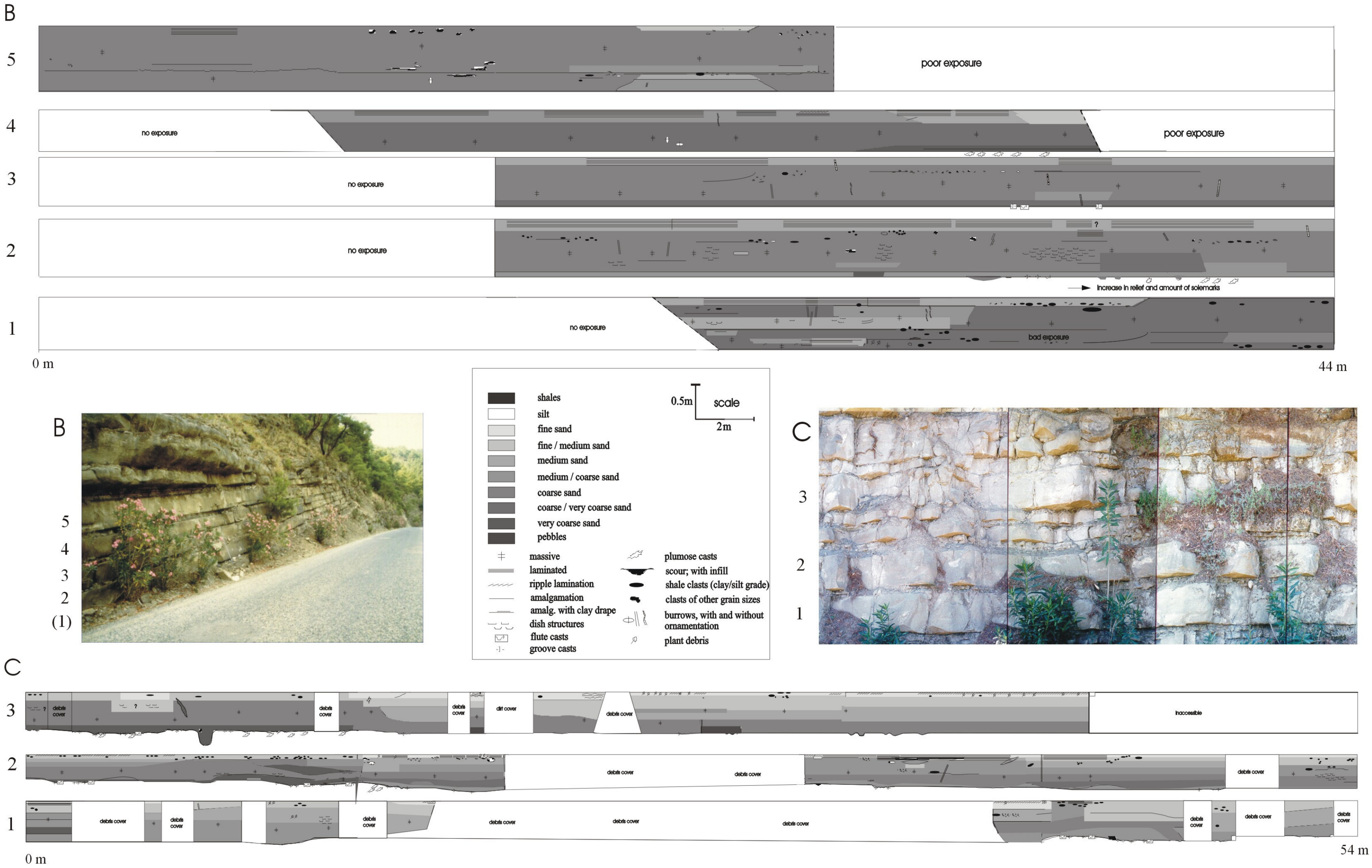


Figure 4.4b,c: Detailed lateral log of selected sandstone beds within central lobe C deposits (B: m 45.15-49.75.5 of (2) of fig. 2.32) and immediately above lobe fringe (C: m 12-14.5 of fig. 2.38; photograph showing lateral log meter 0-13). Bed number 1 of (C) develops laterally into chaotic suit with slump-like structures, probably resulting from incorporation of underlying, semi-lithified sediments into bed #1 flow.

The well sorted, laterally extensive Lobe C deposits are essentially of layer-cake type reservoir, however, with much greater reservoir compartmentalisation than Lobe B deposits due to the greater abundance and thickness of shale-rich deposits (fig. 4.1). Individual lobes are composed of a multitude of relatively thin horizontal flow units which are separated by lower net sand fringe and shale-rich interlobe deposits. If faulting, as occasionally observed in the field, is sufficiently important, it may result in the offset of reservoir lobes against poorer quality lobe fringe or non-reservoir interlobe deposits, strongly compartmentalising the reservoir (fig. 4.3). Interwell correlation will prove to be difficult and for effective hydrocarbon recovery, narrower (<1 – 2 km) well-spacing than in Lobe B deposits is necessary. Considering the growth pattern of the lobes, thin beds will increase in a downdip direction resulting in further reservoir reduction.

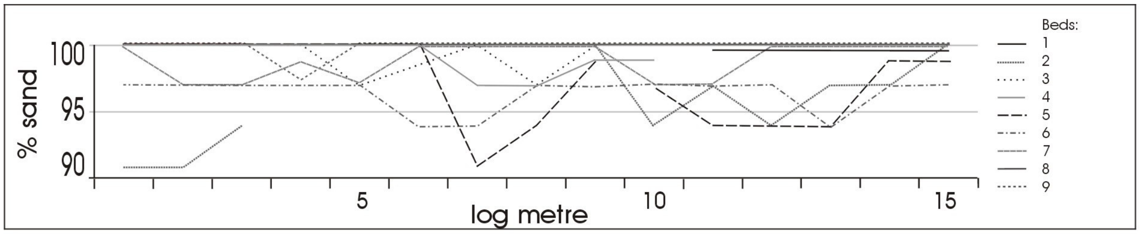


Figure 4.5: diagrammatic representation of net sand content in lateral log (fig. 4.4a). Changes are primarily due to shale clasts nets and thin, inextensive clay-draped amalgamation planes.

4.2 Lobe deposits of the S10 interval, Scapa Sandstone Member

The Scapa field is a structural-stratigraphic trap. The up-dip limit of the reservoir to the NE is by onlap termination onto the Claymore High. To the SW fault closure and/or sand pinch-out into cemented conglomerates associated with the Halibut Shelf boundary fault are present. Limestones and marls of the Valhall Formation form reservoir caprock integrity. The underlying Kimmeridge Clay Formation constitutes the source rock with emplacement thought to have taken place during the Early Tertiary (McGann *et al.* 1991). The Scapa Field reservoir is a good example of diagenesis overriding lithology- and/or component-based reservoir characterisation. The Scapa Sandstone Member has been subdivided into reservoir (SA/SD/SF) and non-reservoir (SB/SC/SE) units which are largely diachronous. The non-reservoir units comprise a higher proportion of heterolithics and shales but also tightly cemented sandstones (Hendry 1994).

SCALE	***RESERVOIR***	***HETEROGENEITIES***	***theoretical PRODUCTION ASPECT***
SMALL	• cs - fs sandstone • clean sandstones • thickness: 0.4 – 0.8 m • DWMS up to 4 m • highly bioturbated tops • GS / S facies	• shale-rich tops • variable calcite cementation and nodule formation	• thin shale breaks bar vertical flow, however, abundant bioturbation may break down structures and reduce those barriers
MEDIUM	• lobe thickness: few 100s m width	• thin shale partings • interbedded SM and SH facies • lateral / distal passing into shale-richer lobe fringe and ultimately fan fringe deposits	• declining reservoir quality towards lobe margins • SM/SH form important barriers to flow
LARGE	• up to 21 m thick • complex lateral and vertical interdigitation of lithofacies / fan components resulting from the largely superimposed localised deposition	• localised debris flows lobes/stacked lobes separated by laterally inextensive shales • linear distributary channels • shale-rich OVB/interlobe, lobe and fan fringe deposits	• no basin-wide barriers of baffles to fluid flow exist • declining reservoir quality towards lobe and field margins

The S10 interval constitutes a sand-rich phase of the SSM, covering nearly the whole of the Scapa syncline. It comprises mostly rocks of the SD reservoir and SE non-reservoir unit. The theoretically good reservoir potential of lobe sandstones (*see below*) is considerably reduced by calcite cementation. A large range of permeabilities were recorded in the major lithofacies resulting from varying degrees of laterally extensive calcite cementation to small, localised calcitic nodule formation (enclosure 1; fig. 3.8).

4.3 Postdepositional changes and reservoir delineation

The elongate and lenticular lobes of the Cingöz Formation and Scapa S10 interval potentially form good stratigraphic traps, however, the delineation of the respective reservoirs is/will be difficult due to the commonly gradual transitions between lobe and interlobe packages. Therefore the recognition and understanding of the growth pattern of lobes is critical to sand prediction and hence hydrocarbon recovery. The orientation of the reservoir bodies and barriers or baffles to flow are an essential part in understanding the reservoir, however, in case of the Cingöz Formation, the lack of 3-D exposures and the essentially time-stratigraphically unconnected study sections, cannot properly resolve sandbody orientation.

Postdepositional changes to a reservoir stem mainly from compaction and diagenesis and are not considered in this study. Differential compaction during burial may affect, for example, the seismic expression of lobe deposits, by preserving or enhancing the overall concave-up lenticular sandbody geometry or result in oversteepened margins. Generally, during burial original porosity may be substantially reduced mechanically at shallow depth or by pressure solution at deeper levels. With burial depth, permeability decreases substantially. The high sand/shale ratio of the Lobe A/B and some of the Lobe C are more likely to retain higher porosities and permeabilities at greater depth than the marginal Lobe C deposits with are interbedded with thicker shale sequences, as shale dewatering during burial can result in early diagenetic cementation. This might only be inhibited by early hydrocarbon migration(McLean 1981). Diagenesis can have an overriding effect on lithologic reservoir characterisation as seen in the Scapa Field. The level of reservoir characterisation carried out on the E-Fan lobe deposits thus provides an indication of the general reservoir geometry and potential for these types of lobe depositional environments.

5 DISSCUSSION OF LOBE DEPOSITS

Depositional lobes are recognised as one of the elemental building blocks of deep-water clastic systems (Mutti & Normark 1987, 1991). They have been identified in a variety of different systems (fig. 5.1) where their development, size and character appear to be fundamentally controlled by the availability of sand to the system (Reading & Richards 1994). Depositional lobes in ancient fans were first defined by Mutti & Ghibaudo (1972) and are located in the outer fan environment (*sensu* Mutti & Ricci Lucchi 1972) as either channel-attached lobes (characterising poorly efficient systems, i.e. high sand : mud ratio) or detached lobes (highly efficient systems: low sand:mud ratio; Mutti & Ricci Lucchi 1975). Diagnostic criteria for their identification in ancient systems were formulated by Mutti & Normark (1987, 1991; *see chapter 1.3.1 for list of criteria*). However, these “classical” lobes (e.g. Marnosa Areneacea: Ricci Lucchi & Valmori 1980; Hecho Group: Mutti & Ricci Lucchi 1975; Mutti 1985b; Macigno Formation: Ghibaudo 1980; Kongsfjord Formation: Pickering 1981) are not common, more often sandbodies with one or more “atypical” depositional lobe characteristics are described, illustrating the dilemma with the rigid *sensu stricto* application. The large-scale lobate geometry, for example, is not readily identified in outcrop and has often been inferred by other field criteria which are primarily based on vertical bed stacking patterns and facies association. However, the analysis of vertical cycles as an instrument to identify depositional environments is among the most controversial ones as are the transport and depositional mechanisms of the deep-water clastics.

The following discussion focuses on these controversial issues as well as the recognition of lobes in the subsurface, limitations of outcrop-subsurface knowledge transfer, the state of deep-water clastic models with respect to lobe deposits and summarises proposed new lobe definitions.

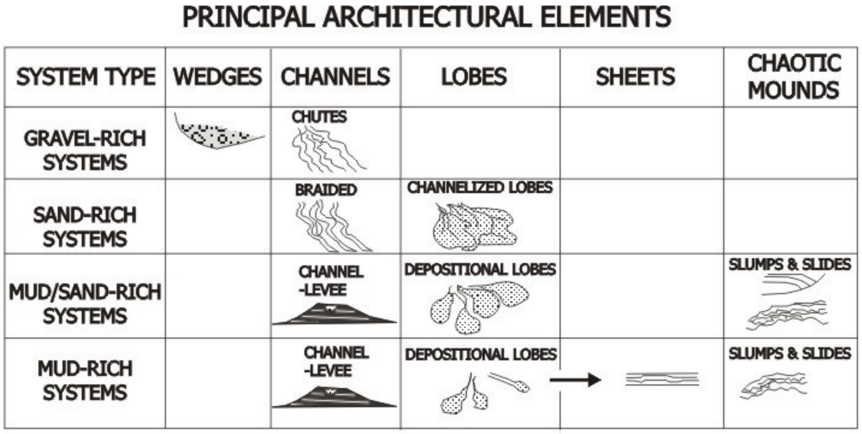


Figure 5.1: Principal architectural elements of deep-marine systems based on outcrop, wireline log and seismic data. Submarine fan, ramp and slope apron systems display a predictable arrangement of architectural elements, which vary between turbidite system class (Richards & Bowman 1998).

5.1 Depositional lobes in ancient systems

5.1.1 Turbidites versus sandy debris flow deposits

Depositional lobes *sensu stricto* are composed of sandstones exhibiting complete classical Bouma sequences (Facies C1, C2 of Mutti & Ricci Lucchi 1972, 1975), which are the product of low density turbidity currents (LDT). In case of turbidity currents containing less fines, coarse grained, graded and internally unstratified divisions of the Bouma sequences dominate and water-escape structures are common (Facies B1; Mutti & Normark 1987). However, normal grading, the fundamental criterion of the turbidite paradigma (Kuenen & Migliorini 1950), was found to be not too common in deep-water clastic systems (e.g. Kneller 1995; Miall 1999). This apparent lack of normally graded Bouma-turbidites and the abundance of inversely graded, massive or normally graded sandstones with floating clasts and quartz granules, has been explained to be the result of high density turbidity currents (HTC; Lowe 1982; Postma 1986; Postma *et al.* 1988), an intermediate between LDT* and SDF* of non-turbulent flow rheology. Kneller's (1995) time-space matrix (fig 1.2) and Kneller & Branney (1995) explore the idea of extremely varied flow behaviour of turbidity currents being responsible for these non-typical attributes. But it is notably Shanmugam *et al.* (1995) and Shanmugam (1996, 2000) who argue against the HDT and related concepts (*see* Shanmugan 1996, 2000 *for detailed discussion on turbidites and sandy debris flows*) suggesting the typical HDT features are in fact the product of SDF (although Pickering *et al.* 1989 suggest that very large SDF may even be turbulent in part). The basic question is if HDT are turbidites or, indeed, sandy debris flows as suggested by Shanmugam (1996; 2000). To date, two schools exist, one advocating the bulk of the deep-sea sediment originating from turbidite (LDT/HDT) deposition (e.g. Hiscott *et al.* 1997; Bouma *et al.* 1997, Lowe 1997; Stow & Mayall 2000), the other stressing the hithero neglected importance of sandy debris flows forming a significant amount of deep-water clastics (e.g. Shanmugam *et al.* 1995; Shanmugam & Moiola 1997; Shanmugam 2000). With the strong HDT paradigma and gradual acceptance of some aspects of the SDF-concept, many workers now believe that a combination of the two processes and other resedimentation processes are responsible for the deposition of deep-water clastics and transformation between the processes is the norm (Stow & Johansson 2000). The latter thus suggest that both HDT and SDF are responsible for forming deep-water massive sands (DWMS) which may develop as lobe and sheet sands forming stacked lobes and distal fan deposits respectively (e.g. North Sea Frigg and Heimdal Fields). Purvis *et al.* (2002) believe at least partial deposition by SDF to be responsible for the massive nature of sands, mounded geometry and lack of classic Bouma sequences of the North Sea Gryphon Field. The lobes of the Miocene Cingöz Formation (*chapter 2*) and the Early Cretaceous Scapa Formation (*chapter 3*) are suggested to result from a combination of LDT/HDT and SDF processes. However, translating the SDF concept *sensu stricto* to the

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* <u>turbidites</u>: Newtonian rheology and turbulent state from which deposition occurs through suspension settling
<u>debris flows</u>: plastic rheology and laminar state from which deposition occurs through freezing (Middelton 1993)

Cingöz lobe deposits (table 5.1), i.e. normally graded deposits with floating clasts and granules represent SDF instead of HDT, very few true turbidites remain, most of the deposit would in fact classify as SDF.

Transport mechanism	Lobe A	Lobe B	Lobe C
turbidites* (LDT/HDT) (NG)	**45**	**59**	**75**
SDF (NG, floating clasts/granules; massive, inversely graded)	**45**	**46**	**58**
"true" turbidites (LDT; NG, Bouma sequence)	**21**	**27**	**44**

Table 5.1:
% normally graded turbidites (LDT/HDT), % SDF of (LDT/HDT) and resulting true turbidites. NG = normally graded
* note that the remaining beds are either massive or inversely graded.

The genetic implication of HDT and SDF transporting mechanisms is of great importance to the petroleum industry as the predicted facies associations, heterogeneities and geometries will be different, affecting reservoir geometry. (Slatt *et al.* 1997; Stow & Johansson 2000):

- Newtonian fluids are more likely to spread laterally than plastic debris flows although SDFs are also capable of producing laterally extensive deposits (e.g. Slatt *et al.* 1997; Shanmugam 2000)
- deposition by settling (LDT) and freezing (SDF) results in different sandbody geometry, the latter may develop debris levees (Shanmugam 2000; Stow & Johansson 2000)
- SDF and HDT may emplace thick units of massive sands in deep-water (Stow & Johansson 2000)
- high frequency LDT and SDF may both develop amalgamated deposits with lateral connectivity and sheet-like geometry (Shanmugam 2000)
- SDF may be more sensitive to basinfloor topography due to their higher density (McCaffrey in Purvis *et al.* 2002)
- SDF can travel long distances (>100 km) on gentle slopes (< 1°) while mud-free sandy turbidity currents are rather short-lived (Schwab *et al.* 1996; Shanmugam 2000, Stow & Johansson 2000)
- SDF may be characterised by a sharp, blocks frontal snout; tension may lead to discontinuous, disconnected frontal sandbodies (Shanmugam *et al.* 1995; Shanmugam 2000).

Presently, the distinction between HDT and SDT is difficult at best and no consensus has yet been reached as far as the dominance of one process over the other is concerned, and the concept of facies-related processes requires further work (Stow & Johansson 2000). Further complicating the turbidite *versus* sandy debris flow debate is the fact that bottom current activity may modify deep-water clastic deposits (e.g. Tertiary Sands Frigg Field/North Sea: Enjolras *et al.* 1986; *for further examples see chapter 2.5.5*), and even produce vertical sequences akin to the Bouma sequence (Shanmugam 2000). However, Mutti & Normark (1987) and Normark *et al*. (1993) suggest that in small basins like the Northern Adana Basin or Scapa Subbasin any significant bottom currents are unlikely to develop.

5.1.2 Vertical sequences – fact or fiction

Mutti & Normark (1987) suggest that depositional lobes are characterised by superposed, small-scale thickening-upward microsequences or compensation cycles. However, the concept of asymmetric vertical bed thickness cycles (or megasequences) as proposed by Mutti & Ricci Lucchi (1972) and Ricci Lucchi (1975b) as an easy, diagnostic tool for the discrimination of depositional environments is obsolete (e.g Miall 1999; Chen & Hiscott 1999a). Amongst mostly random vertical trends dominating fan successions (Anderton 1995), occasional discrete asymmetric vertical bed thickness (and grain size) sequences appear to exist at lobe-scale, but their identification and interpretation in ancient turbidite successions is controversial. Critique is essentially twofold:

- the methodologies employed to discriminate vertical bed thickness trends
- the different types and scales of vertical trends and the responsible mechanisms

Methodologies

In the discrimination of vertical trends subjective, visual appraisal, limited databases (e.g. single section: Lowey 1992; Murray *et al.* 1996), inappropriate test methods (e.g. Fourier analysis testing fixed cyclic periodicities; RUD very sensitive to noise: Murray *et al.* 1996) and incorrectly plotted diagrams (e.g Hiscotts 1981 critique on Ghibaudo's 1980 plotting) produce unreliable results. The general lack of uniformity between workers regarding analysis and interpretation of type of sequences make comparisons between studies difficult and questionable. Lowey (1992), for example, suggests a visual-statistical approach in the identifcation of megasequences, which Murry *et al.* (1996) and Chen & Hiscott (1999a) reject on the basis of not obtaining objective, reproducible data. They latter propose to 1) split a vertical section (one-dimensional data) into segments using a combination of the split-moving window and maximum-likelihood estimation techniques, 2) check potential segment boundaries against field data to exclude potential errors, 3) test for asymmetry (with Kendall's rank, Spearman's rank and Pearson's correlation tests) and 4) test for randomness in order to identify potential symmetric or irregular trends (*see* Chen & Hiscott 1999a *for detailed discussion*). Crucial to their proposed procedure and the application of other statistical methods is their consistent application to large datasets. In the case of the Cingöz and Scapa data, this basic requirement is not fullfilled as sections are very short or contain numerous short breaks. The results have thus to be viewed with caution as already indicated (*chapters 2.4.4 and 3.3.2*). Applying their testing to previously interpreted sections, Chen & Hiscott (1999a) did not find a statistical significance of the discriminated vertical asymmetric trends in identifying the depositional environment.

Mechanisms

Initally, the concept of fan progradation creating thickening/coarsening-upward sequences was paramount (e.g. Mutti & Ricci Lucchi 1972) and Normark *et al.* (1993) still suggest that lobes are commonly characterised by thickening-/coarsening-upward sequences. However, vertical aggradation was soon recognised as dominant mechanism, especially in confined settings (e.g. Ricci Lucchi & Valmori 1980; Ricci Lucchi 1985; Shanmugam & Moiola 1988; Chen & Hiscott 1999a), generating random or thinning/fining-upward cycles (table 5.2: *also see chapter 2.4*). However, to large portions of ancient deep-water clastic systems, any form of regular cyclicity, symmetric or asymmetric, appears to be absent (e.g. Nilsen 1980; Piper & Stow 1991) and Anderton (1995), in fact, advocates the predominance of random

SCALE	PATTERN		MECHANISM	REFERENCE
Microscale [< 10 beds]	asymmetric	thick-up/ coarsen-up	topographic compensation	Mutti & Sonnino (1980) Mutti & Normark (1987)
	symmetric		compensation	Stow & Johansson (2000)
	random		irregular variations in flow volume, concentrations, sorting, grain size, sea floor topography, flow path, nature of obstacle to flow	compilation in Chen & Hiscott (1999a)
Mesoscale [lobe-scale: 10s of m] (megasequences *sensu* Ricci Lucchi 1975b)	asymmetric	thick-up/ coarsen-up	topographic compensation lat. shift of channels & lobes	Mutti (1985b),? Surlyk (1995) MacDonald (1986) Link & Welton (1982)
		thin-up/ fine-up	topographic compensation aggratation retrogradation/lateral shifting	MacDonald (1986) Ricci Lucchi (1985) this study
	random		lobe swithing, upstream channel avulsion, topographic lobe-to-lobe compensation aggratation	Chen & Hiscott (1999a) Ricci Lucchi (1985)

Table 5. 2: Vertical bed thickness trends at intra- and lobe-scale and their interpretation from selected references.

processes, generating a great number of vertical successions[♦]. These are more likely to relate to stable and unstable areas within a fan system. Vertical successions in lobe deposits result from a complex combination of allocyclic and autocyclic mechansism which control deposition in the distal fan (Normark & Piper 1991). Irregular time, space and magnitude of flow trigger (Einsele & Ricken 1991), flow behaviour of differently composed flows, i.e. downcurrent flow expansion on lobes of mixed or sandy flows while large sand flows may initially erode rather than deposit (Savoye & Piper 1990), topographic compensation (e.g. Mutti & Sonnino 1981; Mutti *et al.* 1994), aggradation etc. result in a variety of micro-scale (m-scale) bed thickness patterns. At lobe-scale, asymmetric sequences are commonly related either to progressive lobe progradation, retrogradation in response to changing sediment input and/or sea-level changes and/or lateral migration or as fining upward and/or random organisation implying aggradation (table 5.2).

5.1.3 Geometries – to be or not to be

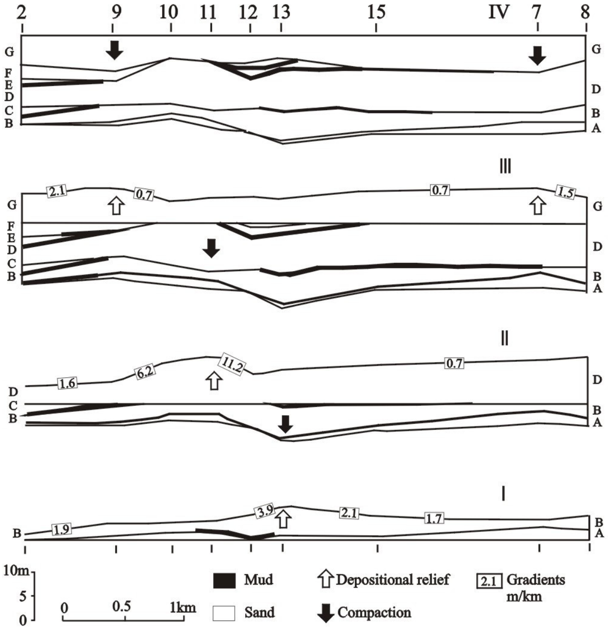

Figure 5.2: Internal stacking pattern of a sandstone body (lobe) deposited in a distal depositional zone of a large Type I system (Miocene Laga Formation, northern Apennines). Note effects of both compensation and compaction on the geometry of individual sandstone beds (from Mutti *et al.* 1994).

All standard models suggest a diagnostic lobate geometry for depositional lobes (e.g. Mutti & Ricci Lucchi 1972, 1975; Stow 1985a; Reading & Richards 1994; Bouma 2000). However, the architecture of deep-water clastic systems in restricted basin settings differs considerably from open deep-water basins and none of these models take into account the modifying effects of basin configuration and underlying seafloor topography which can fundamentally affect the shape, dimension and stacking pattern of lobe deposits (e.g. Normark *et al.* 1993; Reading 1991; Reading & Richards 1994). Thus very few field studies exist where lobate geometries are in fact recorded by either mounded cross-section (e.g. Lauge Koch Land system: Surlyk 1995; limited evidence Cingöz Lobe C) or detailed correlation patterns across 10s of km (fig. 5.2; Mutti *et al.* 1994, Ricci Lucchi 1995). Advocating a strict generic application of the term "lobe" itself (plan view lobate geometry/externally mounded), Normark *et al.* (1993) suggest that the majority of lobe deposits can be described with the sufficiently broad terms: sheet-like, mounded, unconfined and confined. Thus deposits that comprise the lobe element can include:

- sheet-like bodies that in some cases have virtual basinwide extent (e.g. Macigno Formation: Ghibaudo 1980; Hecho Group: Mutti 1985b)
- slightly mounded bodies that can occur at the terminus of basin margin channels (e.g. Lauge Koch Land system: Surlyk 1995; Marnoso-Arenacea Formation/inner Basin, pre-Contessa [lenticular/strongly elongate/wedging] Ricci Lucchi & Valmori 1980; Cingöz Lobe C, Scapa S10 lobes; Kongsfjord Formation: Pickering 1981; Cingöz W-Fan [fig. 5.3] Satur 1999, Satur *et al.* 2000)
- confined bodies that formed as the fill of a variety of both structural and erosional depressions (e.g. Arakinthos sandstone: Schuppers 1995; Lobe A/B: Cingöz E-Fan, Scapa S10 lobes; 'depositional tongues' Cingöz W-Fan [fig. 5.3] Satur 1999, Satur *et al.* 2000; backfilling channel geometries: Mutti & Normark 1991; Normark *et al.* (1993), e.g. lower Lobe A deposits: Cingöz E-Fan).

Many of the documented lobe deposits developed in confined basins. Basin margin or intrabasinal confinement can lead to i) maintaining flow competence over long distances (e.g. Scapa S10 lobes; Normark

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[♦] i.e. ***uniform***: repetion of same process, ***sequence***: progressive change / asymmetric cycles, ***cycles***: patterns changing one way or another: e.g. symmetric cycles, ***chaotic***: random organisation / no patterns can be recognised

& Piper 1991) and/or ii) flow deflection (e.g. E-Fan; Marnoso-Arenacea/Italy: Ricci Lucchi 1981, 1985; Miocene Turbidite Systems/San Joaquin Basin: Nilsen *et al.* 2002; Annot Sandstone/France: Kneller & McCaffrey 1999; Sinclair 2000; Northern Area Claymore: Kane *et al.* 2002) and iii) in localised depositional thickening (e.g. Cingöz Lobe C; Marnoso-Arenacea/Italy: Ricci Lucchi 1981; Gryphon Field/North Sea: Purvis *et al.* 2002; Monterey & Delgarda Fans/offshore California: Wilde *et al.* 1985). Confinement also has a fundamental impact on the stacking and aggradational pattern (fig. 5.2). The highly amalgamated Cingöz Lobe A and B deposits, for example, form thick successions of amalgamated, aggradationally and/or offset stacked lobes with a near negligible amount of fines interbedded. In case of the Cingöz lobes, the fundamental controls appear to be the availability of sand and shale to the system and deposition in a confined space.

Mobilisation by syn- to postdepositional processes can further modify lobe geometry such as sand remobilisation and injection (e.g. Shanmugam *et al.* 1995; Shanmugam 2000; Purvis *et al.* 2002) or extreme differential compaction creating oversteepened, mould-like geometries (Heritier *et al.* 1979; Stow & Johansson 2000).

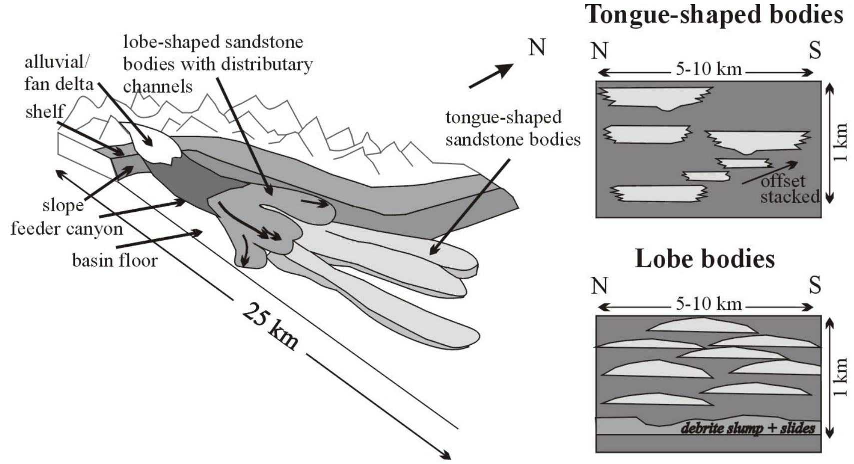

Fig. 5.3: Evolution of the western sector of the deep-water clastic system as sea-level rose in the Lower to Middle Miocene western area of the Cingöz Fan (W-Fan). An alluvial fan/fan delta feeds into the canyon during the early stages of development. The canyon bypasses the contemporaneous shallow marine carbonate shelf. During maximum progradation, the canyon restricts lateral deposition and low sinuousity tongues extend downdip on the basin floor. Later sand lobes with distributary channels develop during retrogradation of the fan. Characteristic sandstone geometry of tongue and lobe-shaped depositional bodies. Compensation cycles and stacking occur within the sheet-like beds of the tongue-shaped bodies. The lobes are composed of laterally thinning and thickening beds that form 30-50 m thick, siltstone and sandstone dominated packages. (From Satur *et al.* 2000)

5.2 Lobes in the subsurface

Mitchum (1985) first related mounded seismic expression with internal bidirectionally downlapping reflections within the lower fan sub-environment to sheetlike lobe sandstones in accordance with the sequence stratigraphic model. And although modern 3-D seismic is able to resolve sandbody geometries within reservoirs revealing stacking patterns and planform geometry (Mitchum *et al.* 1993), it is the combined use of seismic and borehole data which allows a comprehensive analysis of the depositional environments and architectural attributes. Hewlett & Jordan (1993), for example, present one of the first published studies that integrate core data with well logs and multifold seismic, thereby clearly distinguishing individual channel and lobe facies (non-channelized, sheetlike deposits), while Garland *et al.* (1999) were able to recognise depositional lobes in the Miller Field / North Sea. However, lobe deposits do not always appear to be of lobate geometries when interpreted on seismic (fig. 5.4; Pink Reservoir/Gulf of Mexico: Chapin *et al.* 1996), reflecting the strong influence of predepositional topography, depositional mounding, differential compaction and lateral coalescing of deposition on geometries (Garland *et al.* 1999).

Without the aid of seismic, subsurface interpretation relies heavily on the interpretation of single vertical sequences (e.g. individual wells). The recognition of genetic facies associations is important for environmental interpretation (Byant & Flint (1993) and bed thickness measurements and especially the determination of the hierarchically significant bed boundaries are an essential criteria for determining sandbody geometry (Reading 1996; Hurst *et al.* 1999).

5.3 Outcrop versus subsurface data: opportunities and limitations

Outcrop data serve as analogues for subsurface systems with the aim to grasp their potential complexity in order to enhance reservoir characterisation and ultimately hydrocarbon recovery. Purvis *et al.* (2002) demonstrate that simple 1:1 translation of outcrop data may not adequetely represent a complex subsurface system and that sometimes novel approaches are needed. Modelling the Balder reservoir sands of the Gryphon Field / North Sea, they utilised a combination of the Tabernas / Spain and Jackfork Group / USA representing different stages of the field. As with this example and all other knowledge transfer from outcrop to subsurface or modern to ancient systems, one has to be aware of the strengths and limitations of each data set.

a) data sets

Outcrop analysis

It is evident that the lateral extent of outcrops, though limited through tilting formations and outcrop size, allows for a thorough analysis of the depositional environment thus providing valuable information on deep-water clastic systems (Mutti & Normark 1987). With the description of bedding surface hierarchies (Allen 1980), the move from a series of laterally correlated to 1-D vertical sections to 2-D descriptions was taken, however, crucial 3rd dimension in a horizontal direction is lacking mostly due to inadequate exposure (Hurst *et al.* 1999). Detailed mapping and stratigraphic analysis of well-exposed sections, however, may provide some information on the extent and shape of deposits (Mutti & Normark 1987).

Subsurface analysis

In the ideal case, subsurface analysis can draw on both borehole (core and wireline) and seismic data. Although boreholes provide only a billionth of the total reservoir volume, they permit a very detailed description of the reservoir through interpretation of the depositional environment and providing rock property data (Fox 1992). It is imperative to calibrate wireline data with cores. Interwell correlation based on borehole data is difficult at best, mostly operating under severe simplifications (*see below*). Seismic, in contrast, does provide information at interwell scale and modern3-D seismic and/or a densely drilled fields may provide some 3 D information on the distribution, stacking pattern and geometry of the genetic units and heterogeneities (Matheron *et al.* 1987; Mijnssen *et al.* 1993; Mitchum *et al.* 1993).

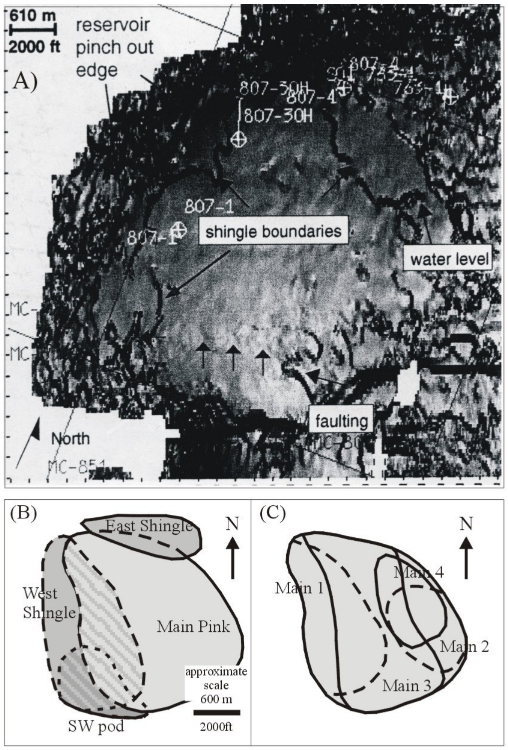

Figure 5.4: A) Seismic dip map, showing some stratigraphic and structural features of Main Pink Reservoir, Gulf of Mexico. Dark gray = high local gradient, light gray = low local gradient. B) Schematic, plan view drawing of four principal sand bodies of the Simple Model. C) Smaller-scale shingles within the Main Pink in the Complex Model. (From Chapin *et al.* 1996)

b) knowledge transfer and limitations

Scale of observation

Outcrop and subsurface data provide different types of data gathered at different scales. Lobe deposits described from outcrop have lithologic significance, whereas lobes described on multichannel seismic reflection or side-looking sonar data are strictly a geometric description unless further data indicates their depositonal lobe character (e.g. Hewlett & Jordan 1993; Garland *et al.* 1999). In order to produce useful comparisions between geological features in deep-water systems it is imperative that these are made at similar spatial and temporal scales and their interpretations should be constrained within an accurate stratigraphic framework (Mutti & Normark 1987). Although the actual lobe deposits of the Cingöz

Formation and Scapa Sandstone Member are nearly of similar scales (i.e. thickness), the temporal and spatial evolution of the two systems differ fundamentally.

Scaling

In the subsurface upscaling, from, selected small-scale sedimentary key features that in turn are diagnostic of larger-scale geometric features limits their value in reservoir characterisation. Particularly data such as permeabilities and porosities which represent the properties of the immediate surrounding of the wells (micro-scale) are, with severe simplifications, upscaled to meso- and mega-scale and used for interwell correlation (Mijssen *et al.* 1993). Hurst *etal.* (1999) propose the reverse, to downscale mapped or seismically detectable features to interwell-scale packages ever mindfull of the underlying paleotopography. They believe that once these features are constrained, modelling will result in a better reflection of the reservoir including its smaller-scale characteristics.

Translating the detailed outcrop study (Lobe A/B/C) in terms of heterogeneities to an imaginary core, fundamentally different results would be expected for upscaling. The discontinuous shale-draped amalgamation planes of the Lobe C may be overemphasised to represent continuous shale-barriers because of the overall "shale-rich" nature of the deposits while the paucity of shales in Lobe B might lead to underestimating the proven lateral extend, i.e. erosional cut-off as observed in Lobe A.

Bounding surfaces

Introduced by Allen (1983) for fluvial deposits, the concept of bounding surfaces has been translated to channelized deep-water clastic deposits (e.g. Pickering *et al.* 1995). The importance of the scheme is that it reflects changes in depositional pattern. It assumes that similar architecutral elements (or building blocks) of ancient and modern systems are comparable based on facies, geometry and bounding surface hierarchy through plan and/or sectional analysis. Hurst *et al.* (1999) suggest that this approach already allows for enhanced comparison between outcrop and subsurface data.

Correlations

In outcrop as well as in subsurface correlations rely on biostratigraphical data, correlatable marker horizons, pressure data, the application of submarine fan models and seismic data. However, high sedimentation rates in sand-rich systems may prevent detailed biostratigraphic correlation patterns (e.g. E-Fan, Cingöz Formation), while in the case of the Scapa S10 interval, biostratigraphy provides the only viable source of interwell correlation. Also, marker beds prove to be only of local significance (S10 interval) or are absent (E-Fan). The application of wireline data for subsurface systems is equally limited (*see above*).

Bed thickness is generally an unreliable characteristic for interwell correlation. Hurst *et al*. (1999) found that individual beds and bed packages display thickness variations driven by offset-stacking over distances > 100 m and would thus be inadequate for interwell correlation with typical well spacing of 0.7 to 1 km. They propose the use of thicker composite units for correlation which can be traced and identified over kms. Mutti *et al*. (1994) suggest that high-resolution correlation patterns are possible in deep-water clastic systems based on high-frequency cyclic stacking patterns, e.g. cyclic stacking pattern of Oligocene Ranzano Sandstone/Northern Apennines.

5.4 Lobes - a fundamental element in models

Results from COMFAN I (Bouma 1983) revealed that modern and ancient fan systems are highly dynamic and complex features. The initial vision of an all-encompasing model with fixed fan segments such as inner, middle and outer fan (e.g. Mutti & Ricci Lucchi 1972; Walker 1978; Shanmugam & Moiola, 1988) proved to be too simplistic and was subsequently abandoned (Normark 1991; Walker 1992; Miall 1999). However, the lobe element, including sheetlike, mounded and confined non-channelized deposits, continues to be recognised as a fundamental deep-water clastic element (fig. 5.1; e.g. Stow 1985a; Mutti & Normark 1987, 1991; Reading & Richards 1994; Richards *et al.* 1998; Bouma 2001), where the formation of lobes is requiring relatively stable channels to focus multiple flows onto specific sites in the basin (Galloway 1998). However, Shanmugam (2000) criticizes that fan models comprising channels and lobes are all too simplistic and continue to dominate deep-water sedimentology and sequence stratigraphy. Shanmugam's (2000) critique may be somewhat justified as lobe elements are well documented in ancient systems on which many models are based but in modern systems they are still largely unknown (Mutti & Normark 1991), which partly stems from the difficulty of properly sampling modern sandy deposits. And while modern systems basically represent a static snap-shot of the present, ancient systems cover a significant time and evolutionary span and may consequently be more complex. Nevertheless, small, sand-rich fans are very common and form the majority of outcrop studies and in subsurface hydrocarbon exploration. One may suspect that "this results from greater economic interest or better preservation potential for these fans, but it probably does reflect their importance as a depositional environment" (Kenyon *et al.* 2002).

Deep-water clastic systems and the lobe element are controlled in their development by many factors including the basin size and configuration, amount and type of sediment avialable for resedimentation processes, rates of deposition, (frequency and volume of gravity flows), local tectonic control, bottom current activity, and relative sea level variations (e.g. *chapter 2.5*; Normark *et al.* 1993). Each system is governed by a combination of these and other factors resulting in unique facies characteristics, internal stacking patterns and types of geometry of, e.g. the lobe element, which may vary greatly between systems. Embracing this variety with broader definitions to include hitherto non-typical lobe deposits is suggested (*see below*; Normark *et al.* 1993).

In modern and subsurface systems, lobes are a decidedly geometric feature. Recognition of lobes in the subsurfaces is aided by the sequence stratigraphic concept as it provides the base for linking mounded seismic facies with bidirectionally downlapping reflectors with sheet-like turbidite deposits (Mitchum 1985; Shanmugam 2000). The sequence stratigraphic fan model is particulary relevant to seismic stratigraphy as seismic tends to reflect chronostratigraphic boundaries rather than lithostratigraphic units (Bryant & Flint 1993). The sequence stratigraphic model feeds on the central assumption that sedimentation increases during relative sea-level lowstand and many researchers associate the maximum depositional activity with the late phase of the sea level lowering and the beginning of a transgressive systems tract (e.g. Kolla & Perlmutter 1993). However, many recent studies have shown that in tectonically active basin, with narrow shelfs and direct connection with the hinterland via incised canyons, sea level variations may be of lesser significance (e.g. Cingöz Formation, Scapa Sandstone Member; *chapter 2.5.2*). Typically, the base of channel incision is considered to be a major timeline in sequence stratigraphy, however, Cronin *et al.* (1998) demonstrate that in the Campodarbe Group, the major phase of basin reorganisation is related to slump and debris flow deposition and suggest that, contrary to popular believe, sandy channeling presents a period of relative quiescence. This demonstrates that no simple relationships exist between sea level and deposition in deep-water clastic systems, limiting the application of the sequence stratigraphic concept.

5.5 Lobes or what?

Like other studies before, this study has shown that the term depositional lobe *sensu stricto* is too restricted to reflect the variety of laterally extensive, non-channelized sand deposits observed in deep-water clastic systems. While the majority of criteria appear to fit, fundamental differences were recorded where geometry and vertical sequences are concerned. In the last decade it has become clear that a more embracing *sensu lato* definition is needed to adequately reflect the variety of documented, non-typical lobes. In a first step, Normark *et al.* (1993) formulated a broader definition which enables to include the majority of the documented non-channelized, sandy deep-water clastic deposits in the lobe elements such as sheetlike, mounded, unconfined, confined deposits (*see chapter 5.2.3*).

In their models, Reading & Richards (1994) and Richards *et al.* (1994) differentiate between channelized

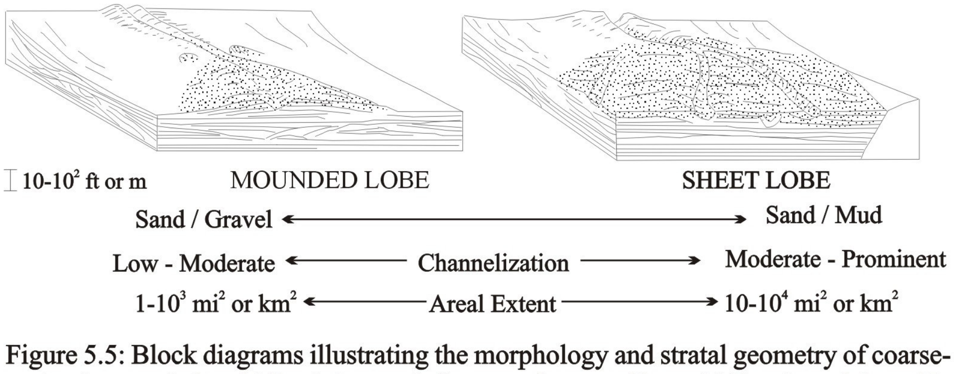

Figure 5.5: Block diagrams illustrating the morphology and stratal geometry of coarse-grained mounded turbidite lobes and finer sand to muddy turbidite sheet lobes. No horizontal scale. (From Galloway & Hobday 1996).

and depositional lobe and sheet deposits. Channelized lobes have been described in modern and ancient systems, for example the depositional lobes of the Mississippi, which are essentially made up of channelized, laterally less extensive sand deposits (Schwab *et al.* 1996) or the channelized lobe of the upper Ebro fan of Nelson *et al.* (1985), which Shanmugam & Moiola (1991) interpret to represent a channel-levee complex. The Lobe A and B of the E-Fan Cingöz Formation display some degree of channeling which differs greatly from the above examples, while the Scapa S10 lobes may represent a "hybrid" model where structural confinement leads to prolonged flow competence and relatively distal channeling in connection with overall lobe deposition. Galloway & Hobday (1996) suggest that grain size is a fundamental control in the appearance of the lobe, coarser lobes are mounded and contain less channeling while finer-grained lobes are of sheetlike geometry and with some channeling (fig. 5.5); while Reading & Richards (1994) and Richards *et al*. (1998) propose the opposite (fig. 5.1). Their sheets and lobes are differentiated based on sand content (sheets: < 30 %; lobes: 30 – 70 %) and geometry.

The recognition of depositional lobes *sensu lato* can be carried out by various means. In outcrop they may simply be defined as set of unchannelized sandstone bodies located in the proximal to distal fan environment which are fed by channelized flows from adjacent basin margin areas and/or by sheet flows directly derived from large shelf edge failures (Ghibaudo 1980, Normark *et al.* 1993). Careful facies analysis provides further information on the nature of the lobe deposits and Shanmugam (2000) cautions to keep depositional processes in mind when carrying out environmental interpetations. Larger-scale (> 100s of m) mapping can help reveal the sandbody geometry. The documentation of the latter in conjunction with the stacking pattern are recognised as critical in characterisation of any architectural element (Stow & Mayall 2000). Chen & Hiscott (1999b) advocate the use of statistically determined degree of sandbed clustering as an additional tool for discrimination. They found lobe deposits to be characterised by a moderate clustering of bed thickness, grain size and sandstone percentage, inferred by a medium Hurst *K* and a moderate departure from the mean value of *K* for random sequences. Hurst *K is* an estimator of the degree of clustering of high and low values or thin and thick beds.

Following this discussion, depositional lobes *sensu lato* or the lobe element can be described as:

- laterally extensive, non-channelized, sandy deep-water clastics
- in proximal locations or confined settings, some degree of channeling may be present
- geometries range from sheetlike, mounded, confined to unconfined (Normark *et al.* 1993)
- transport and depositional mechanisms range from low density (LDT) to high density (HDT) turbidity currents and sandy debris flows (SDF) resulting in a suite of graded, non-graded, inversely graded and massive primarily sandy deposits (e.g. Stow & Johansson 2000; Shanmugam 2000)
- individual or compound beds may range in bed thicknesses from thin- to thick-bedded and in sand-rich systems to megabeds or DWMS (*sensu* Stow & Johannson 2000)
- bed amalgamation, shallow scouring and floating clasts appear to be common
- vertical sequences are not diagnostic of the depositional environment. At micro- to mega-scale they may range from distinctly asymmetric to random generated by a variety of auto- or allocyclic mechanisms
- characterised by moderate sand bed clustering (Chen & Hiscott 1999b)
- much of the lobe character is a direct result of the controlling mechanisms and of the availibility of sand to the basin.

6 CONCLUSION AND FURTHER WORK

The study of the non-channelized sand lobe element has shown that lobe deposits are characterised by a range of features which do not conform with the *sensu stricto* definition of Mutti & Normark (1987, 1991). Studying lobe deposits in outcrop enhanced the understanding of potential controlling factors on the lobe development of the S10 lobes, and although the Miocene Cingöz Formation and the E-Cretaceous Scapa Sandstone Member share some broad characteristics, i.e. tectonically controlled deposition during overall transgression, the scale and temporal differences make the Cingöz Formation (E-Fan) an unsuitable analogue for the Scapa Formation (S10 interval).

I. Depositional lobes *sensu lato* can be defined as laterally extensive, non-channelized sandy deep-water clastic deposits resulting from LDT/HDT and SDF processes. In proximal or confined settings, some degree of channeling may be present. They are of sheet-like, mounded, unconfined and/or confined geometry. Diagnostic vertical sequences do not exist, however, occasional symmetric or asymmetric sequences may result from a variety of auto- and/or allocyclic mechanisms. Moderate sandbed clustering may be a statistically diagnostic criteria. The unique character of a depositonal lobe depends largely on the controlling mechanisms (e.g. sand:mud ratio, tectonic setting, sea level changes, rate and type of sediment supply) governing the respective system and on the availability of sand to the system.

E-Fan, Cingöz Formation:

II. The E-Fan of the Mid-Miocene Cingöz Formation (southern Turkey) represents a regressive, extremly sand-rich, multi-sourced deep-water clastic system deposited in a triple junction escape basin sourced from the emerging Tauride Orogen.

III. Time-stratigraphic changes saw the E-Fan system evolve from a gravel-dominated system during late? Burdigalian to a sand-dominated system in late Burdigalian – Langhian times and from a type II to type I ? system *sensu* Mutti (1985a), probably resulting from progessive sea-level rise and denudation of the hinterland. The changing spatial and temporal distribution and the character of the resedimented deposits points to tectonism as the fundamental mechanism controlling the sediment supply pattern and the depositional geometry of the fan and its building blocks. Locally enhanced deposition, (western-) lateral restricted dispersal and the apparent eastern deflection of the E-Fan are the most apparent results. The overall retrogradation of the E-Fan is driven by the rising sea level and progressive denudation of the Taurus orogen.

IV. During the sandy growth stage, the bulk of the sand accumulated in laterally extensive, thick, coarse-grained, sheet-like bodies of channel-lobe transition (Lobe A), proximal (Lobe B) and distal (Lobe C) depositional zones. Lobes A and B do not fit the classical lobe definition *sensu* Mutti & Normark (1987, 1991), while Lobes C are more akin to it. The size, geometry and vertical stacking of the lobes reflect to some degree their restricted spatial, aggradational development. Unique component associations characterise the various depositional environments, with some degree of channeling characterising the proximally located lobes. Conspicuous downcurrent changes involve a decrease in the net sand content, an apparent increase in internal organisation. Conspicuous fining upward at lobe and system scale reflect the gradually rising sea level, while sporadic phases of progradation and/or coarse clastic sediment supply, suggest that a combination of higher frequency sea-level fluctuations and tectonism control lobe development. Lobe stacking becomes increasingly less common.

V. The macro- and megascopic reservoir characterisation of the Cingöz lobe deposits clearly shows their interest as exploration target due their great areal extend, the overall high net sand content and the extremly good vertical and lateral connectivity. Flow barriers, such as shale layers, are absent in the most proximal areas (Lobe A/B) and only appear in a down-current direction, compartmentalising the distal reservoir (Lobe C).

VI. Contrary to previous development models, thick, dominantly muddy debris flow deposits form a major feature in the E-Fan and indicate repeated tectonic activity throughout the sandy growth stage. The W-Fan prograded into the formerly E-Fan depositional area during late Burdigalian times was active much longer than previously suggested. The net sand transfer from west to east is unknown.

Further work:

The study of the E-Fan, the Cingöz Formation and subsequently the Neogene fill of the Northern Adana Basin would benefit from the integration of yet unpublished seismic and core data located further to the south which could help construct a more comprehensive model of the gravelly and sandy growth stage of the E-Fan and other formations. Together with a more detailed biostratigraphic and geochemical framework, hithero non- or poorly integrated sections may be tied into the overall framework. Especially the geochemical data could counteract problems arising from faulting or missing biostratigraphy.

S10 interval, Scapa Sandstone Member:

VII. The S10 interval of the Lower Cretaceous Scapa Sandstone Member (Scapa Field, UK block 14/19, North Sea) is akin to a multiple sourced mud/sand-rich to sand-rich submarine ramp system *sensu* Reading & Richards (1994) with some features of a slope apron system. The multiple feeder zones funnel sediment off the Halibut Shelf and together with minor sources off the shelf, slope, Claymore High and intraformational sources give rise to a system with compelex interdigitation of facies lacking clear proximal-distal trends. The S10 interval records renewed deep-water clastic progradation into the central Scapa Field area.

VIII. Although the S10 interval was deposited during gradually rising sea level, tectonism appears to be the fundermental control overriding sea level fluctuations. Lateral, northward migration during subzones VJ-VI and local retrogradation of the system is in response to locally decreasing sediment supply and shifting sources caused by differential uplift of the source area. Source area tectonism controlled local sea level, the sediment volume and pathways into the Scapa syncline and thus the geographic location. Basinal tectonism resulted in probably fault-controlled intrabasinal depressions which captured flows resulting in thick aggradational patterns and localised, confined sediment accumulation. Localised basinal uplift resulted in areally confined erosion.

IX. The S10 interval is dominated by sandy lobe deposition and a subordinate distributary system. The little to non-channelized depositional lobe and lobe fringe deposits are unlike classical lobes *sensu* Mutti & Normark (1987). Sediment bypass close to the conglomeratic fringe resulted in detached lobes developing basinward from the base-of-slope. The shifting activity of the various feeder zones combined with a complex basinfloor topography resulted in localised, stacked, aggradational lobe accumulation of elongate geometry indicating that deposition was not altogether free to move. Individual lobes are mainly composed of high- and low-density sandy turbidites and possibly sandy debris flows *sensu* Shanmugam (1996).

X. The chronostratigraphic S10 interval comprises the diachronous SD reservoir unit and parts of the SC/SE non-reservoir units. The sandstones of the S10 lobe deposits display a wide range of permeability values indication that flow units and reservoir compartmentalisation are fundamentally controlled by the degree of carbonate cementation.

Further work:

To gain a more complete picture of the development of the S10 interval and the Scapa Sandstone Member and thus the factors governing lobe accumulation in small, fault-controlled basin, further work would benefit from a refined biostratigraphic framework to fully include some of the study wells and refine S10 depositional model. The inclusion of seismic data may further help to unravel sandbody geometry. Additionally, extending the present environmental and depositonal model of the S10 interval for the whole SSM would enable to examine larger spatial and temporal changes within the Scapa system including their controls.