Deep-water sedimentation on an evolving fault-block:
the Braux and St Benoit outcrops of the Grès d’Annot

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Abstract: The record of sediment fill contained in sub-basins of the western outcrops of the
Grès d’Annot indicates that, throughout the period of deposition of the sandstones, there
was very little synsedimentary tectonic activity. However, evidence of syntectonic sedimentation
is preserved in the basal portion of the fill of the Annot sub-basin. The lowest portion of the
turbidite fill of the Annot sub-basin crop out around Braux and St Benoit. These
outcrops are separated by the St Benoit Fault, which is thought to have developed as a
result of sinistral strike-slip movement on the eastern Rouaine Fault to the south. The St
Benoit Fault has a normal offset of up to 400m to the east. Detailed mapping within the
Calcaires Nummulitiques, Maraes Beues and Grès d’Annot, has led to the recognition of
several features that indicate a syntectonic sedimentary evolution for the outcrops. These
record a three-phase progressive evolution of the St Benoit Fault through the upper Calcaires
Nummulitiques to the lowermost Grès d’Annot. As part of this, there are implications for
deposition from turbidity currents on encountering topographic barriers. To our knowledge,
this area contains one of the few outcrops examples of half-graben formation within the
confined basins of the Grès d’Annot.

Interaction of turbidity currents with topography is well known to have an effect on flow
dynamics and directions (e.g. Edwards et al. 1994; Kneller & McCallen 1999; Tomasso
2001). Whilst bounding slopes have an effect on turbidity current flow, the gradients of these
slopes are usually low, typically less than 15° in the Annot sub-basin (Sinclair 1994; Pickering
& Hilton 1998; Tomasso 2001). Enhanced topography, such as that caused by an exposed or
draped fault plane, will have the effect of sub-dividing a basin and creating a series of minor depocentres.

This style of sub-basinal division in a deep-water setting is best exposed at outcrop in the Triassic
of eastern Greenland (Svendson 1978). The effects of the confinement of turbidity currents in this
way are of particular importance to sub-surface prediction of turbidite reservoirs. The way
sediment is deposited in the region of the fault will have a significant effect on both the reservoir
characteristics (e.g. sandstone: mudstone ratio) and whether any hydrocarbon charge can leak
out of the area.

Although these basins were in an active tectonic regime, with interaction between the south-
westward propagating Alpine orogen and the previous northward verging, Pyreneo-Provençal
orogen (Siddans 1979; Appx 1987; Dewey et al. 1989; de Graciansky et al. 1989; Ford et al.
1999), the sedimentary record of the Grès d’Annot is remarkably unaffected by syntectonic
deformation. However, there is some evidence of synsedimentary faulting, but this mainly occurs
near enclaves of sandstone on to marl, where there is differential compaction of the marls
(Sinclair 1994).

In the southern Annot sub-basin, whilst there is a large, tectonically induced, slump unit within the
sandstone fill of the basin (Appx 1987), there is little else in the way of deformation throughout
this fill. This leads to the assumption that either the filling of the confined basins occurred during
a quiescent phase in Alpine compression, or that the basins filled with sediment extremely quickly.
However, the basal portion of the fill, here exposed around the villages of Braux and St Benoit (Fig. 2),
crops out on either side of a large-scale contemporaneous normal fault. The St Benoit Fault
downthrows to the east, and is responsible for a thickening of the marls of up to 400m across the
fault.

211, 267-283. 0305-8716/04/$15.00 © The Geological Society of London.
This paper aims to provide information on the syntectonic sedimentary evolution of the area surrounding the St Benoit Fault, based upon detailed fieldwork and compilation of other studies. In detail, a three-phase evolution of the fault is proposed, which has wider implications for the deposition of sediment from turbidity currents on encountering enhanced topographic barriers. Eight outcrops (Figs 2 & 3) are described and interpreted, followed by the generation of a new model to explain the tectono-stratigraphic evolution of this area.

Outcrop descriptions and interpretation

The outcrops within the study area can be divided into the three formations of the 'Triologie Pratonièine' (Bousac 1912): Calcaires Nummulitiques, Marnes Bleues and the Gres d'Annot. For stratigraphic purposes, the Gres d'Annot can be divided into two separate sub-units here, termed the Braux-Lower sub-unit and the Braux-Upper sub-unit. The division is determined by their separation by a marl-rich layer and differing stratigraphic dips, as well as slight differences in sedimentology between the two sections. Apps (1987) suggested that the St Benoit Fault, exposed just to the east of the section, played an important role in the deposition of sediment, at least in the lowermost two formations (Calcaires Nummulitiques and Marnes Bleues). This fault is a spaly of the Rouaille Fault, running from SW to NNE. The fault is oriented in the same SW-NE plane as a series of similarly aged faults along the Var River valley, with extensional movement occurring during the Eocene (Ravenne et al. 1987). The evidence for movement on the St Benoit Fault will be assessed as part of this description.

The outcrops can also be sub-divided based upon the discrete fault blocks of the St Benoit Fault, into the western (Braux) footwall block, and the eastern (St Benoit) hanging wall block.

The exposure of the footwall block on the D110 road section running to Braux (localities 7a and 8a in Figs 2 & 3) consists of a thick series of sandstones onlapping from east to west on to a shallow topographic slope in the underlying marls. The total outcrop is approximately 1 km long and over 100 m thick. The beds are of varied thickness, having a maximum thickness of around 2 m and thinning to 2-3 cm.

Originally, the rocks of this section were interpreted as mid-canyon slope sediments by Stanley (1975) and tributary canyon deposits by Stanley et al. (1978), due to the low sandstone: mudstone ratios when compared with the Les Scaffarelles section, which were interpreted as canyon-fill facies. Hilton (1995) re-interpreted this section as representing the lower slope facies of distal deltaic deposits, originating in the St Antonin area. The latest modification, by Kneller & McCaffrey (1999), suggests that the sandstones were deposited from a localized point-source to the east, somewhere in the region of St Benoit. In this paper the section is further interpreted from detailed analysis of the local area, with some modification to the model presented by Kneller & McCaffrey (1999).

Outcrops in the hanging wall of the St Benoit Fault are located to the north of the village of St Benoit. Sayer (1995) and Srinigar et al. (1998) studied logged sections through the Calcaires Nummulitiques, identifying several separate palaeoenvironments. Mougin (1978) conducted a stratigraphic and micropalaeontological study on the Marnes Bleues underlying the Gres d'Annot at Braux, Tete du Ruch and Col du Fa, enabling confident biostratigraphic dating of these sections.
**Sedimentation on an Evolving Fault-Block**

Fig. 2. Detailed geological map of the Braux-St Benoit study area, with outcrop localities discussed in the text. Note the Marnes Bleues partition that separates the lower and upper sub-units of the Grès d'Annot in this region.

**Sedimentology of the Calcaires Nummulitiques and Marnes Bleues**

**Footwall block.** The Calcaires Nummulitiques form the main escarpment of the St Benoit Fault to the east of the section exposed on the D110 road to the town of Braux. The mean bedding of the limestones at the escarpment is 183/31° W. They are light grey in colour, with a high faunal diversity, and have been interpreted

Fig. 3. Series of superimposed west-east cross sections through the study area, with the numbers of localities discussed in the text indicated. There is no vertical exaggeration on the sections. The stratigraphic relationship of the different units across the St Benoit Fault can be readily determined.
as representing a shallow water shelfal carbonate succession (Sayer 1995).

At locality 1 in Figures 2 and 3, the plane of the St Benoit Fault is exposed (Fig. 4). Currently the fault plane has a strike and dip of 355/32° E which, on restoration of the bedding of later sediments, increases to 53°. The immediate wall rock to the fault plane is brecciated, the clasts of which are mixed Nummulitic and Cretaceous limestones. These clasts are angular to sub-angular, of 40 mm maximum dimension, grey and yellow-brown in colour, and are held in a very fine-grained light grey matrix. The fault plane has been polished smooth by movement on the fault. There are two sets of striations on the fault plane, one of which is parallel to the dip surface and one of which is oblique to this, pitching towards 058°. The sense of shear cannot be determined from these. The marks that have been deposited directly on to the hanging wall contact with the fault plane are sheared.

The contact between the Calcaires Nummulitiques and Marnes Bleues formations can provide information about relative movements on the St Benoit Fault, as faunal variation can be linked to relative sea-level rise as a fault moves. In the upper section of the Calcaires Nummulitiques in the footwall block, several features are of note (localities 2a, 3 and 4 in Figs 2 & 3). Sayer (1995) and Sinclair et al. (1998) provided a logged section through the top 28 m of the Calcaires Nummulitiques at Les Scaffarelles, 1 km to the west of the St Benoit Fault (locality 2a; Fig. 5). The high diversity of the faunal population within this succession is typical of a shelfal carbonate facies (Sinclair et al. 1998).

Near the scarp of the St Benoit Fault, exposure of the uppermost Calcaires Nummulitiques on the D110 road leading to Braux (locality 3; Figs 6b & 7b) shows an increase in the content of shelly material within the limestones. The upper 5 m of this section (logged in Fig. 7b) shows a distinct variation in colour and micro-fossil content. The true Calcaires Nummulitiques in this location have a medium to dark grey colour, and are characterised by a large quantity of small Nummulites foraminifera (<5 mm), plus occasional larger, broken, bivalve shells (50–40 mm), in a very fine-grained matrix. These pass upward into a metre of medium grey coloured marly limestones. There is a decrease in the Nummulites content, with inclusion of several small solitary corals. Within this, there are also two fine- to very fine-grained calcareous sandstone stringers, 2–5 mm in thickness. This is overlain by a 2.5 m section of light grey marly-rich limestones. These have an increase in Nummulites, several sub-horizontal and vertical burrows (8 mm wide, >70 mm long) infilled with broken shelly material and calcareous sands, and larger solitary corals (up to 10 mm in diameter). In the top 25 cm of this section, there is an overall coarsening upward from wackestone to packstone due to an increase in broken bioclastic material. At the top of this section, the contact between the Calcaires Nummulitiques and Marnes Bleues, there is a 5 cm thick preferentially
hardened cap (Fig. 7b). This is a yellow-brown grainstone, with a very high quantity of broken bioclastic material. The bioclasts are very diverse, containing Nummulites, bivalve, gastropod and coral fragments. On top of this, the true Marais Bleues occur for the first time, onlapping the Calcaires Nummulitiques. These are heavily weathered, blue-grey in colour, and have some broken shelly material included in the lower 10 cm. This faunal variation that occurs in the uppermost few metres of the Calcaires Nummulitiques is interpreted as being firstly due to a slow deepening of the section (change in colour, reduction in faunal diversity). This is then followed by a rapid increase in water depth, resulting in a break in limestone sedimentation and formation of a drowning surface (the preferentially hardened cap to the limestones).

In the valley 600 m to the southwest of this outcrop (locality 4), the contact between the limestones and the overlying marls is marked by a series of three calcarenite beds (Figs 6a & 7a). Each bed is around 25-60 cm thick, brown-grey in colour, fine- to medium-grained, well
Fig. 6. Photograph of the contact between the Calcarenites Nummulitiques and the Marine Brea. (a) Calcarenite beds generated through movement on the St. Bertin Fault, locality A. (b) Drawing surface at the top of the Calcarenites Nummulitiques, indicating rapid deepening, locality B.
cemented, and in places contains a high proportion of broken bioclastic material. The beds exhibit normal grading, and thin very rapidly towards the northeast. There are thin marl-rich partitions between the beds, with the bases having a high concentration of horizontal and vertical burrows. The bedding is parallel to that of the Calcaires Nummulitiques. Sparse palaeocurrent data from flute marks indicates a SW–NE flow. These beds are interpreted as calciturbidites deposited at the boundary between the Calcaires Nummulitiques and Marnes Bleues as the result of sediment destabilization by fault movement.

**Hanging wall block.** A logged section through the top portion of the Calcaires Nummulitiques by Sinclair et al. (1998) (locality 2b, Figs 2, 3 & 5) shows that, whilst in the footwall block there is high faunal diversity through to the top of the limestones, in the hanging wall block there is a distinct reduction in faunal diversity and an increase in the Discocyclina population. There is also a gradual flaring-up through this limestone section. The low faunal diversity indicates a mid-ramp setting, whilst the high Discocyclina populations are indicative of low light, low energy deeper water settings (Sayer 1995; Sinclair et al. 1998). This is interpreted as a being representative of a rapid deepening of the hanging wall block, in response to movement on the St Benoit Fault.

The Marnes Bleues in the hanging wall are greatly thickened (400 m; Ravenne et al. 1987; Pickering & Hilton 1998) when compared with those in the footwall section (70–80 m on the footwall crest), and dip to the west into the fault zone. The bedding in the marls decreases in dip towards the top of the marl section, in a series of discrete steps (locality 5; Figs 2 & 3). To the east of the section in Figure 3, the bedding in the marls is sub-parallel to that of the underlying limestone block. The marls that crop out to the north of St Benoit, below locality 7b, can be seen to undergo at least three rapid changes in dip (Fig. 8). These shallowing-upward stepwise bedding changes are in the order of 7–12°, with the upper marls unconformably onlapping towards the east the bedding of the lower marls. These step-wise changes in bedding are interpreted as being related to a series of discrete movements on the St Benoit Fault, which were separated by periods of tectonic quiescence.

**Sedimentology of the Grès d’Annot**

**Footwall block.** As discussed earlier, the Grès d’Annot are grouped here into two separate
sub-units, the Braux-Lower sub-unit and the Braux-Upper sub-unit. These sub-units are divided by a 20 m thick section of grey-brown marls.

Braux-Lower sub-unit (locality 7a). On the D110 road leading to Braux, the sub-unit crops out in two locations (Fig. 9). These two localities were separated by a shallow paleo-topographic high in the underlying marls, on to which the sandstones thin, pinch out and drape. The lower sub-unit below the roadside (Figs 9 & 10a) pinches out at both exposed ends, whilst the outcrop above the roadside (locality 7a; Figs 2, 3, 10a & b) can be traced along the section to the NNW for 120–130 m, before being lost in undergrowth; this sub-unit then cannot be found at the next exposed part of the section. It is interpreted to be pinched out at this margin, in similar form to the outcrop below the roadside.

Above the roadside, the sub-unit consists of a 10–12 m thick series of thinly bedded siltstones and sandstones, the majority of the beds being less than 2 cm in thickness (up to a maximum

Fig. 8. Photograph showing the step-wise decrease in the bedding of the Marnes Bleues in the hanging wall depocentre of the St Benoît Fault, locality 5. This indicates a series of separate discrete movements on the fault, separated by periods of tectonic quiescence.

Fig. 9. Photograph of the Crois d’Arment in the footwall Braux section, showing both the Braux-Lower and Braux-Upper sub-units. These are separated by a 15–20 m thick Marnes Bleues section.
of 1 m) separated by marl-rich mudstone horizons (Fig. 10b) (Sinclair 1994; Pickering & Hilton 1998; Kneller & McCaffrey 1999). The bedding strikes approximately SSW–NNE (194–201°), with an average dip of 40° towards the west. The sandstones are generally fine- to medium-grained, becoming silty as they drape and pinch out on to the underlying marls along the section to the SW. The beds display mainly parallel lamination, with some convolute and climbing-ripple lamination in the thicker beds, and also a high amount of both vertical and horizontal burrowing of the sandstones. Mudstones and siltstones in the uppermost portion of the section are highly convoluted and sheared. There are no palaeocurrent indicators apparent that can be measured with confidence, with weathering surfaces on exposed intra-bedding planes being easily mistaken for primary current lineation. However, using magnetic fabric analysis, a palaeoflow direction in a north–south direction has been determined (Tomasso
The sandstone unit is capped at this location by a 15-20 m thick succession of marls, above which lies the Braux-Upper sub-unit.

Below the roadside, the exposure of the Braux-Lower sub-unit is a 12.5 m thick outcrop of fine- and medium-grained sandstones and siltstones separated by marl-rich mudstones, similar to those of the above-roadside outcrop (Fig. 10a). The bedding attitude is the same as the above roadside outcrop, being 201°/40° W. The maximum bedding thickness is 1 m, with the average for the sandstone beds being 20-50 cm and 10 cm for the siltstones. Along the exposure, the beds thin and pinch out on to the underlying marls in both a SSW and NNE direction. Both the sandstones and siltstones are parallel laminated, with some ripple cross-lamination. At 9.5 m in the section there is a 1 m thick bed of highly contorted mixed grain-size sandstone and siltstone. Above the outcrop section another 20 m of marl-rich mudstones are exposed before entering the sandstones of the Braux-Upper sub-unit.

Braux-Upper sub-unit. This sub-unit is separated from the lower sub-unit by 15-20 m of marls (Fig. 9). It is exposed over a 2 km long, NNE-SSW-trending section along the easterly-facing hillside of the Crête-de-la-Barre. At the southwestern part of the exposure, the sandstones can be seen onlapping onto a formerly eastward-dipping topographic slope in the underlying marls (locality 8a, Figs. 2 & 3). The beds have an average strike and dip of 190°/20° W, which is 20° shallower than the dips of the lower sub-unit. The exposure consists of a 60 m thick section of tabular bedded sandstones (Fig. 9) (Stanley 1975; Stanley et al. 1978, Sinclair 1994, Hilton 1995; Pickering & Hilton 1999; Kneller & McCaffrey 1999).

In any one section, the lower 10-12 m are composed of thin (20 cm) parallel and cross-laminated fine-grained sandstones and siltstones, separated by dark grey mudstones. These are overlain by a succession of thickly bedded sandstones up to the top of the exposure. The beds of this succession have an average thickness of 1 m, with the thickness varying from a minimum of 20 cm to a maximum of 4 m. The thinner beds are composed of parallel laminated siltstones and fine-grained sandstones. The thick beds are composed of fining upwards coarse- to fine-grained sandstones, with mudstone and siltstone interbeds. The individual sandstone beds are generally massive in the lower portion, with parallel and ripple lamination in the upper, finer portions. Within the massive portions of the beds, there are often parallel layers of dark grey mudstone clasts (or the spaces left as they are preferentially eroded). Associated with these mudstone clasts, within the middle portion of some of the beds are highly convoluted finer sandstones containing a high proportion of matrix-bound clasts (predominantly mudstones); these are interpreted as debris flow 'sandwich beds' (Kneller & McCaffrey 1999). The beds are heavily bioturbated in places, with at least one bed exhibiting what appears to be a 2 m long vertical escape burrow. There is a wide variety of palaeocurrent data to be found in these sandstones, from flute- to groove-casts on the base of beds, to ripples and primary current lineations within the beds themselves. There are two main palaeoflow directions observed here, representing north-south and east-west directions of flow (Kneller & McCaffrey 1999; Tomasso 2001). Kneller & McCaffrey (1999) interpreted these directions as being the result of deflection of turbidity currents on encountering a NNW-SSW-striking palaeoslope in the underlying Maries Blanches.

Hanging wall block. The equivalent of the Braux-Lower sub-unit is exposed in the hanging wall of the St Benoit Fault, for the most part, as a series of inaccessible cliff sections just over a kilometre to the north of St Benoit (location 7b; Figs. 2 & 11). The sub-unit forms an 80 m thick package of sandstones gently conforming to the marls, which can visually be traced through the trees for 800 m to the west until they finally pinch out against the marls that drape the plane of the St Benoit Fault. These sandstones are overlain by a 20-25 m thick series of marls (Hilton 1995), which can variably be correlated across the St Benoit Fault to those marls that overlie the roadside outcrop of the Braux-Lower sandstones (Fig. 3).

The main (eastern) cliff outcrop is composed of a series of tabular bedded sandstones, with a strike and dip of 194°/05° W. There is a gentle thinning of the basal beds to the west, implying a westward onlap on to the underlying marls. The beds of the lowermost 45 m thick package average 1 m in thickness, with a bed thickness maximum of 4 m, and are composed of fining upwards coarse- and medium-grained massive sandstones (Hilton 1995). There is some parallel lamination present in the upper part of the beds, with the beds being separated by thin mudstone layers. Above this is a 5 m layer of mudstones and thin siltstone and fine sandstone beds. The 30 m package above this is composed of thick, amalgamated medium- and coarse-grained sandstone beds, with few mudstone layers present. Palaeocurrent data collected from sparse
Fig. 11. Photograph of the lowermost Grès d’Arnet exposed in cliffs in the hanging wall block, to the north of St Benoit. The thickened Braux-Lower sub-unit which overlies the underlying Marne Bleue (locality 7b) is separated from the overlying Braux-Upper sub-unit (locality 8b) by a marl succession.

groove casts here suggests a NNW-SSE direction of flow (Hilton 1995; Pickering & Hilton 1998).

In the western cliff exposure, the sandstones onlap abruptly against the marls. Although this 50 m thick section is inaccessible, it is very similar to the upper half of the eastern cliff exposure. The basal part of the outcrop consists of ~10 m of thick, tabular bedded sandstones separated by thin darker layers (inferred to be mudstones). These are overlain by a ~2 m section of mudstones containing several thin beds of either siltstone or sandstone. Above this is a thick (30–25 m) set of amalgamated sandstone beds, again overlain by a thin (~2 m) series of mudstones and thin siltstones/sandstones.

The Braux-Upper sandstones to the north of St Benoit (locality 8b; Figs 2 & 3) are similar in form to those in the footwall section, with thickly bedded sandstones separated by thin mudstone partitions (Hilton 1995; Pickering & Hilton 1998). They can be visually traced around to the above roadside Crête-de-la-Barre section (Fig. 3).

Evidence of synsedimentary structures

Evidence of tectonic activity during this period is contained at the contact between the Calcaires Nummulitiques and the Marne Bleue. Over a 400 m section to the west from the footwall crest, the limestones gently dip at 36–36°W for 200 m, and are then folded in a monocline (locality 6; Figs 2, 3 & 12), the dip increasing rapidly over 40 m to 85°W and then immediately shallowing to around 20°W. The lowermost section of the marls, lying directly above the calciturbidite beds is also monoclinally folded. The marls above this, however, rapidly shallow off to a dip of around 35–40°. The marls on this western, footwall side of the St Benoit Fault thicken westward from 70–80 m at the crest of the footwall to 300 m in the Coulomp Valley 2 km to the west, before the lowermost Grès d’Arnet are encountered. The bedding strikes approximately north-south, with dips shallowing from 35–40°W below the Braux-Lower sandstones to 20°W below the Braux-Upper sandstones.

Monoclinal folding of this kind can be related to compressional, extensional or strike-slip structural models. Monoclinal folds classically develop above propagating thrust faults, as tip folds related to shortening during thrusting (e.g. Davis 1978; Williams & Chapman 1983). However, monoclinal drape folds can form in extensional environments where they lie above buried normal faults, developing as the fault moves and propagates upward (e.g. Friedman et al. 1976; Willey et al. 2002). In both these compressional and extensional cases, as the strike of the fold is parallel to that of the St Benoit Fault, this buried fault would lie parallel to the St Benoit Fault. However, there is no field evidence in the Calcaires Nummulitiques or Cretaceous limestones lying below the region of the folding to support either hypothesis. An extensional basal décollement surface lying at some point below the Calcaires Nummulitiques might result in gravity-induced folding (e.g.
Fig. 12. The monoclinal fold exposed in the uppermost Calcaires Nummulitiques/lowermost Marnes Bleues of the footwall block; locality 6. (a) Photograph of the fold, taken from the roadside above. (b) Line drawing enlargement of the fold, including bedding data.

Buffler 1983; Duval et al. 1992; Turner 1995). This assumes that the folding takes place in the hanging wall of the detachment; the outcrops here lie within the footwall of the fault. Again, there is no field evidence for the development of this style of folding within the study area, although in this region of the southwest Alps there are deep decollement surfaces within Triassic-aged units that are related to the westerly movement of the Digne Thrust (Fry 1989). The preferred interpretation of this folding is that it is due to a strike-slip component of movement on the St Benoit Fault during fault-block evolution, resulting in the slight changes in the direction of extension. The oblique striations on the plane of the St. Benoit fault (locality 1) indicate that there has been at least some lateral movement on this fault. The established structural regime of the area (Paillot 1971; Raveneau et al. 1987) supports this interpretation.

On the eastern, hanging wall side of the St Benoit Fault, the thickness of the marl increases to 400 m (Raveneau et al. 1987; Pickering & Hilton 1998). The bedding attitude of the marls on this side of the fault shallows up through the exposure in a series of rapid changes (Figs 3 & 8), with thickening of the marls towards the fault.

Geological synthesis of the study area

The most recent work on the Braux–St Benoit section (Kneller & McCaffrey 1999) interprets
the sandstones as being deposited from a static localized point-source. This source has since been eroded, but is suggested to have been located around the village of St Benoit. This superseded Hilton's (1995) interpretation of a distal delta system, with the main source being in the St Antonin region to the SE.

Taking into account the above field observations, and assimilating the published work by Mougis (1978), Apps (1987), Ravenne et al. (1987), Sinclair (1994, 2000), Sayer (1995), Sinclair et al. (1998) and Kneller & McCaffrey (1999), and the mapping by the BRGM, a new depositional model for this outcrop can be established. This new depositional model can be described in terms of four main divisions (Fig. 13), discussed below.

1. Early to Mid-Eocene (>40 Ma; Fig. 12a)

As the thrust wedge of the Alpine orogen propagated to the west, carbonate ramps developed on the distal crustal margin due to a lack of
tarrygenous clastic input (Sinclair et al. 1998). Two formations were deposited during this interval: the Inferanian Nummulitic Formation (Sinclair et al. 1998) and the Calcaires Nummulitiques (the basal portion of the Tertiary succession in the Aromat area).

An Upper Eocene-aged post-Pyrenean-Provençal extensional phase is reflected by normal faulting along the River Var and the Rouaine Fault (Ravenne et al. 1987), and also in the Deyrol region to the north (Meckel et al. 1996). This generated a series of SW-NE-striking normal faults, downthrowing to the SE. This extensional phase is associated with the rapid deepening of the basin carbonates, which pass from shelf to slope types containing thin gravitational sediments with progression into the basin (Ravenne et al. 1987).

The Calcaires Nummulitiques in the Braux area are part of the shelfal carbonate succession (Sayer 1995; Sinclair et al. 1998). A sinistral sense of strike-slip on the Rouaine Fault (Pickering & Hilton 1998) generated a north-south-striking, normal fault downthrowing to the east reflected by the Benoi splay fault (Painis 1971). This cut through the limestones, creating an eastern (St Benoit) block and a western (Braux) block. The fault plane, visible at locality 1 in Figures 2 and 3, has a strike and dip of 355/32° E.

2. Mid to Late Eocene (40–38 Ma; Fig. 13b)

Rapid normal fault movement on the St Benoit Fault caused the downthrow of the St Benoit Block (Painis 1971). This downthrow and associated deepening of the St Benoit block is reflected by faunal change in the upper carbonate succession of the Calcaires Nummulitiques (Sayer 1995; Sinclair et al. 1998). Whilst in the footwall block the faunas represent a shallow-water inner ramp or confined lagoon setting, in the hanging wall block the section thicknesses increase (indicating a syntectonic deposition) and see a trend to lower faunal diversities, typical of a lower energy mid-ramp setting (Sinclair et al. 1998).

Further movement and rotation of the fault blocks led to a deepening of the shelfal carbonates of the Braux block. This is reflected by faunal changes at the top of the Calcaires Nummulitiques (locality 3; Figs 2 & 3) followed by a drowning surface, consisting of a thin bed of reworked bioclasts capped by a thin reddened bioclastic bed. Both of these beds are heavily bioturbated, an indication of a break in sedimentation. Above these there is an immediate change into the hemipelagic Marnes Bleues Formation. Fault-block movement and rotation is also recognized as the source of the calciturbidites further to the SW (locality 4), containing finely disseminated bioclasts resulting from sediment destabilization towards the footwall crest. These beds pinch out towards the fault zone to the NE.

Increase in the relative water depth, both through tectonic and eustatic changes (Ravenne et al. 1987; Sinclair et al. 1998), allowed hemipelagic Globigerina-rich marls (the Marnes Bleues Formation) to drape the underlying carbonate topography of the area. Mougin (1978) plotted ratios of planktonic foraminifers within the marls that indicated an overall deepening towards the top of the succession. The marls thicken in the St Benoit Fault Block towards the fault, with stepwise change in the dip of the marls indicating that the fault was still undergoing sporadic extensional movement at this time. These marls are dated as being in the P1.5 stage of benthi foraminifera (Mougin 1978), which represents a time range of 40–38 Ma (Li et al. 1995).

3. Uppermost Eocene time (38–37.6 Ma; Fig. 13c)

Marl deposition continued to drape the underlying topography. Sinistral strike-slip movement on the St Benoit Fault (Painis 1971; Ravenne et al. 1987) created a monoclinal fold in the footwall block, visible at locality 6 in Figures 2 and 3. The limbs of this fold strike sub-parallel to the fault plane, deforming the Calcaires Nummulitiques and lower Marnes Bleues. The fault movement and associated folding resulted in a topographic high over the fault plane, with a depression in the footwall. Continued deposition of the marls, as draped over this footwall depression, formed a series of shallow undulating topographic lows.

Initiation of theifting of the Corsica-Sardinian Massif and the opening of the Ligurian Sea (Stanley & Mutti 1968), possibly coupled with the climate change at this time (Ravenne et al. 1987; Bestland 2000), would have increased sediment supply to the St Antonin delta system to the SE of Braux (Hilton 1995; Sinclair 1994, 2000). The first sandstones were now deposited from turbidity currents, forming the Braux-Lower sub-unit. These are predominantly preserved as thick-bedded sandstones, containing the T4 and T6 divisions of the Bouna (1962) sequence, on the eastern (hanging wall) side of the St Benoit Fault. The more dilute portions
of the flows were able to surmount the barrier created by the fault, and deposited sandstones in the shallow lows of the footwall marls. This preserves the thin, well-structured and well-sorted fine-grained sandstone beds exposed at the roadside section (locality 7a; Fig. 10). Flows moved through these lows in a NNW direction (palaeoflow determined from magnetic fabric analysis [Tomasso 2001]).

Further fault-block rotation caused the sandstones of the Braux-Lower sub-unit on the footwall block to move to the steeper bedding dip angle they have at present when compared with the Braux-Upper sub-unit. This movement is reflected by a 1 m thick sheared and slumped unit at the top of the Braux-Lower sub-unit.

After the initial sandstone event, there was a break in siliciclastic sedimentation. This allowed another 15-25 m of hemipelagic marls to be deposited on top of both the footwall and hanging wall successions. These marls are dated as being mid P16 age on the benthic foraminiferal biostratigraphic scale (Mougin 1978), which corresponds to approximately 37.6 Ma (Li et al. 1995).

4. Lowermost Oligocene (post: 37.5 Ma; Fig. 13d)

Sediment supply from the SE increased, and the sandstones of the Braux-Lower sub-unit were deposited, onlapping on to the underlying eastward dipping topography of the marls. The presence of thickly bedded, normal-grained turbidite sandstones on the footwall block indicates that the St Benoit Fault was no longer a major barrier to deposition.

Deposition of the Grès d’Annot: a discussion

The sandstone deposits of the study area comprise some of the lowermost fill of the Annot sub-basin. These were initially confined within a half-graben topographic low bordered by the fault scarp of the St Benoit Fault, draped by the Marnes Bleues. The sedimentation processes within this topographic low are analogous to the filling of the Annot sub-basin itself: Sinclair & Tomasso (2002) have defined a four-phase depositional sequence, that occurs within topographically confined turbidite basins, that is based upon outcrop work in the Grès d’Annot and the Taveyanne Sandstones of eastern Switzerland [Sinclair 1992], and sub-surface data from the Gulf of Mexico. Briefly, this consists of flow ponding (phase 1), flow stripping (phase 2), flow bypass (phase 3) and blanketing (phase 4), and is termed the ‘confined basin sequence’ (Sinclair & Tomasso 2002).

In the fill of the St Benoit hanging wall, it is possible to recognize at least the first two phases of the confined basin sequence. The lowermost sandstones of the Braux-Lower sub-unit in the hanging wall block are typical of the flow ponding phase, with all of the sediment deposited from the turbidity flows. This gives a succession of bedded sandstones separated by mudstone and marl interbeds. The sandstones above this are more thickly bedded, coarser-grained and amalgamated, with much less preserved mudstones. Equivalent sedimentation on the footwall block is preserved as thinly bedded fine-grained sandstones, siltstones and mudstones, confined to shallow topographic lows.

This difference in both grain-size and sedimentary style is attributable to the flow-stripping phase of the confined basin sequence (Sinclair & Tomasso 2002). Whilst originally described from turbidity current flows in submarine channels (Piper & Normark 1983), it is possible for flow separation to occur within heterogeneous gravity currents on encountering topographic obstructions (e.g. Baur et al. 1997; Kneller & McCaffrey 1999; Kneller & Buckee 2000) such as within a confined basin. Filling of the topographic low with sediment lowers the relative height of the topographic barrier, reaching the point at which some of the sediment can flow out of the confining area, thus being stripped from the flow. For the amalgamated sandstones of the St Benoit Block, encountering the topographic barrier of the fault scarp allowed the sediment to be flow-stripped, with the deposition of the stripped sediment deposited within topographic lows in the footwall high.

Conclusions

Examination of the limestones, marls and sandstones of the Braux-St Benoit area had led to a modified model for the geological evolution of this study area. The model recognizes the fact that movement on the St Benoit Fault played an important role in the different depositional styles of the Braux-Lower and Braux-Upper sub-units of the Grès d’Annot. Regional extension initiated faulting, reflected by the development of the St Benoit Fault. Fault-block rotation and deepening is reflected by faunal variation across the fault, along with a drowning surface and calciturbidites at the top of the Calcaires Nummulitiques and internal onlaps within the bedding of the marls in the
The authors acknowledge the University of Birmingham and BP Exploration and Operating Co. Ltd for funding a Ph.D. studentship (MT), and the AAPG Grant-in-aid Foundation for contribution to the cost of fieldwork (MT). We also thank B. Kneller and J. Van Den Driesche for their constructive reviews, which greatly improved the final version of this manuscript.

References


PAKIR, J.-L. 1971. Effects de la tectonique en 'coina' sur
la marge orientale du synclinal d'Annot. Géologie


deposition patterns and flow characteristics.
Navy Submarine Far, California Borderland.
Sedimentology, 30, 681–64.

RAVENNE, C., VIALL, R., Riche, P. & TROMBETTANIS, P.
1987. Sedimentation et tectonique dans la basin
marin Eocene Superieur-Oligocene des Alpes du
sud. Revue de l'Institut Francais du Pétrole, 42,
529–553.

Depositional Styles in a Foreland Basin Setting; Eocene,
of Durham.

SIDDAMS, A. W. B. 1979. Arcuate fold and thrust
patterns in the Subalpine Chains of Southeast

during Alpine thrusting: the Taveyanne Sandstone
of eastern Switzerland. Sedimentology, 39,
837–856.

SINCLAIR, H. D. 1994. The influence of lateral basin
slopes on turbidite sedimentation in the Annot
Sandstones of SE France. Journal of Sedimentary
Research, 64, 43–54.

SINCLAIR, H. D. 2000. Delta-fed turbidites infilling topog-
raphically complex basins: a new depositional
model for the Annot Sandstones, SE France.

Carbonate sedimentation during early foreland
basin subsidence: the Eocene succession of the
French Alps. In: Wright, V. P. & Burchette, T. P. (eds) Carbonate Ramps; Geological Society,

evolution of intra-slope turbidite sub-basins.
Journal of Sedimentary Research, 72, 452–457.

STANLEY, D. J. 1975. Submarine canyon and slope
deposition (Gris d'Annot) in the French
Maritime Alps. 9th International Sedimentological
Congress, Nice.

STANLEY, D. J. & MUTTI, E. 1968. Sedimentological
evidence for an emerged land mass in the Ligurian
Sea during the Paleocene Natura, 218, 33–46.

Coarse sediment transport by mass flow and
sediment transport processes and downslope tran-
sformations in Annot Sandstone canyon-fan
valley systems. In: STANLEY, D. J. & KELLING, G.
(ed) Sedimentation in Submarine Canyons, Fans,
and Trenches, Dowden, Hucshinson & Ross,
Stroudsberg, PA, 185–200.

SURLYK, F. 1978. Submarine fan sedimentation along
fault scarps on tilted fault blocks (Jurassic-Cretace-
sous boundary, East Greenland). The Geological

TOMASSO, M. 2001. Sedimentary Evolution of Topo-
graphically Confined Turbidite Basins. The Annot
Sandstones of Southeast France. Unpublished

TURNER, J. P. 1995. Gravity-driven structures and
rift basin evolution: Rio Muni basin, offshore
equatorial West Africa. American Association of

WILLIAMS, G. & CHAPMAN, T. 1983. Strains developed in
the hangingwall of thrusts due to their slip/
propagation rate: a dislocation model. Journal of
Structural Geology, 5, 563–571.

Early evolution of an extensional monoclinal by a
propagating normal fault: 3D analysis from com-
bined field study and numerical modeling. Journal
of Structural Geology, 24, 651–669.