Deep-water sedimentation in the Alpine Foreland Basin of SE France: New perspectives on the Grès d’Annot and related systems— an introduction

PHILIPPE JOSEPH¹ & SIMON A. LOMAS²

¹IFP School/Geology-Geochemistry Division, Institut Français du Pétrole, 228–232, avenue Napoléon Bonaparte, 92852 Rueil Malmaison Cedex, France
(e-mail: philippe.joseph@ifp.fr)
²Baker Atlas GeoScience, Stoneywood Park North, Aberdeen AB21 7EA, UK
(e-mail: simon.lomas@bakeratlas.com)

The Grès d’Annot and geologists, a long-term love affair!

For over 150 years, the fascinating outcrops of the Grès d’Annot Formation of SE France have attracted the interest of many geologists, from different countries and from academic as well as industrial spheres. As Stanley relates in this volume, the initial interest was stratigraphic (identification of contemporaneous formations corresponding to continental to marine settings) and structural: the recognition of large displacements of Alpine nappes led to new concepts of mountain formation. Concerning the sedimentology of deep marine deposits, major advances were made in the late 1950s and early 1960s with the progressive emergence of the turbidite concept and its recognition in the field (Faure-Muret et al. 1956; Kuenen et al. 1957; Bouma 1962; Lanteaume et al. 1967), and the development of the first submarine canyon/fan valley model (Stanley 1961). From that time onwards the Grès d’Annot outcrops were used as a training area in the field, with the organization of numerous meetings and field courses (for example Beaudoin et al. 1975; Stanley 1975). Renewal of this research activity was stimulated in the 1980s by the upsurge of intensive exploration on continental margins and the emergence of seismic stratigraphy; the Grès d’Annot were studied in order to help seismic interpretation and, at the same time, complementary flume experiments of submarine avalanches were developed for better understanding of turbidity current processes (Laval et al. 1988). The critical field studies in the 1980s led to the first comprehensive palaeogeographic scheme for the Grès d’Annot basin sensu lato, based on palaeocurrent directions, onlap orientation and correlation of key marker levels (Ravenne et al. 1987), which is still largely used at present. In parallel studies, the influence of folding on basin floor topography was recognized (Apps 1985, 1987; Elliott et al. 1985). A second renewal of interest in the Grès d’Annot occurred in the late 1990s with the development of detailed studies of the architecture of the turbidite sandstone bodies, in order to improve the characterization of analogous deep-water subsurface hydrocarbon reservoirs. During that period and up to the present day, many international teams have worked intensively on the Grès d’Annot with complementary approaches, and the purpose of the 2001 ‘Confined Turbidite Systems’ research conference, jointly organized in Nice by the IFP and the University of Aberdeen, was to promote exchanges between these teams, to establish the state-of-the-art and to identify new avenues for future research.

From these studies, and following the classification of Reading & Richards (1994) based on grain size and nature of the feeder system, the Grès d’Annot is now considered as a benchmark example of a sand-rich delta-fed turbidite system. Its depositional character was strongly influenced by a predominance of large magnitude flows carrying relatively coarse-grained sand, interacting with significant basin-floor relief induced by alpine tectonics. Its characteristics are very different from those of canyon-fed systems, as in the classic sand-rich ‘suprafan’ model (e.g. the present Avon and Calabar submarine fans offshore Nigeria), or mud-rich channel-levee systems (e.g. Amazon and Zaire deep-sea fans). A recent analogue could be the Eastern Corsica fan system recently described by Gervais et al. (in press). The Grès d’Annot has frequently been used as an analogue for sand-rich turbidite hydrocarbon fields where topographic control has played a key role in defining the reservoir bodies, like in the North Sea (e.g. Gannet fields and Gryphon field; Newman et al. 1993) or on the Brazilian margin (Campos basin; Moraes et al. 2000).

The global study area is located in the French departments of Alpes Maritimes, Alpes de Haute Provence and Hautes Alpes. From a structural point of view it belongs to the Southern Subalpine
Chains, part of the Alpine Foreland Basin. Figure 1 displays the structural and stratigraphic framework of the Grès d’Annot, with the location of the different research areas: a code number has been given to each paper of this volume, and is attributed to each research area in the legend of this figure. The two introductory historical papers of Stanley and Bouma & Ravenne, and the geodynamical paper of Ford & Lickorish, deal with the whole system. The remnants of the Upper Eocene–Lower Oligocene Grès d’Annot and related systems (Fig. 1) are located on the para-autochthonous Digne Thrust verging southward in the Castellane Arc, and overlain by the allochthonous Embrunais–Ubaye Nappes (Autapie and Parpaillon) located...
around Barcelonnette. The whole system is delimited by two crystalline and Palaeozoic massifs: Pelvoux to the north and Maures–Esterel to the south. Two regional structural cross-sections have already been published (Graham in Elliott et al. 1985, fig. 2.1, and Ford et al. 1999, fig. 2): they differ in the degree of involvement of basement in the alpine thrusts, but both are still largely speculative at depth as no seismic profiles or boreholes are available for the area.

This volume is organized in different sub-themes to reflect the varying approaches of the researchers. Here we present an overview of those themes and try to emphasize where consensus has been reached, the new perspectives recently proposed, and key potential areas for future research.

Geodynamic and structural evolution

Using a global reconstruction of the peri-alpine foreland basin from Eocene to Pliocene times, Ford & Lickorish highlight the complex trajectory of the Alpine orogenic prism and the variability of shortening rates through time. During early collision between Italy (Apulia) and Europe in Eocene times, an increasingly arcuate, peripheral flexural basin migrated rapidly NW across the European plate. The Early Oligocene was characterized by a decoupling of the orogenic prism from its south-western border (Southern Subalpine Chains) by means of several transpressive strike-slip faults: for these authors the evolution of the Grès d’Annob basin is subsequently governed mainly by the gravitational sliding of the internal Embrunais–Ubaye Nappes over the external foreland basin.

For Apps et al., the complex palaeotopography of the Grès d’Annob basin was controlled by the interaction of three different orogenic events: (1) the Pyreneo-Provençal east-west oriented fold and thrust belt, linked to the Iberia–Europe collision (Late Cretaceous to Palaeocene); (2) the NW–SE oriented alpine folds and thrusts due to the Apulia–Europe collision to the East (Mid Eocene); and (3) to the South the subduction of the Tethyan oceanic crust (related to Apulia) below the SE margin of the Iberia plate (Maastrichtian to Eocene). This ‘East Iberian’ orogenic induced the uplift of the Corsica–Sardinia massif and the rejuvenation of the Maures–Esterel structures, which provided sediment to the Grès d’Annob basin during the Late Eocene. During Early Oligocene (Rupelian) times, the SE rollback of the subduction hinge induced the beginning of the NE–SW oriented rifting of the Liguro–Provençal basin (Gulf of Lion), and therefore the shut-off of sediment supply from the Corsica–Sardinia massif (Séranne 1999).

In agreement with the subsidence modelling of Vially (1994), Apps et al. consider that the deformation of the Grès d’Annob basin was dominated by the SW-directed Alpine thrusting, local thin-skinned extension (Gialorgues) and strike-slip faulting (Rouaine) being minor components in an overall compressive setting. They consider with Ford & Lickorish that the Mesozoic and Palaeozoic basement (Barrot, Argentera) must be involved in this thrusting, even if there are a number of structural repetitions of the Mesozoic cover. In contradiction to previous interpretations that consider a late exhumation (Late Miocene) of the Argentera area, Apps et al. propose an early uplift of the Barrot Massif, emergent and eroded to its Permian core by the Mid Eocene (Lutetian), and providing an input of clastic material to the basin.

In this framework, Evans et al. examine the relationship between the westernmost Barrême Basin and the other Grès d’Annob sub-basins. The shallow-marine turbidite formation of Grès de Ville is time-equivalent to (or slightly younger than) the last Grès d’Annob deposits (Mid Rupelian). Evans et al. show that the Grès de Ville is not a feather-edge to the Grès d’Annob, but accumulated in a narrow thrust-sheet-top basin, separated from the Grès d’Annob system by a synsedimentary antcline. These two distinct sub-basins were fed by different sediment transport paths, linked only to the Maures–Esterel massif (and not to Corsica–Sardinia) in the case of the Barrême Basin. The Grès de Ville correspond therefore to the last stage of filling of Grès d’Annob related sub-basins during Oligocene times, before the complete emergence of the foreland deposits.

New perspectives on structural evolution

The structural complexity of the Grès d’Annob basin results from the interference of different orogenic events, acting on a Palaeozoic and Mesozoic basement characterized by significant heterogeneity in terms of thickness and rheology. During Eocene–Oligocene times, the deformation velocity field appears to have been highly variable, with a blocking of Alpine thrusting to the south and NW by the Maures–Esterel and Pelvoux crystalline massifs, already emergent at that time (Fig. 1). A better understanding of the structural evolution would require full three-dimensional modelling (analogue and/or numerical) of the foreland basin evolution,
using three-dimensional tools of forward deformation and taking into account the effects of sedimentation on the deformation field.

Chronostratigraphy and palaeogeography

The Grès d’Annot Formation corresponds to a heterogeneous pile of sand-rich gravity flow deposits, up to 1200 m thick in a given vertical section, that range from Mid Eocene (Bartonian) to Lower Oligocene (Rupelian). This formation belongs to the classic ‘Trilogie Priabonienne’ (Boussac 1912) but in fact its age is not limited to Priabonian and it is better to refer to it as the ‘Nummulitic Trilogy’. (More generally, Sinclair 1997 termed this type of foreland basin-fill succession the ‘Underfilled Trinity’.)

This trilogy consists of three lithostratigraphic units (Fig. 2: see Joseph et al. 2000 for more details):

1. The ‘Calcaires Nummulitiques’ rest unconformably on the Mesozoic series which were severely deformed during the Pyreneo-Provençal compression phase. Several décollement levels are identified in the Mesozoic series: Triassic evaporites, Middle and Upper Jurassic black shales and mid-Cretaceous black shales. The unconformity is locally marked by the presence of non-marine ‘Infra-Nummulitic’ conglomerates (‘Poudingues d’Argens’), preserved in local depressions at the border of palaeohighs (see Apps et al.). The Calcaires Nummulitiques Formation comprises bioclastic limestones and resedimented polygenic breccias, which are interpreted respectively as shallow marine and slope deposits developed at the beginning of the Tertiary transgression.

2. The overlying ‘Marnes Bleues’ comprise hemipelagic marlstones deposited on a slope or distal ramp setting (Ravenne et al. 1987). The transition to the Grès d’Annot at the top of the Marnes Bleues is named ‘Marnes Brunes Inférieures’ because of the progressive increase in thin brownish turbidites (see Stanbrook & Clark).

3. The Grès d’Annot sensu lato are gravity flow deposits (siliciclastic turbidites and debris flow deposits) that lap on to the Marnes Bleues palaeoslope with an angle of up to 20°. Three key horizons 20 m thick are used...
for correlation in the northeastern Sanguinie area (Jean 1985; Jean et al. 1985; Elliott et al. 1985 and Fig. 2): two mud-rich debris flow deposits (which include blocks of sandstone, shale and limestone up to 10 m thick) and an extensive shale-rich unit located towards the top of the series. The very top of the series is marked again by brownish marls (‘Marnes Brunes Supérieures’).

To the NE, the Nummulitic Trilogy is capped by the ‘Schistes-à-Blocs’ Formation, which is a thick heterolithic olistostrome emplaced on the sea floor at the front of the advancing Autapie Nappe (Kerckhove 1969). Emplacement of the Schistes-à-Blocs was associated with deep erosion of the upper levels of the Grès d’Annot.

The chronostratigraphic data presented in this volume are based on the ‘P zonation’ defined by Berggren et al. (1995) for planktonic foraminifera and the ‘NP zonation’ defined by Martini (1971) for calcareous nannofossils (Fig. 3).

Du Fornel et al. present the results of systematic sampling of the top of the Marnes Bleues and fine-grained levels inside the Grès d’Annot, in conjunction with an estimate of the palaeobathymetry from benthic foraminiferal associations (generally in a range 200–500 m). This work provides a new and well-constrained framework for the correlation of the different Grès d’Annot remnants: a better picture of the topography of the different sub-basins may be drawn (Fig. 4), thanks to palaeocurrent data (giving mean transport directions), onlap surface orientations (enabling the reconstruction of palaeoslopes) and palaeobathymetry estimates. This figure clearly shows the diachronous onset of filling of the successive sub-basins (displayed by shading identical to that used in Fig. 3):

- The Eastern Italian sub-basin (Bevera and Mortola, 10 km NE of Menton) was actively filling during Bartonian times (P14 foraminiferal zone).
- The Contes-Piéra Cava system was probably separated from the previous one by the Sospel–Oliveta palaeohigh (finer-grained facies and west-directed palaeocurrents, and proximity of Triassic outcrops: see Amy et al.); deposition here began at Early Priabonian (P15 sup zone).
- The Mont Tournairet area, of the same Early Priabonian age (P15 sup–NP 19 zone), may correspond either to the westward extension of the Piéra Cava basin, or to a distinct sub-basin. The possible extension of this system to the Lauzanier area to the north of the Argentera Massif is based only on the palaeocurrent directions and is highly speculative because of the lack of intermediate outcrops and the lack of biostratigraphic data from the Lauzanier area.
- The Sanguinie sub-basin became active during the Late Priabonian (P16–NP19/20 zone). It was probably fed by a fan delta (less developed than the St Antonin one) that has been recently identified in the Quatre Cantons area (Joseph & Ravenne 2001). This narrow sub-basin was confined between the Argentera and Barrot–Allos submarine palaeohighs.
Fig. 4. Palaeogeographical evolution of the main Grès d’Annot sub-basins with age of onset of filling. Onlap and palaeocurrent directions are derived from Bouma & Coleman (1985): Contes, Menton, Peira Cava; Ford et al. (1999): Champsaur, Devoluy; Ravenne et al. (1987): Annot, Barrême, Grand Coyer, Sanguinière, Trois Evêchés. (clear onlaps can be recognized on both eastern and western borders of the sub-basin). It passed downstream to the Trois Evêchés sub-basin (Lomas et al. 2000) and progressively widened westwards to the Allos area during the Early Rupelian.

- During the Late Priabonian (P16–NP19/20 zone), the Annot sub-basin was a fully confined
The complex palaeogeography of the Grès d’Annot basin and the beginning of clastic sedimentation in each sub-basin are now better constrained thanks to recent research on palaeotopography and biostratigraphy, but the exact timing of the filling of each sub-basin remains a matter of debate due to the limited chronostratigraphic resolution for the Lower Oligocene (Rupelian). Some areas remain poorly controlled (Lauzanier, Quatre Cantons, Mont Tournairet, Contes, some parts in Trois Evêchés). Systematic dating and correlation, using new techniques such as chemostratigraphy, might be used to lift the remaining uncertainty concerning the relationship between adjacent sub-basins.

Sequence stratigraphy

Using a novel sequence stratigraphic approach focused on the Annot sub-basin, Callec interprets the Grès d’Annot as the regressive part of a second-order transgressive-regressive cycle (sensu Mitchum & Van Wagoner 1991: duration around 10 Ma) including the whole Nummulitic Trilogy (Calcaires Nummulitiques, Marnes Bleues and Grès d’Annot). He relates the constituent third-order depositional sequences (estimated mean duration 1–3 Ma) to global sea level variations, which are highly modulated by the tectonic deformation of the foreland. In agreement with Evans et al. for the Grès de Ville in Barrême, he proposes that the uplift induced forced regressions of the sandy depositional systems, with an increase of the sediment flux, a reinforcement of the erosive third-order sequence boundaries and a morphological confinement, with tilting and migration of the depocentres (Callec 2001).

Using the new chronostratigraphic data previously described, Du Fornel et al. provide a detailed correlation between different Grès d’Annot remnants (Fig. 6). This correlation is based on the recognition of fourth-order depositional sequences (sensu Mitchum & Van Wagoner 1991, i.e. sequences of around 200–400 ka duration), made up of groups of genetic units (fifth-order sequences: likely mean duration around 20 ka, Guillocheau et al.). This analysis constrains the correlation of major surfaces (erosive sequence boundaries, shaly maximum flooding surfaces). In this sequence stratigraphic framework, a detailed evolutionary scheme is proposed for the St Antonin–Annot–Grand Coyer–Chalufy sub-basin (Fig. 4), evolving from ponding during the Priabonian to spilling, then blanketing during the Early Rupelian. This evolution is essentially in agreement with the...
Fig. 5. Schematic palaeogeography of the Grès d’Aumône system in Early Oligocene times (A: Amor, C: Centes, CC: Col de la Ceyolle, CH: Chalafy; CM: Col de la Moutière; G: Galloglaise; GC: Grand Coyer, LA: Lauzanier, MT: Mont Tournier, PC: Petra Cava, QC: Quatre Cantons, SA: St. Antonin, TE: Tres Estelles).
Fig. 6. Regional correlation panel of the St Antonin–Annot–Grand Coyer–Chaluy sub-basin (see Du Fornel et al. this volume; modified from Joseph & Ravenne 2001).
thick high resolution genetic units (fifth-order parasequences, *fineit* Mitchum & Van Wagoner 1991), which are interpreted as the results of high resolution sequence stratigraphy and prediction of the nature and the architecture of Figs 1 & 4), Guillocheau *et al.* recognize 10 m thick high resolution genetic units (fifth-order parasequences, *sensu* Mitchum & Van Wagoner 1991), which are interpreted as the results of preceding (but less detailed) palaeogeographic reconstructions of Pickering & Hilton (1998) and Sinclair (2000). *Du Fornel et al.* show a downward current transition from the feeder fan delta to transit channels then sheet-like lobes.

*Euzen et al.* validate the proposed evolution of the sub-basin using *three-dimensional stratigraphic modelling* of gravity flow processes of erosion, transport and deposition. The main controlling parameters of the stratigraphic architecture are the initial topography of the basin, the tectonic activity that induced third-order cycles of uplift-denudation of the feeder massifs (Corsica-Sardinia and Maures-Esterel massifs), and the variations of sedimentary supply (of climatic and/or eustatic origin), which controlled the fourth-order sequences.

In agreement with this modelling, Puigdefábregas *et al.* relate the sudden influx of very coarse sand and gravels in Annot (Gastres Unit = discontinuity at the base of Unit C of *Du Fornel et al.*; see Fig. 6) to a significant tectonic rejuvenation of the hinterland.

New perspectives on sequence stratigraphy

This first correlation of depositional sequences must now be extended to the other sub-basins. Three-dimensional stratigraphic modelling seems to be a powerful tool for ensuring the internal consistency of the reconstruction, for evaluating scenarios where geological data are scarce, and also for visualizing the complex interaction between sediment supply, sea level variations and tectonics in filling of the sub-basins. Some disagreement still remains on the main controlling parameter of the sequence stratigraphic organization (global eustatic variations versus tectonic activity): a quantification of the range of variation of these parameters would lead to a better estimation of the relative importance of deformation rate versus eustatic variations for the different areas and sedimentation periods of the basin. Such an enhanced data base would allow better prediction of the nature and the architecture of gravity deposits developed in a ‘fill-and-spill’ setting (initially ponded systems).

High resolution sequence stratigraphy and depositional model

In the Sanguinière sub-basin (see location in Figs 1 & 4), Guillocheau *et al.* recognize 10 m thick high resolution genetic units (fifth-order parasequences, *sensu* Mitchum & Van Wagoner 1991), which are interpreted as the results of 20 Ka eustatic cycles (speculatively comparable with variations in orbital precession). Each genetic unit is characterized by a progradational phase with clinoforms, followed by an aggradational phase of spreading. In contradiction to previous interpretations of the Grès d’Annans as shallow marine deposits in that area (Sinclair 1993), the authors consider that the facies organization fits well with a model of a flood-dominated fluviol-turbiditic ramp (*sensu* Mutti *et al.* 2000). Because of the direct connection between the shelf and the slope, the sequential organization of the turbidite deposits on the slope can be related to the activity of the feeding fan delta on the narrow shelf (perhaps with an important contribution from hyperpycnal flows induced by fluvial floods, cf. Mulder & Syvitski 1995).

Broucke *et al.* demonstrate the influence of a kilometre-scale synsedimentary flexure on the geometry of these genetic units. The downstream increase of available space is accommodated by small normal faults induced by gravitational sliding; this increase induces a downstream thickening of genetic units and the pinching-out of some of them upstream, but their internal organization (facies preservation and cycle geometry) does not seem to be strongly affected.

New perspectives on the depositional model

There is now a broad consensus on the general depositional model for the Grès d’Annans. Following the first reinterpretation of the St Antonin conglomerates as a fan delta (Stanley 1980), the Grès d’Annans system is no longer considered as a classic canyon-fed submarine fan, but as a *sand-rich turbidite submarine ramp fed by multiple-source fan deltas* at the border of the Corsica-Sardinia massif (cf. Pickering & Hilton 1998; Joseph *et al.* 2000; Sinclair 2000). ‘Fill and spill’ concepts, in conjunction with the new correlations linking the sub-basin fills (*Du Fornel et al.*), have provided key insights into the mode of basin infilling. However, these new results seem to argue against an essentially two-dimensional sequential infilling and downslope overspilling of successive mini-basins (cf. the ‘fill and spill’ model for the northern Gulf of Mexico slope: Winker 1996; Prather *et al.* 1998). For the Grès d’Annans, interconnections between the sub-basins may have been more three-dimensional (Fig. 5), and hence sediment dispersal was likely to have involved more three-dimensional pathways, which evolved over time as the basin floor relief changed with infilling and ongoing tectonics.
Within this general framework, detailed work remains to be done on the nature of the processes (short-lived gravity surges versus sustained hyperpycnal flows), the link with the shallow marine areas (fan or braided deltas) and the effect of the confinement on the resulting facies. Ultimately, these results should provide valuable predictive keys in comparable confined systems in the subsurface such as the Gulf of Mexico, offshore Brazil or the Tertiary of the Central North Sea.

Synsedimentary tectonics

In the Sanguinieire sub-basin, Lansigu & Bouroullec identify evidence of tectonic activity during the deposition of the Grès d'Annot. They show that a network of synsedimentary normal faults (forming a succession of tilted blocks) was strongly influenced by rheological discontinuities of sedimentary origin, and especially by the mud-rich layers limiting the genetic units (equivalent to maximum flooding surfaces): these layers acted as the nodes of antithetic and synthetic secondary faults, and the rheological contrasts between mud-rich and sand-rich layers induced a staircase geometry of the fault surface, with a vertical succession of segments with different angles and curvatures. The deepest mud-rich layers of the series accommodate the downdip displacement of the tilted fault blocks by layer-parallel movement (listric faults).

Bouroullec et al. quantify the timing of fault activity, which seems to have been discontinuous but frequent (periodicity between 35 and 70 ka). They demonstrate its effect on the geometry of genetic units: increase of the overall thickness in the hanging wall, with a decrease of sandstone:mudstone ratio (‘net-to-gross’) because of a better preservation of fine-grained facies (heterolithics), and downdip pinching-out of thicker sandstone bodies where the fault growth is significant. These observations reveal a strong coupling between high-resolution sedimentary sequences (genetic units) and the development of a synsedimentary fault network. Most of these faults are sealed upwards by the Schistes-fi-Blocs Formation.

In the Annot sub-basin near Braux, Tomasso & Sinclair examine the synsedimentary activity of the St Benoît fault (also-called the Gros Vallon fault, Pairs (1971), and Le Savelet fault, Puidefábregas et al.), which is a north–south satellite of the NE–SW Rouaine fault (location on Fig. 1). This fault displays three phases of activity:

1. successive extensional activity during Mid Eocene (Bartonian) times induced the progressive development of a half-graben filled by the Calcaires Nummulitiques and the lower part of Marnes Bleues (draping the St Benoît palaeocliff that limited the half graben westwards);
2. during the Late Eocene (Priabonian), the fault was characterized by a transpressive sinistral strike-slip motion that induced a monoclinal fold parallel to the fault: the residual palaeotopography in turn induced ponding of the first Grès d’Annot deposits (Lower Braux Unit) and flow stripping of the diluted upper part of the turbiditic flow above the palaeoslope;
3. during Oligocene (Early Rupelian) times, the fault activity ceased and coarse-grained turbiditic flows spilled over the remaining palaeotopography. This change in the regime of fault activity might be related to the modification of the migration direction of the internal thrusting units, firstly northwards during the Lutetian–Bartonian, then westwards during the Priabonian–Rupelian (Ford & Lickorish).

In the Grand Coyer remnant, Stanbrook & Clark discuss the relationship of the Marnes Brunes Inférieures to the overlying Grès d’Annot deposits: they argue that this shaly transitional facies corresponds to a distal and lateral equivalent of the coarser Grès d’Annot, because of their local interstratification, the similarity of palaeo-current directions and the contemporaneity of the fine-grained deposits on the slope and the coarse-grained sediments in the basin. They bring to light evidence of synsedimentary deformation during the deposition of the Marnes Brunes Inférieures, with dip changes, slump development and a slight angular unconformity between Marnes Brunes Inférieures and Grès d’Annot.

New perspectives on synsedimentary tectonics

Previously, the Grès d’Annot has classically been considered as having accumulated during a period of tectonic quiescence. These recent studies have led to the recognition of minor but frequent tectonic activity (synsedimentary faults with throw of a few tens of metres, and kilometre-scale flexures). This tectonic activity strongly interacted with the turbidite sedimentation and influenced the geometry and facies organization of small-scale sedimentary
sequences (genetic units a few metres thick). Good examples of both dip and strike evolution are now available along two-dimensional transects, but the real three-dimensional impact of the tectonic activity is still poorly understood and needs more detailed studies, coupling outcrop observations with modelling of the interaction of small-scale brittle deformation and sedimentation processes. An effort must also be made to integrate these small-scale observations into a comprehensive regional model of deformation of the entire foreland basin.

**Interaction between turbidity flows and basin-floor topography**

Sea floor topography has strong impact on the behaviour of turbidity flows, in terms of spatial variation (termed flow non-uniformity) and temporal evolution (termed flow unsteadiness; Kneller 1995). Changing topography induces specific trends in facies organization and bed sequences (e.g. Kneller & McCaffrey 1999).

In this volume, using examples near Annot, McCaffrey & Kneller identify three scales of spatial non-uniformity of turbidity currents:

1. **Basinal scale non-uniformity** is linked to changes in slope gradients and is revealed by the very presence of thick sedimentary deposits;
2. **Flow scale non-uniformity** is related to specific geometries, in particular the confinement of turbidity flows in elongated mega-scours or channels;
3. **Sub-flow scale non-uniformity** results from variability in the sea-floor topography, which locally modifies the behaviour of the flow and induces specific heterogeneity in the resulting deposits.

In poorly-exposed or subsurface systems, these different scales must be identified before inferring geometries and facies changes, because small-scale effects may overprint large-scale effects controlling the overall architecture of the turbidite system.

Using the same approach and comparing tank experiments with outcrop observations in the Peira Cava remnant, Amy et al. attempt to quantify the impact of a lateral basin floor slope on the velocity field of the incoming flows and the resulting deposits. The results suggest that lateral confinement reduces the spreading of the flow, and induces thicker deposits along the slope compared with the basin if the flow velocity is low, and bypass if the flow velocity is high. But it also seems necessary to take into account the spatial non-uniformity of the flow concentration to make a reasonable prediction of the lateral evolution of the sediment thickness.

In the same sub-basin, Lee et al. discuss the origin of decametre-thick sandstone units that were deposited close to the base of slope. These sandstone bodies may have resulted either from remobilization by low-efficiency flows of sediments previously deposited higher on the slope, or to the progressive filling of ‘spoon-shaped’ erosional megascours (a few hundred of metres wide) that were created at the break in slope by the hydraulic jump of gravity flows going down the slope. Attention is drawn to the fact that in two-dimensional sections these local deposits may be confused with the fill of long-lived channels of very different three-dimensional geometry.

**Geochemical variability**

By comparing the geochemical compositions of Grès d’Annot deposits sampled in different areas and different stratigraphic levels (with the exception of the Grès de Ville of the Barrême Basin), Garcia et al. show that the chemistry of the clastic components is nearly uniform and consistent with a southern granite-dominated provenance (Corsica–Sardinia massif). The authors examine the effects of transport and depositional mechanisms on chemical variations at the bed scale: archetypal turbidites are found to display a geochemical trend related to vertical decrease of grain size (K-feldspar–quartz–zircon-type heavy minerals) and an upward increase in clay content, which are both related to the grading by a waning flow in non-channelized systems. On the other hand, the sorting of zircon-type heavy minerals in lateral deposits of channelized systems may be explained by traction-dominated overbank deposition from sustained steady flows, spilling over the channel margins. These observations are integrated into a differentiation model related to hydrodynamic processes, which may explain the specific geochemical signature of different facies found at a single location.

**New perspectives on topographic controls**

A better understanding of the interaction between topography and gravity flows is now achieved, but as has been the case for structural modelling over the past decade, systematic (but time-consuming) experiments of different configurations, together with three-dimensional
numerical modelling of sedimentary processes, will be necessary to better quantify the results in terms of depositional geometry and facies organization. This may improve the prediction of reservoir facies in analogous subsurface cases where the depositional palaeotopography may be inferred (with some uncertainty) from seismic picks and analysis of seismic attributes such as amplitudes. Geochemical analysis, generally used for provenance and correlation studies, might also be used as a complementary tool to better understand the segregation processes.

**Onlap architecture**

Remarkable exposures of large-scale onlap relationships are a hallmark of the Grès d’Annot outcrops. Puigdefabregas et al. reconstruct the complex palaeotopography of the onlap surface in both the Annot and Chalufy areas, which belonged during Oligocene times to a common outer basin margin (St Antonin–Annot–Grand Coyer–Chalufy sub-basin; see Fig. 4). The authors discuss the origin of soft-sediment deformation (‘slumps’) and muddy ‘debrites’ that are associated with the onlap surface: the sudden arrival of coarse-grained high-density turbidity currents onto the basin-flank slope would create sub-horizontal injection and de-lamination of previous deposits by overpressure, and their entrainment as overturned beds (‘slumps’). In agreement with Kneller & McCaffrey (1999), this phenomenon may explain the common occurrence close to the palaeoslope of chaotic ‘debrites’ intercalated within single turbidite sandstone beds (‘tri-partite’ beds).

Using the same Chalufy exposures, Smith & Joseph test a simple geometric model reproducing the onlap pattern of the Grès d’Annot on the Marnes Bleues palaeoslope. Two end-members are predicted depending on the ratio of coeval slope to basinal aggradation rate, which is related to the volume of the turbidity flows and their sand/shale ratios: ‘pure’ abrupt onlap occurs when sand-rich flows deposited sandstone beds with no or limited slope drapes (no slope aggradation); ‘feathered’ aggradational onlap occurs when mud-rich flows deposited sandstone beds that interfingered with muddy slope drapes (contemporaneous slope aggradation). The cyclicity of alternating sand-rich and sand-poor packets results in a stepped climbing trajectory of the diachronous onlap surface. In subsurface cases, the two end-members may or may not be resolved depending on the frequency content of available seismic data: the two end-member cases lead to very different geometrical configurations and vertical connectivities of the reservoir bodies.

**Seismic modelling**

By using as a test case a three-dimensional facies model reconstructed from an outcrop of the Sanguinieres sub-basin, Bourgeois et al. compare two methods of seismic modelling: three-dimensional full wave modelling gives more realistic results than multi-one-dimensional convolution, because the method takes into account the lateral heterogeneity in the vicinity of each reflecting point, and therefore more information on the distribution of petro-acoustic heterogeneity in the sedimentary pile (reservoir analogue). The synthetic three-dimensional seismic model is used to analyse the seismic signature of different sedimentary architectures, and to test seismic interpretation of comparable subsurface reservoirs. The main shaly permeability barriers (sedimentary maximum flooding surfaces) are detected, and the limits of the main sand-bodies (‘reservoir zones’) are identified on amplitude time slices, but advanced seismic processing (migration, impedance inversion, attribute analysis) seems necessary to derive confident quantitative information on the small-scale architectural heterogeneity.

**Subsurface analogues**

Outcrop analogues are increasingly frequently used to help in the modelling of subsurface deep-water oil and gas fields, where limited information on sedimentology and small-scale architecture is available because of the limits of well coverage and seismic resolution. Using an example of a Brazilian Cretaceous oil field, Moraes et al. discuss the selection criteria for relevant use of such outcrop analogues. At the reservoir scale, the first-order control parameters seem to be the palaeotopography and the geometrical characteristics of the confining conduits (rather than the tectonic context at a larger scale: for example, active versus passive margins); the second-order control parameters are the grain size and the sand/mud ratio of the sediment input, which influence the nature of the gravity flows, and thus the depositional geometries and their patterns of heterogeneity.

Subsurface modelling may benefit from the quantitative parameters derived from the outcrop studies (such as channel dimensions, extent of shale breaks, facies continuity quantified by
correlation lengths), but the use of these statistics must be based on the recognition of the similarity of the sedimentary processes acting in the outcrop and subsurface cases.

New perspectives on applications as subsurface analogues

An integrated approach is developing for the study of deep-water outcrops that serve as analogues for subsurface fields (see examples in the GCSSEPM 2000 conference volume, Weimer et al. 2000). Thanks to rapid progress in the development of geomodelling software tools, three-dimensional models can be constructed, displaying sedimentary body architecture and facies distribution in three dimensions. These models may be used as test cases for seismic or fluid flow modelling, to identify the seismic and dynamic signature of specific sedimentary architectures and to test their sensitivity ranges. Parallel development of three-dimensional tools for the numerical simulation of sedimentary processes provides a better understanding of the relationships between gravity flow processes and the resulting facies. A logical next step would involve a comparison between high-resolution seismic surveys on recent deep-marine systems (providing detailed images of horizontal organization) and comparable outcrop studies (giving details of internal organization and vertical evolution).

Concluding remarks

The Grés d’Annot basin is the birthplace of important developments in the study of deep-marine sedimentation (recognition of turbidites by Kuenen; Bouma sequence for low-density turbidites; Stanley’s model of canyon and fan valley) and a classic area for field work and courses on gravity flow deposits.

The scale and outstanding quality of the exposures makes this region an excellent natural laboratory in which to study the interaction between foreland basin evolution and deep-marine sedimentation, on both regional and local scales. Recent research presented in this volume provides novel ideas on the correlation between sub-basins, their relative timing of filling, the nature of gravity flow processes and their impact on facies distributions, the relative frequency of tectonic activity, and the interaction between topography, tectonic deformation, eustatic sea-level changes and variations of sediment supply, in a better-constrained chronostratigraphic framework. A consistent depositional model of a fan-delta-fed turbidite submarine ramp, differing from the classic radial fan model, is now posed, even if further research is needed to clarify many of the details, and to ascertain the significance of poorly-studied areas. In addition, this volume highlights some exciting new avenues for research (three-dimensional process modelling; three-dimensional coupled structural and stratigraphic modelling; seismic modelling; chemostratigraphy; geochemistry; sedimentological data quantification) that may help to better understand the large- and small-scale architecture of sand-rich deep-water confined systems, and provide some predictive keys for better modelling of analogous subsurface systems.

The authors would like to thank E. Albouy, A. Mascle and J. Turner for their very helpful comments and suggestions on the manuscript.

References


NEW PERSPECTIVES ON THE GRÈS D’ANNOT


