Process controls on the development of stratigraphic trap potential on the margins of confined turbidite systems and aids to reservoir evaluation

William McCaffrey and Benjamin Kneller

ABSTRACT

Stratigraphic trapping at pinch-out margins is a key feature of many turbidite-hosted hydrocarbon reservoirs. In systems confined by lateral or oblique frontal slopes, outcrop studies show that there is a continuum between two geometries of pinch-out configuration. In type A, turbidites thin onto the confining surface—although the final sandstone pinch-out is commonly abrupt—and individual beds tend not to erode into earlier deposits. In type B, turbidite sandstones commonly thicken toward the confining slope, and beds may incise into earlier deposits. These two types may occur in combination, to give a wide spectrum of pinch-out characteristics. Our analysis suggests the principal control in determining pinch-out character is flow magnitude, with smaller flows producing type A and larger flows producing type B.

In areas of poor seismic control it can be difficult to assess either pinch-out character or the proximity of wells to confining slopes. Because estimates of paleoflow magnitude can be made from core or high-quality log image data, however, it is possible to make reasonable estimates of pinch-out character even from wells such as exploration wells, which may be placed conservatively, away from the field margins. Furthermore, systematic paleoflow variations and thickness trends are commonly seen in individual turbidite sandstones as they approach confining slopes. For example, dispersal directions indicate flow deflection parallel with the strike of confining topography; beds thin toward type A onlaps and thicken toward type B onlaps. These relationships can be exploited via analysis of vertical successions to constrain well position with respect to the slope. Similarly, the presence, location, and frequency of locally derived debrites can provide information on the presence and proximity of confining slopes.

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INTRODUCTION

Over the last three decades, turbidite accumulations have come to assume great economic significance as hydrocarbon reservoirs, occurring in more than 80 sedimentary basins worldwide and at least 15 examples having estimated recoverable reserves in excess of 1.0 billion bbl of oil equivalent (Weimer and Link, 1991). Turbidite reservoirs occur in a variety of tectonic settings, including lacustrine and marine rift settings; postrift intracratonic basins; passive margin basins (including those influenced by shale and salt diapirism and by growth faulting); and forearc, transform, and foreland basins (see review in Weimer and Link [1991]). In many of these settings, the development of turbidite systems is influenced by turbidity current flow around or over confining topography (e.g., Apps et al., 1994). Indeed, seismic recognition of lateral pinch-out geometries is proposed as a key identification criterion for turbidite fans in general (Posamentier and Erskine, 1991).

Where turbidites form topographically constrained sheet systems (sensu Haughton, 1994a), the possibility arises of stratigraphic trap development at system margins. For example, the late Pleistocene Brazos-Trinity system, deposited in salt-withdrawal minibasins on the Gulf of Mexico continental slope, is partially characterized by onlapping sheet sandstones and is used as an analog for more deeply buried ponded fans (Winker, 1996). Recognition and exploitation of stratigraphic traps form a key component of many turbidite-hosted plays (Pettingill 1997, 1998). Fields containing ponded sheet sandstones include the Neogene Auger and Mars fields from the Gulf of Mexico (Mahaffie, 1994; McGee et al., 1994). Despite studies such as these, evaluation of pinch-out geometries is still hampered by an imprecise understanding of the processes that control sand deposition against confining slopes.

The majority of published work on the interaction of turbidity currents and confining surfaces has focused on determining whether deposits show evidence of deflection and/or reflection (e.g., Kneller et al., 1991; Smith and Anketell, 1992; Clayton, 1993; Haughton, 1994b; Sinclair, 1994; Kneller, 1995; Kneller and McCaffrey, 1999). The facies analysis in these studies is principally concerned with using paleoflow data together with the structure of individual beds to evaluate the relative importance of these processes. Only more recently (Haughton, 1994b; Hurst et al. 1999; Kneller and McCaffrey, 1999) has there been any attempt to characterize the sandstone geometries developed against confining slopes (e.g., basin margins or topographic highs) or evaluate the controls on their development. These studies, however, focused on those types of pinch-out configurations in which turbidites thin toward the confining slope and did not consider the effects of aggradation. The aims of the outcrop studies of the Annot Sandstone detailed in following sections are first to further our understanding of the controls on the development of pinch-out configurations, including those in which turbidites thicken toward the confining slope. A second aim is to assess the development of systematic spatial variations in sedimentary character induced as confined systems aggrade and to assess their usefulness in reservoir evaluation.

THE TERTIARY ALPINE FORELAND BASIN OF SOUTHEAST FRANCE

The Annot Sandstone (Grès d'Annot) of southeast France and its correlative deposits (e.g., the Champsaur Sandstone) form a widespread unit of lower Tertiary turbidites deposited in the Alpine foreland basin (Elliott et al., 1985; Sinclair, 1997). This is an ideal system in which to characterize sandstone geometries developed against confining slopes, because the basin floor was bathymetrically complex, being divided into a series of discrete subbasins. This division is related to the development of a piggyback basin (Elliott et al., 1985; Apps, 1987), and the Tertiary subbasins are interpreted as the surface expression of a thrust system within the underlying Mesozoic section. In the Maritime Alps, mild postdepositional deformation and good exposure aid the characterization of pinch-out geometries at the margins of these subbasins. The outcrop studies detailed here focus on confining slopes preserved at the margins of the Annot and Peira Cava subbasins (Figure 1). Our analysis is divided into two sections: characterization of sandstone geometries developed against the confining slope and characterization of facies changes observed approaching the slope.

Stratigraphy

The Alpine Tertiary foreland succession rests with erosional unconformity on a basement of Mesozoic limestones and comprises three distinct lithostratigraphic divisions: a basal bioclastic (Nummulitic) limestone of up to 200 m thickness; an intermediate hemipelagic (*Globigerina*) marl that is between 50 and 300 m thick;

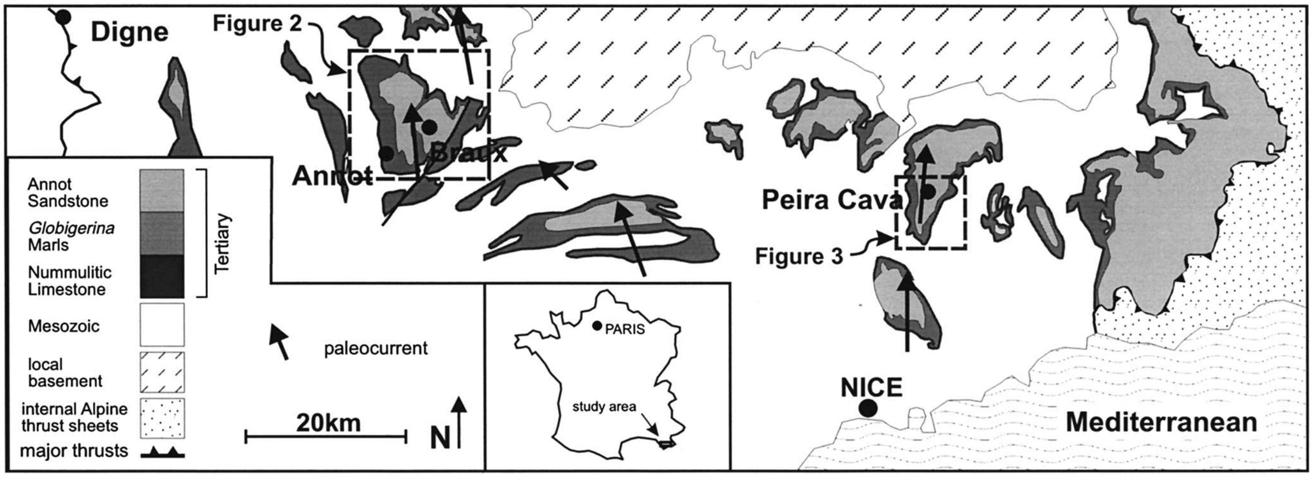

Figure 1. Locality map for the Annot Sandstone, showing regional paleocurrent patterns; data from Elliott et al. (1985), Ravenne et al. (1987), and Sinclair (1994). Simplified regional stratigraphy based on a Bureau de Recherchés Géologique et Minières BRGM map (Kerckhove et al., 1979).

and the upper turbidite interval. The micropaleontology of the uppermost marls suggests that water depths were about 900 m at the onset of turbidite sedimentation (Mougin, 1978). Although thickness variations in both the limestone and the marls indicate that they partially filled the paleotopography (Ravenne et al., 1987), the turbidity currents nevertheless encountered significant submarine relief. Despite regional paleocurrent patterns showing northward dispersal for much of the turbidite system (e.g., Pickering and Hilton, 1998), local paleocurrent patterns are much more variable within individual subbasins, owing to ponding and deflection of the turbidity currents and the presence of bypass pathways between subbasins.

The Annot Subbasin: Braux System

The basin margin bounded the subbasin preserved around the village of Annot (Hilton and Pickering, 1995) (Figure 2); intrabasinal highs related to ramps in the underlying thrust system separated it from other subbasins (Elliott et al., 1985; Apps, 1987). This subbasin contains at least two temporally distinct turbidite systems, of which the older Oligocene Braux system is included in this article. The Braux system constitutes a moderately sandy sheet complex, point-sourced in the east, that has a sand/shale ratio of about 2:1 overall (Kneller and McCaffrey, 1999). The section described in this article was deposited after earlier sandstones had buried the initial basin-floor topography (Apps, 1987; Ravenne et al., 1987), so the turbidity currents were able to expand across a relatively flat basin floor until confined by an east-northeast–dipping slope on the southwest side of the subbasin. This basin-margin slope provides an example of oblique frontal confinement. Its gradient before compaction has been estimated at about 12° (Sinclair, 1994; Kneller and McCaffrey, 1999).

The Peira Cava System

The fill of the Peira Cava subbasin comprises one of the oldest turbidite complexes in the basin and probably

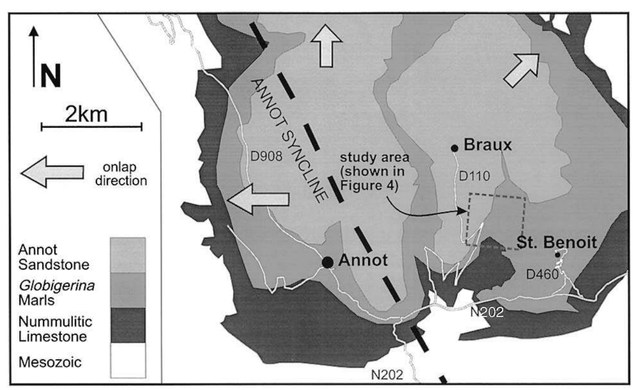

Figure 2. Sketch map of the Annot/Braux area, based on a BRGM map (Bordet et al., 1980). Onlap directions within the Annot Sandstones based on data from Elliott et al. (1985). Outlined study area corresponds to the basal plane of Figure 5 and to the area of Figure 11.

one of the bathymetrically deepest. It constitutes a ponded sheet sandstone system that has the westerly confining slope preserved on the western limb of a north-south syncline (Figure 3). The eastern basin margin is not preserved but was almost certainly the contemporary Alpine thrust-front (see discussion in the following section). Thus the likely overall structure of the Peira Cava basin was an elongate trough that had its long axis oriented north-south. Although paleocurrent patterns can be complex in detail, sole structures indicate that flow was generally directed to the north, parallel with the local basin margin (e.g., Bouma, 1962) (Figure 4). The western margin therefore provides an example of lateral confinement. The gradient before compaction is estimated at about 11° (based on pinch-out geometries against the confining slope and taking an overall sand-to-shale value of about 0.6).

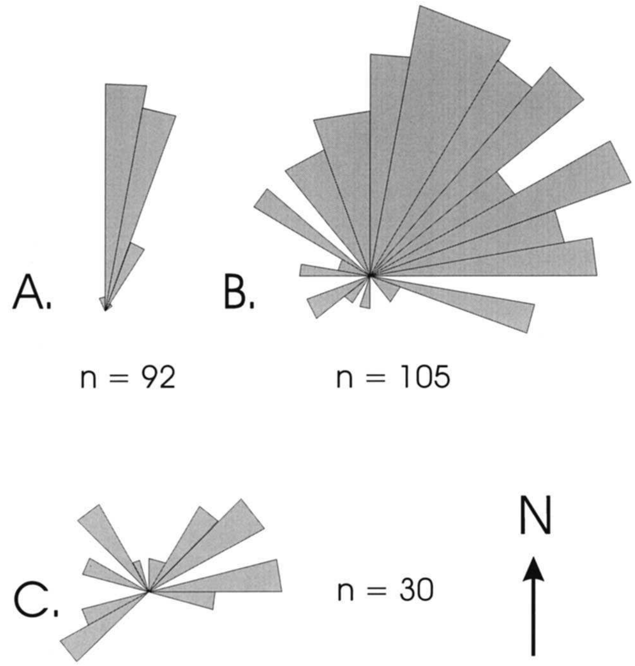

Figure 4. Summary paleocurrent data collected from the D21 road section at Peira Cava. (A) Sole structures. (B) Ripple cross-lamination data. (C) Ripple cross-lamination data whose transport direction diverges more than 30° from their associated sole structures. Sole structures exhibit a single mode, showing consistent transport to the north. The ripple cross-laminations show transport to the north and east, with a weaker mode to the west-southwest.

TURBIDITE GEOMETRIES DEVELOPED ADJACENT TO CONFINING SLOPES

The Braux System

We measured four outcrop sections at Braux, whose positions with respect to the confining paleoslope are shown schematically in Figure 5. The sections are presented in Figure 6. We made accurate correlations between the sections, physically tracing one key bed across the hillside between sections and establishing the others by inspection and photointerpretation,

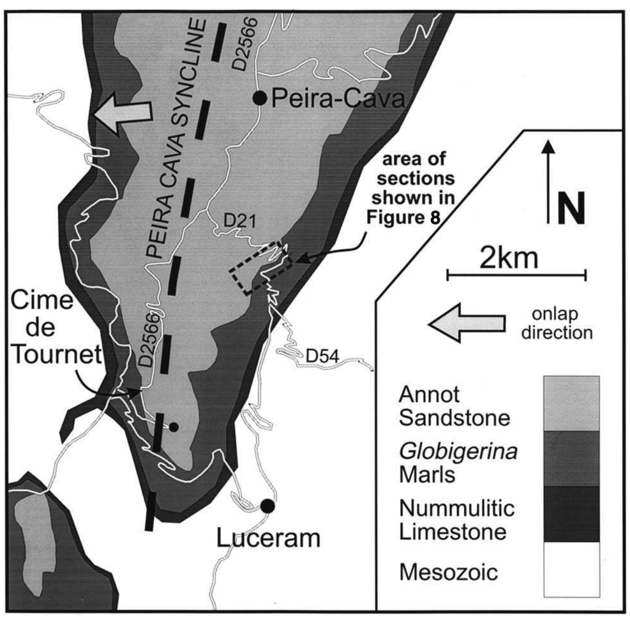

Figure 3. Sketch map of the Peira Cava area, based on BRGM maps (Goguel, 1967; Geze et al., 1968). The measured sections are located on and around the D21 road section within the outlined study area.

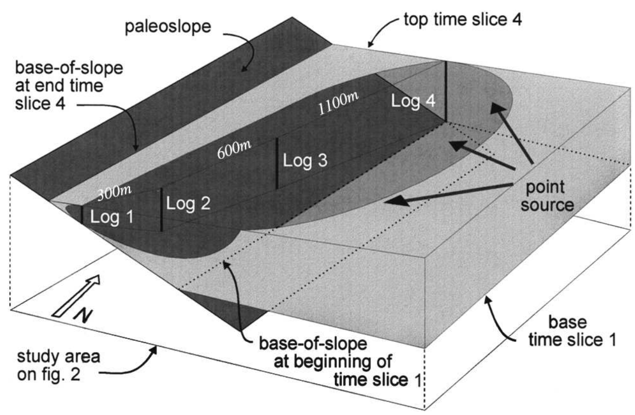

Figure 5. Schematic illustration of the Braux paleoslope. Cutaway is to show the relative positions of the four measured sections with respect to this slope. Dark arrows illustrate the radial distribution pattern inferred for turbidites on the basin floor. The time slices are illustrated in Figure 6.

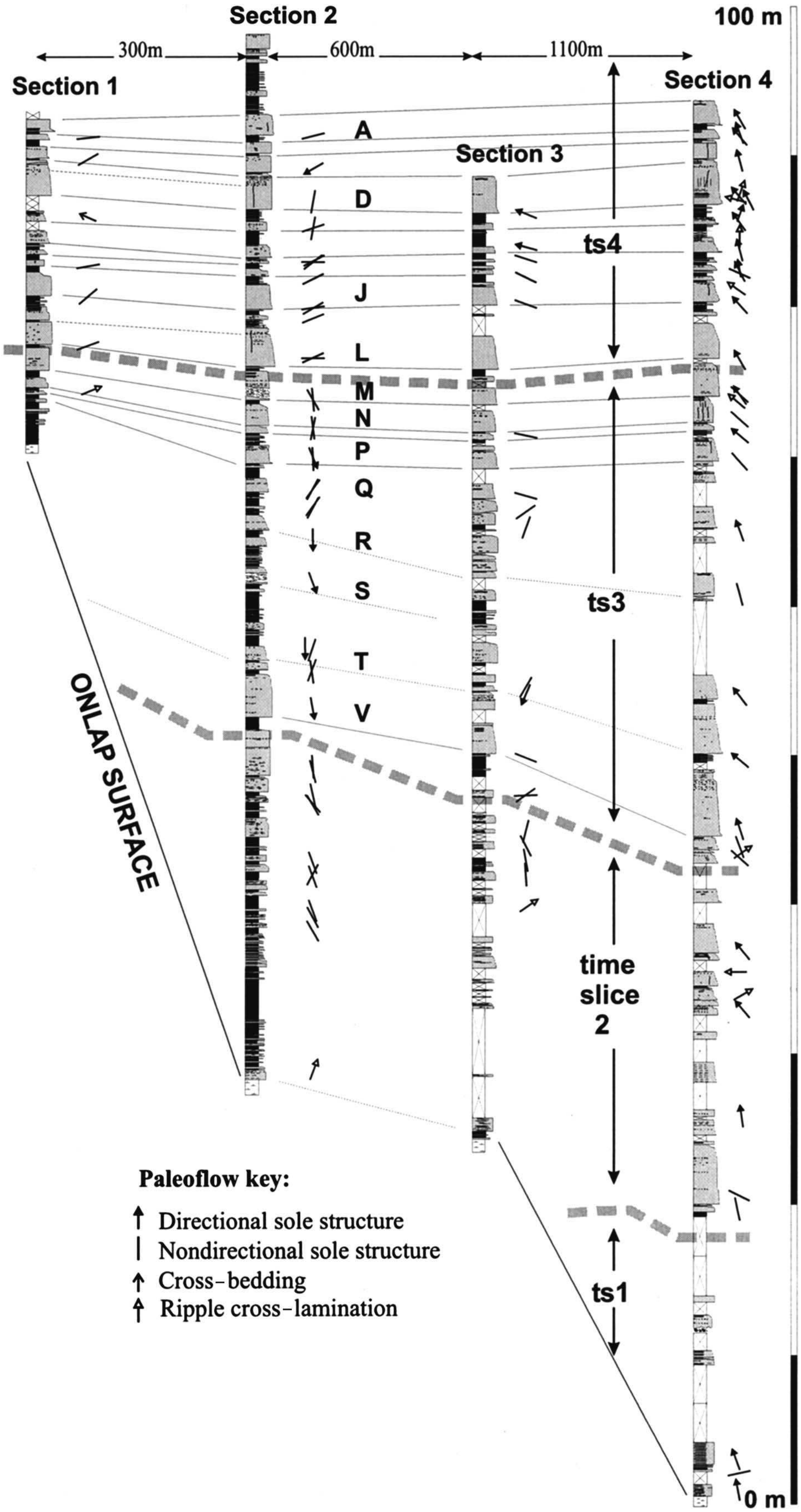

Figure 6. Correlated outcrop sections measured at and away from the Braux pinch-out (modified after Kneller and McCaffrey, 1999). Section 2 is measured along the D110 highway. Beds generally thin onto the onlap (e.g., beds L, N, and V), resulting in the development of a type A pinch-out geometry. The confining slope, however, is interpreted not to be planar but to have minor ridges and embayments. Compensation into this secondary topography results in some beds locally thinning basinward before thickening again (e.g., the bed at the top of time slice 1). A general downward thinning succession toward the confining slope can be seen (e.g., section 2 from bed V downward).

allowing us to observe bed thickness and other facies transitions in individual beds as they approached the confining slope and to determine plan-form dispersal patterns (Kneller and McCaffrey, 1999).

In sections immediately adjacent to the confining slope, the sandstones are typically thin (up to about 0.5 m), well-sorted, and horizontally or ripple cross-laminated. Individual beds tend not to have erosional bases. The final sandstone pinch-out against the confining surface is commonly abrupt (Figure 7), although a thin drape of fine sandstone is commonly deposited some way up the confining slope before it, too, pinches out. A turbidite mudstone drape commonly persists farther up the slope than the sandstone, suggesting that the mud-bearing part of the flow was eventually ponded to a higher level than the sand pinch-out. Sinclair (1994) and Kneller and McCaffrey (1999) note that repeated normal grading is common within the thinner beds, with several repetitions of a succession some 5 to 10 cm thick, comprising structureless through horizontally to ripple cross-laminated sandstone, sometimes having truncated convolute laminae or minor load structures at the breaks in grain size. This facies is commonly developed adjacent to confining surfaces in other basins (e.g., Haughton, 1994b; see subsequent section "Data from Other Pinch-Out Margins"). As these pinch-out successions are traced out onto the basin floor, the facies typically are transitional into massive, moderately to poorly sorted, coarse-grained sandstones, in beds up to about 4 m thick (Figure 6), separated by thin mudstones. The thicker sandstones are commonly ungraded except at the top (delayed grading, sensu Lowe, 1982) and have flat (nonerosive) bases; dewatering structures are relatively common, as are sandstone injections into the adjacent facies (Kneller and McCaffrey, 1999).

Figure 6 illustrates how individual beds tend to thin toward the confining slope (e.g., beds L, N, and V). This results in an overall downward thinning succession toward the confining slope over tens of meters, as described by Sinclair (1994) from other outcrops. Section 2 from bed V downward provides a good illustration of such a trend. Examination of beds such as T suggests that slope-induced thickness changes cannot be detected beyond about 500 m into the basin. The Braux outcrops form an example of a type A pinch-out configuration.

The Peira Cava System

We measured some 650 m of section along or adjacent to the D21 highway, representing a near-vertical section upward from the confining surface; the lowest 200 m are reproduced in Figure 8. Two distinct pinch-out geometries are seen in this system. Thin-bedded sandstones in the lowest about 40 m of section above the onlap slope show laminated facies related to the confining slope, as described in the previous section, on the Braux pinch-out. Above this section the succession contains a wide variety of facies. Of particular interest are base-of-slope massive sandstones and thick, sheet-form, graded beds.

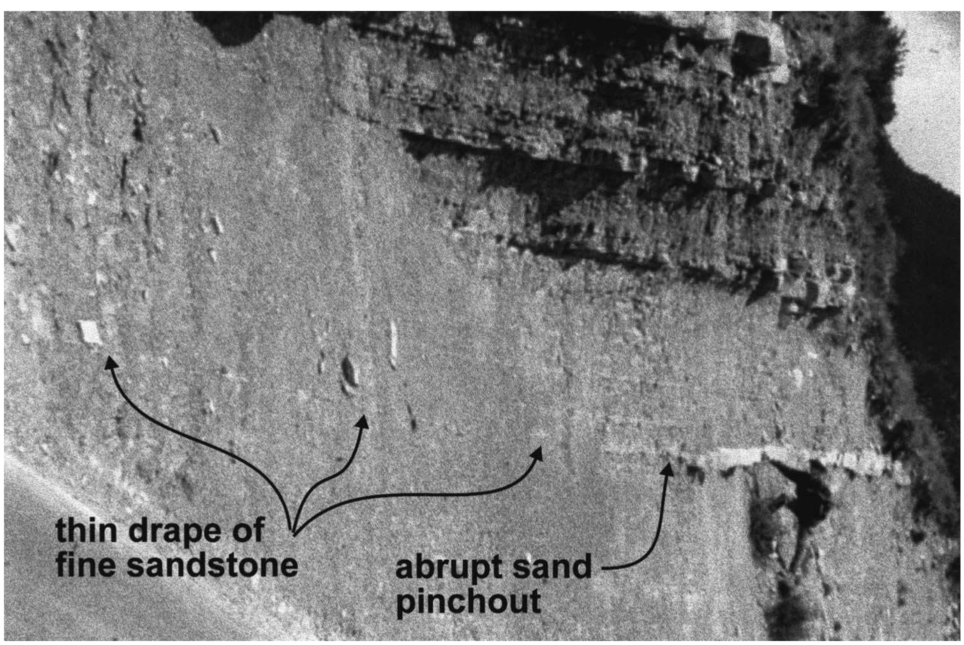

Figure 7. D110 Braux Road section, Annot Sandstone, southeast France, illustrating turbidite sandstone thinning toward the confining surface and pinching out abruptly against it (modified after Kneller and McCaffrey, 1999). The pinch-out point corresponds to the paleo–base-of-slope, and the thin drape of fine-grained sandstone picks out the paleoslope. This comprises a type A pinch-out geometry (see text for discussion).

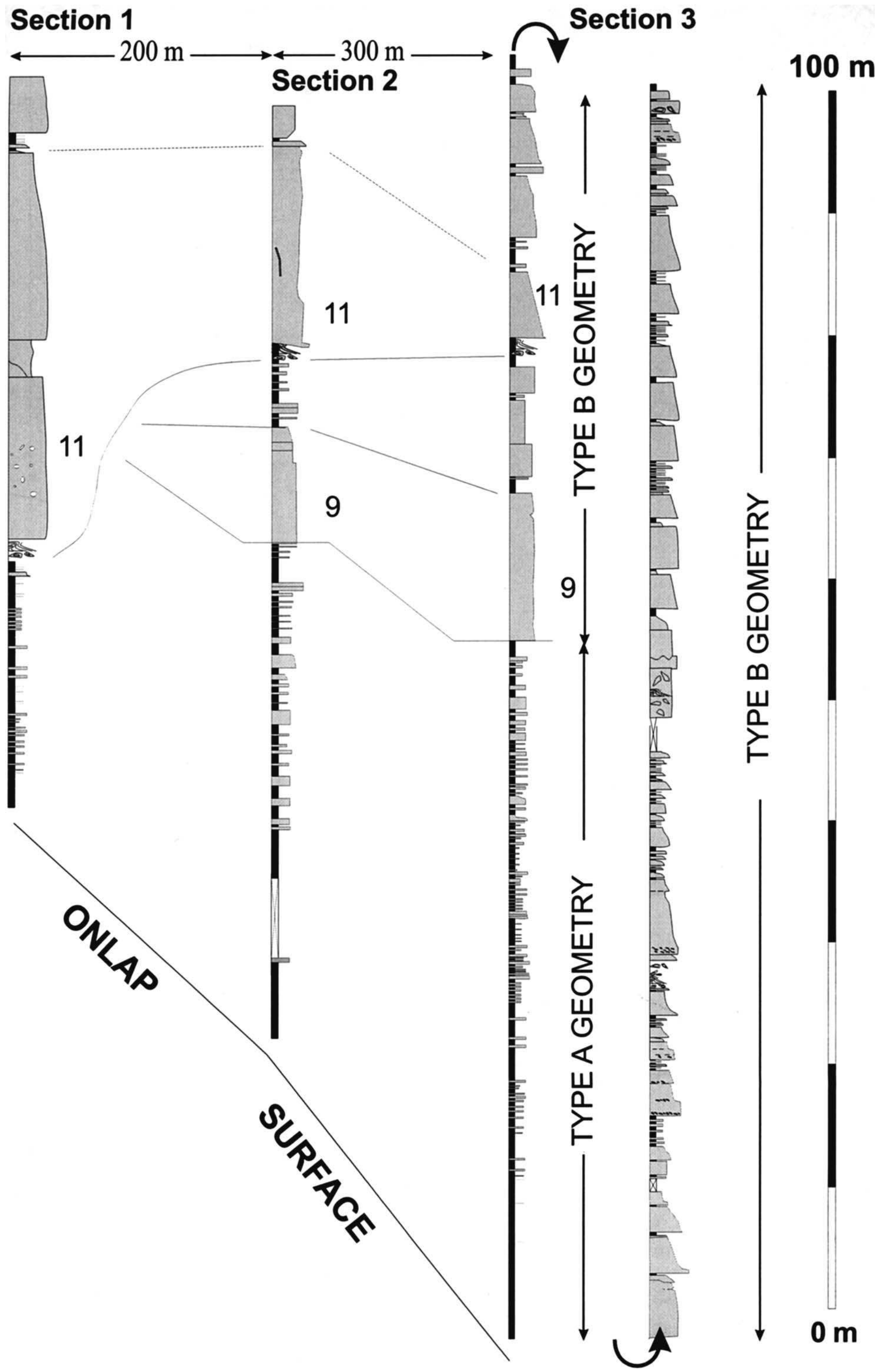

Figure 8. Correlated outcrop sections measured at and away from the Peira Cava pinch-out slope. Section 1 was measured on the hillside above the D21/D54 highway junction. Sections 2 and 3 were measured along the D21, where the same stratigraphy is intersected along two adjacent sections of road separated by a hairpin bend (the restored slope dips ~12° to the east). This outcrop is an example of a mixed system, exhibiting a type A geometry in the lowest part of the section, followed by an abrupt transition into a succession that is predominantly of type B. Note: amalgamation within base-of-slope sections precludes the use of mud-cap thicknesses to establish correlations.

Linear Base-of-Slope Sandstones

A conspicuous feature at all the pinch-out sections exposed in the southern Peira Cava basin is the presence of very thick (up to 35 m) massive sandstones developed close to the confining slope. These massive beds correlate with thinner, generally normally graded sheet sandstones out in the basin. Because they are localized to the base-of-slope, these massive sandstones are interpreted to have a linear form, although this cannot be demonstrated at Peira Cava because of the obliquity of the outcrop section to the strike of the confining slope. The base-of-slope sandstones are generally structureless, although they may be normally graded (particularly over the top few meters) and commonly contain discrete horizons, or zones up to a few tens of centimeters thick, of mud clasts. The base-of-slope sandstones may also be stacked, with each unit (up to 35 m thick) commonly overlying a debrite unit. An example is shown in Figure 8 (section 1, bed 11) in which a massive sandstone overlies 20 m of thin-bedded turbidites and a 2 m–thick muddy debrite. The sandstone is more than 35 m thick and locally contains large shale clasts and numerous cobbles of reworked carbonate. The debrite and sandstone fill a large erosional scour in the thin-bedded turbidites (Figure 9). The sandstone crops out farther from the base of slope

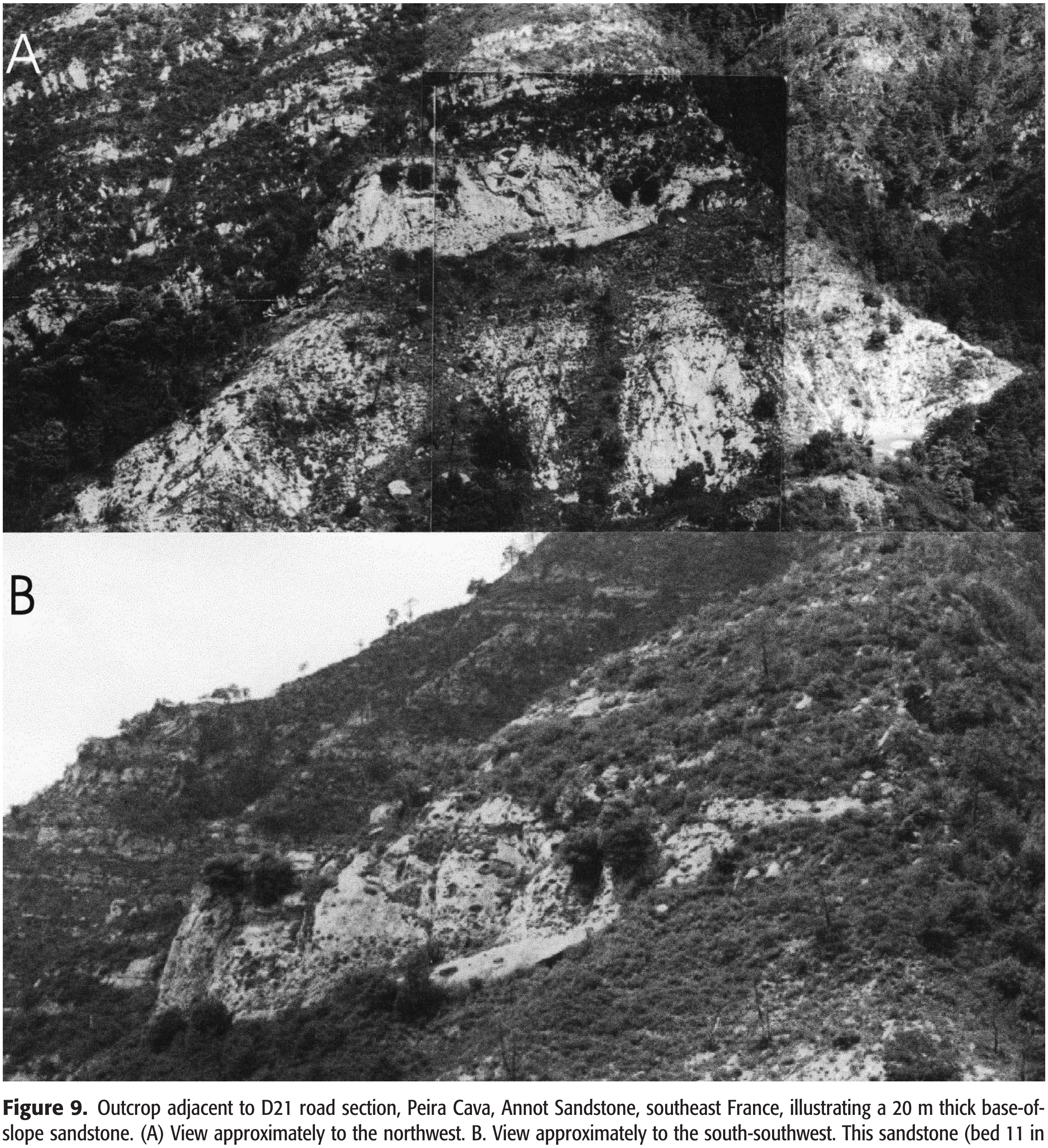

Figure 9. Outcrop adjacent to D21 road section, Peira Cava, Annot Sandstone, southeast France, illustrating a 20 m thick base-of-slope sandstone. (A) View approximately to the northwest. B. View approximately to the south-southwest. This sandstone (bed 11 in Figure 8) can be traced basinward, where it thins to $\sim$ 5 m over a horizontal distance of some 200 m. This bed is of type B pinch-out geometry (see text for discussion).

on two sections of the D21 highway (sections 2 and 3 of Figure 8), and in both sections overlies a correlative of the muddy debris flow. The sandstone thins abruptly away from the slope and, in the most basinal section (section 3), consists of a massive, normally graded, apparently sheet-form sandstone. This is an example of a type B pinch-out geometry. The distance between sections 1 and 3 measured normal to the strike of the paleoslope is approximately 300 m. The upper 150 m of section 3 (Figure 8) shows how the vertical succession of massive sandstones thickens downward toward the confining surface. In section 3, however, this interval does not intersect the onlap slope, as it overlies a roughly 40 m section of type A geometry, and so a fully developed thickening trend is not seen. The trend can be inferred, however, from the lateral relationships within bed 11, which in section 1 directly overlies the confining slope.

A 35 m–thick massive sandstone in an analogous position with respect to the confining slope, but 250 m higher stratigraphically, is seen 2.5 km to the southwest at Cime de Tournet (Figure 3). This bed can be traced visually across the hillside for at least 2 km, into a basin floor position, where it takes the form of a massive, sheet-form, normally graded sandstone some 6.5 m thick. These and other examples further illustrate how these massive sandstones apparently form wedges localized along the confining slope that connect to thinner, sheet-form sandstones deposited from the same flows on the basin floor (see following section).

Normally Graded Sheet-Form Beds

Away from the influence of the confining slope, the Peira Cava system is characterized by sheet-form graded beds. Though by no means universal, normal grading is frequent throughout the succession. Commonly the grading is stepwise, having interspersed intervals of abrupt coarsening superimposed on an overall progressively upward-fining trend. In fact the Peira Cava section is unusual in the extent to which well-developed normal grading is seen in thick and relatively coarse-grained sandstones. Several of these sheet-form sandstones have thicknesses exceeding several meters (see, for example, the basinal expression of bed 11, section 3 in Figure 8). Many are capped by thick, cogenetic turbidite mudstones, likely deposited by direct fallout from suspension. This relationship suggests that the flows, including their muddy upper parts, were completely ponded by the topography bounding the local subbasin (e.g., Hodgson et al., 1992; Haughton, 1994b).

Determining Paleoflow Magnitude from Sedimentary Deposits

The analysis of the outcrop data presented in the following sections suggests that flow magnitude is the principal variable that determines which type of pinch-out geometry is developed in laterally or obliquely confined systems. Some criteria follow that may be used to evaluate paleoflow magnitude from sedimentary deposits.

Guidelines

We interpret flow magnitude in terms of the sediment discharge rate per unit width, which can be expressed as the product of flow thickness, mean velocity, and depth-averaged concentration. When analyzing the processes that control sandstone deposition against confining slopes, the key variables are flow thickness and velocity, through their control on the vertical distribution of sediment within the flow. Although there are many potential pitfalls in determining paleohydraulic conditions from sedimentary deposits, we believe the risk of error in assessing flow magnitude is reduced through the application of the following guidelines:

1. Analysis of flow magnitude is best performed on data collected from relatively basinal areas, where there is no slope overprint. Analysis of the field data described previously suggests that slope effects cannot be detected at distances greater than about 500 m into the basin in beds of type A geometry (such as those described from Braux) and about 300 m in beds of type B geometry (such as those described from Peira Cava).
2. Deposit thickness is not necessarily a direct indicator of the magnitude of the depositing flow. For example, thick intervals of sediment can be deposited by long-lived steady flows of low magnitude (Kneller and Branney, 1995). This observation illustrates the importance of assessing the steadiness of the parental flow. Although most turbidite sections are somewhat heterogeneous in detail, the best approach is to assess the grading profiles of individual beds (and in particular the degree of normal grading expressed in the thickest beds).
3. Sediments that are weakly normally graded or ungraded in the basin likely were deposited by steady or quasi-steady flows (e.g., Kneller, 1995). Although some flows of this type can be produced via retrogressive submarine slope failure, current

thinking emphasizes the importance of river input, either directly, via hyperpycnal inflow (e.g., Mulder and Syvitski, 1995), or indirectly, by ongoing over-steepening and collapse of delta front foresets (e.g., Prior and Bornhold, 1988). River mass transfer rates are much lower than those of turbidity currents produced by large-scale slope failure (Hughes Clarke et al., 1990; Mulder and Syvitski, 1995). Thus, although they may have been long-lived, the majority of steady turbidity currents likely were relatively low magnitude events.

4. Normally graded beds in the basin likely were deposited by surge-type flows (e.g., Kneller, 1995). In this case, the thickness of deposit may give some sense of flow magnitude, thicker beds being deposited by higher magnitude flows.

Braux System

At Braux, the generally ungraded or weakly normally graded character of most of the thick basinal sandstones recorded in the basin indicates that the bulk of the turbidity currents that left a record were more or less steady or very gently waning through most of their depositional history; the normally graded tops indicate a terminal waning phase (Kneller and McCaffrey, 1999). Thus in this case, the development of moderate (3 to 4 m) thicknesses of sandstone in the basin can be ascribed to flow longevity. The turbidity currents that deposited these units—and developed type A geometries at the slope—were, therefore, probably relatively small-magnitude (low discharge) steady or quasi-steady flows.

Peira Cava System

The basinal beds that correlate to the type A pinch-out interval at Peira Cava comprise thin, weakly normally graded or ungraded beds and were thus likely deposited by small-magnitude steady/quasi-steady flows. The basinal beds that correlate to the type B pinch-out interval are sheet-form and graded. The pronounced normal grading suggests a temporal reduction in bed shear stress characteristic of waning flow. In this case, therefore, bed thickness can give a sense of flow magnitude, and we conclude that the flows that deposited these beds were large, surge-type flows. A significant proportion of these flows were probably very large scale phenomena, filling the entire width of the basin and generating reflections at both lateral slopes (see the interpretation of paleoflow data in the following sections). The presence of large, base-of-slope sandstones (of type B onlap geometry) was not observed at Braux. Their presence at Peira Cava seems related to the fact that large magnitude, surge-type flows were predominant in this basin.

Interpretation: Flow Magnitude Control on Pinch-Out Character

To understand why flow magnitude affects pinch-out character, it is necessary to evaluate why large flows preferentially produce base-of-slope sand accumulations and why such flows are more likely to scour the base of slope.

We infer that thick base-of-slope sand accumulations probably occur owing to the downslope remobilization of sand that was deposited in a gravitationally unstable position on the slope. The localization of the sand thick against the base of slope suggests a low-efficiency remobilization process, probably a combination of grain flow and/or short-lived sandy debris flow. These processes are more likely to affect the deposits of large flows owing to the combined effects of two factors (Figure 10). First, the change of gradient from slope margin to confining slope occurs gradually rather than abruptly, owing to the effects of deposition from earlier flows. Because

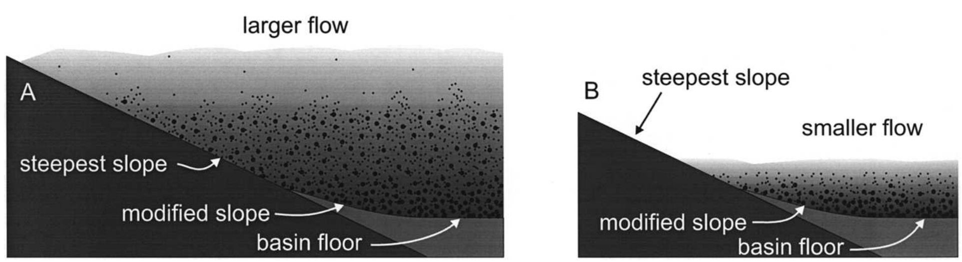

Figure 10. View normal to paleoflow of (A) a relatively large and (B) a relatively small turbidity current confined by a lateral slope. Note the gradual increase in dip from the basin floor onto the confining slope. Larger flows are more likely to deposit sandstone onto steeper, unmodified slopes by virtue of their greater thickness and their weaker grain-size stratification compared to smaller flows.

large magnitude flows typically are thicker than smaller magnitude flows, they are more likely to deposit sand on steeper slopes, where it is more prone to remobilization. Second, because large magnitude flows typically travel at high velocity, they are likely characterized by relatively high bed shear stresses (Middleton and Southard, 1984). Thus, their sand load is likely to be better vertically mixed than that of slower flows (Middleton, 1993; Garcia, 1994; Altinakar et al., 1996). Sand is therefore likely to be carried relatively higher in large magnitude flows than in lower magnitude flows, increasing the overall volume of sand deposited on the slope and increasing, too, that proportion of it being deposited on steeper slopes, from where it may be remobilized.

Base-of-slope scour has been documented in both ancient and modern systems (e.g., the Laurentian channel [Shor et al., 1990] and Peira Cava [see previous discussion]). One explanation is that helical secondary flow cells are magnified against lateral confining surfaces. Although this should occur across a range of flow magnitudes, large-scale erosion by such vortices may be more common beneath larger flows. This occurs first because turbidite mud and/or hemipelagic drape typically mantle the basin floor between the passage of successive flows. The muddy, cohesive bed may resist erosion by flows below a certain magnitude (which do not exert sufficient shear stress on the bed). Second, larger flows are more efficient than smaller ones of the same grain-size distribution (Mutti and Normark, 1987). Thus deposition from large flows may be preceded by a phase of bypass (with the potential for enhanced erosion), whereas small flows are more likely to be entirely depositional.

SYSTEMATIC CHANGES DEVELOPED TOWARD CONFINING SLOPES

Assessing the proximity of wells to a confining surface can be problematical, especially where seismic control is poor. The aim of the following section is to investigate which facies or systematic variations in sedimentary character (observed in vertical sections that closely approach or intersect an onlap slope) indicate slope proximity.

Bed Thickness Trends

As noted previously, pinch-outs of type A geometry are characterized by sequences that thin downward toward the confining slope. Pinch-outs of type B thicken downward to the slope.

Paleoflow Trends

In turbidite systems, paleoflow directions can be determined from either erosional sole structures, such as flute casts and tool marks, or aggradational structures, such as parallel lamination, ripples, and dunes. It is important that these two categories of structure be interpreted separately (Kneller et al., 1991; see also following sections.

In the Braux system, radially dispersing turbidity currents were deflected to run parallel with the confining slope (Figure 11). In vertical sections, however, there is a progressive downward shift in dispersal direction, from the local basinal trend into a slope parallel trend (e.g., from west-southwest–directed to south-southeast–directed, shown in section 2 of Figure 6). Ripple cross-laminae tend to show flow at a high angle to the slope (Kneller and McCaffrey, 1999) (Figure 4).

Paleocurrent data from the D21 road section at Peira Cava are summarized in Figure 4. Sole structures consistently show transport to the north, parallel with the confining slope. Associated ripple cross-laminations, however, commonly show quite different current directions, irrespective of whether they are collected from sections of type A or type B geometry. Within the thin-bedded sandstones of type A geometry

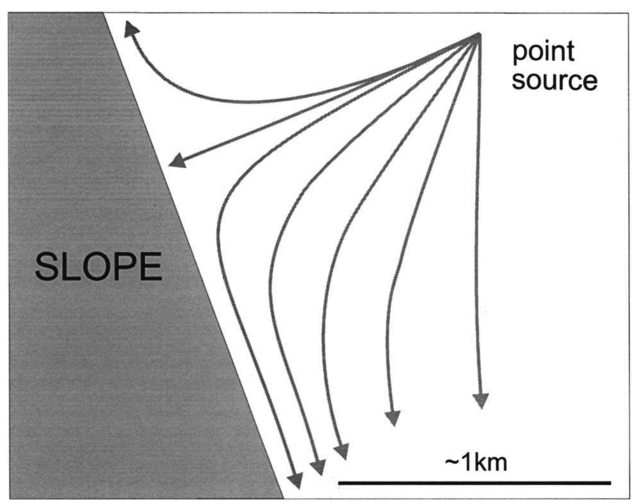

Figure 11. Interpretation of the flow regime at the Braux pinch-out section in map view, showing flow deflected to run parallel with the slope. The accurate correlations between the sections permit plan-form dispersal patterns to be determined (interpretation following that of Kneller and McCaffrey, 1999).

in the lowest 40 m or so of section 2 in Figure 8 multiple current directions are seen that have some near-symmetrical ripples. In the thicker, sheet-form, graded beds, multiple sets of cross-lamination that have repeated sawtooth grading (i.e., sudden minor increases in grain size within an overall normally graded unit) or intervening parallel-laminated units are common. Multiple current directions are seen within the associated cross-laminated units (Kneller, 1995).

Interpretation of Paleoflow Trends

Kneller and McCaffrey (1999) argue that the basal parts of well stratified turbidity currents are commonly deflected parallel with confining slopes, but they did not consider the implications of this interpretation on the development of spatial trends in paleoflow direction during system aggradation. Kneller and McCaffrey (1999) note that the position of the zone of deflection appears to be more or less fixed with respect to the slope. This zone should, therefore, track the base of slope as the system aggrades and thus migrate in an upslope direction, having an angle of climb that parallels the dip of the slope. In a vertical section, therefore, one might expect the paleocurrent data (measured from sole structures or basal grain fabrics) to show a progressive swing from the basinal dispersal direction at the top of the section into parallelism with the confining slope at the bottom. This is precisely the trend seen at Braux (e.g., section 2 of Figure 6,). Such vertical trends in paleoflow therefore indicate increasing proximity to a confining slope.

No deflection should occur in laterally confined systems where there is no obliquity between the input direction of the incoming turbidity currents and the trend of the paleoslope (e.g., the Peira Cava system), and so no vertical changes in paleoflow should be expected. Wherever there is any component of oblique-frontal topography on the slope, however, (caused by secondary structures such as ridges and valleys, for example) turbidity currents should be deflected against it, raising the possibility of detecting the presence of the slope via analysis of vertical paleoflow trends.

Kneller and McCaffrey (1999) also propose that the upper parts of turbidity currents commonly detach from the rest of the flow and run upslope. Where the detached flow is confined by the slope, it is commonly reflected back into the basin with a transport vector approximately normal to the strike of the slope (Kneller et al., 1991; Edwards et al., 1994; Haughton, 1994b; Kneller, 1995). The ripple cross-laminae measured at Braux that indicate flow directed at a high angle away from the confining slope are interpreted as the deposits of reflected flow (Kneller and McCaffrey, 1999). Similarly, we interpret the Peira Cava ripple cross-laminated units, whose paleoflow direction differs from that of associated sole structures, to indicate reflection of the more dilute parts of the flow away from the bounding topography. We interpret a strong east-directed mode as showing reflection from the adjacent north-south–trending confining surface (Figure 4C); the weaker west-southwest–directed mode may record reflection from the other (north-northwest–south-southeast trending) side of the basin. This orientation closely matches the present-day strike of the thrust system and probably that of the contemporary thrust front that bounded the basin to the northeast. The west-southwest mode illustrates the possibility that some flows may have been large enough to produce reflections that traversed the basin. The correct interpretation of ripple geometries within sheet systems may thus be critical when reconstructing the position and orientation of the basin margins and the reflection histories of individual flows—whether in outcrop or in subsurface systems (Kneller et al., 1991; Kneller and McCaffrey, 1995).

Debris Flow Location and Frequency

Debris flow deposits (debrites) are common within turbidite successions. In the study areas, a distinctive unit—a "sandwich bed"—is commonly present, in which the debrite is encased within a single turbidite sandstone (e.g., Figure 12A, B). The lower boundary of the sandstone bed commonly preserves erosional flute casts on its base (confirming that the basal sandstone was deposited by a turbulent flow, i.e., a turbidity current). The upward transition from turbidite sandstone to debrite is abrupt, without the preservation of a fine-grained capping section. The debrite commonly consists of clasts and deformed rafts of turbidite mudstone and fine sandstone, in places having clasts of *Globigerina* marl (representing the hemipelagic drape of the adjacent slope), generally in a matrix of sand. The upward transition from debrite back into turbidite sandstone is generally abrupt, and commonly the sandstone immediately above and below the debrite is of the same or similar caliber. The upper turbidite sandstone commonly contains trains of mud clasts, which diminish in frequency upward away from the debrite. The upper sandstone is commonly capped by a normally graded succession, including a mudstone cap. At the Braux section (Figures 5, 6), no debrites

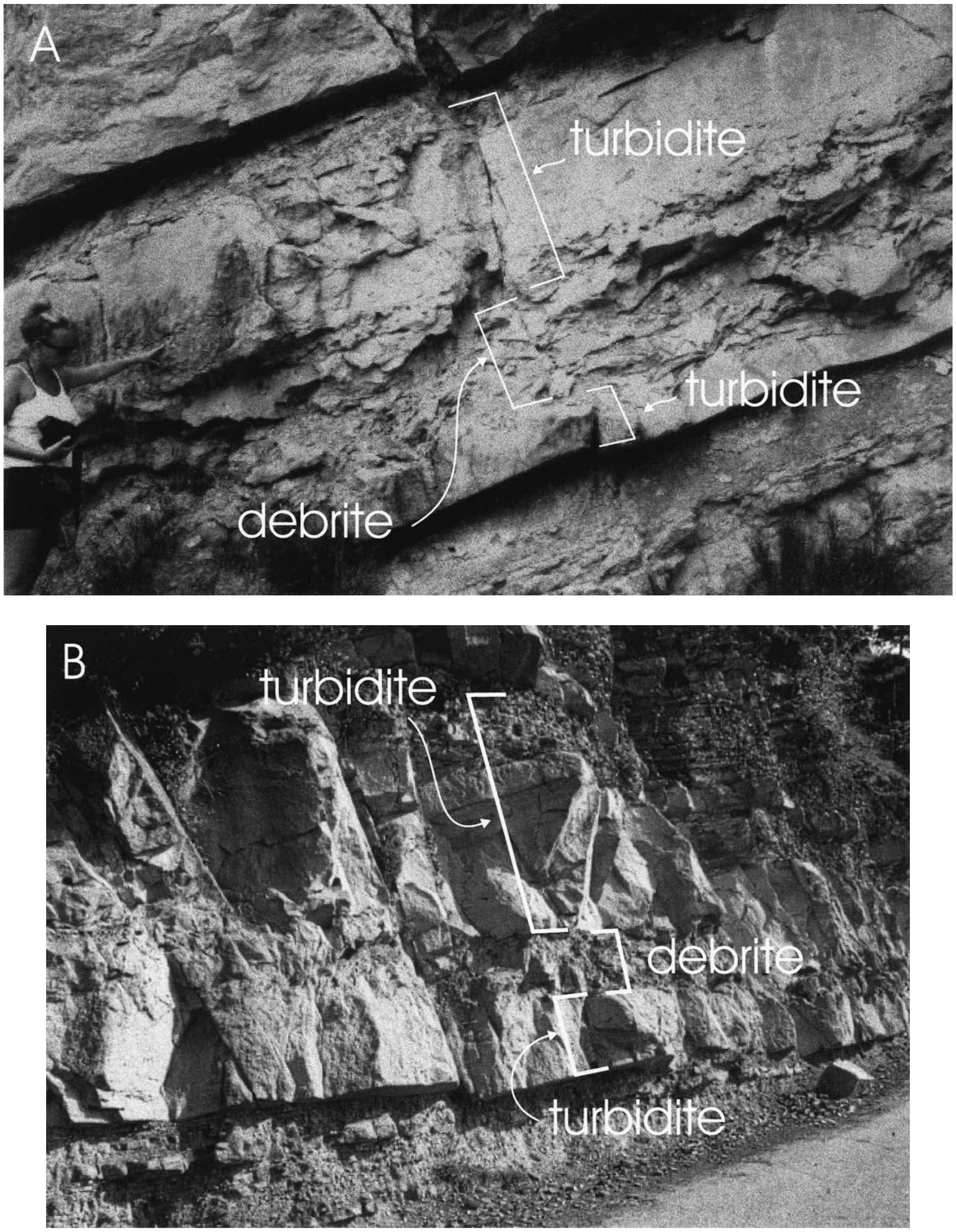

Figure 12. Locally sourced debrites encased within the deposits of the turbidity currents that are interpreted to have triggered them (see text for discussion). (A) Braux road section (section 2, bed M in Figure 6) (modified from Kneller and McCaffrey, 1999). (B) Peira Cava (composite sandstone is ~ 3 m thick)

were identified in the most basinward section (the upper part of section 4), but they become more common in sections closer to the slope; the debrites cannot be correlated between adjacent outcrop sections, although they appear to pass basinward into trains of mud clasts within otherwise vertically continuous sandstone beds.

Interpretation of Debrite Location and Frequency

The field relations detailed in the previous section imply that debrite emplacement commonly occurred during deposition of a single turbidite. The most plausible explanation for this emplacement sequence is that the turbidity current triggered a debris flow on the local basin flanks. Thus, the debris flow traveled outward from the confining slope, overrunning the earliest deposits of the triggering turbidity current. The debris flow undercut the ongoing turbidity current so that the turbidity current overran first the moving debris flow and then its deposit, entraining mud clasts from the upper debrite surface and dispersing them as trains of rip-up clasts (which possibly extend over an area greater than that of the source debrite). In time, the debrite was entirely buried by turbidite sand. A normally graded sequence, and possibly a mud cap, were deposited when the turbidity current finally waned. An alternative explanation, that co-genetic pairs of turbidity currents and debris flows traveled down the basin axis together (Stanley, 1982), is unlikely, however, because these two flow types travel at different speeds and likely become separated along the transport path and/or may take separate paths and so diverge (Masson, 1994).

Thus within sheet systems, identification of sandwich beds in core indicates proximity to a confining slope. In channelized systems, similar relationships might be produced adjacent to channel margins owing to bank undercutting by turbidity currents. No evidence of channel development within the systems described in this article exists, however (cf. Bouma and Coleman, 1985); the sandstone beds containing the shale clasts are tabular in form, and the only lenticular sand bodies we identify are those of the base-of-slope accumulations described in previous sections (see also Ravenne et al., 1987).

Because the debrites cannot be correlated between adjacent sections, they were probably point-sourced on the slope, fanning outward as lobes of limited extent. Thus in a sandwich bed–prone vertical section adjacent to a confining slope, we infer that the observed frequency of such beds might first increase downward with increasing proximity to the slope, then decrease in frequency closer to the slope, as occurs in the Braux section.

The position of the debrite within the turbidite sandstone may potentially yield information regarding relative slope proximity. In sections deposited close to the slope, there is relatively little time for sand to be deposited before the passage of the debris flow, and thus debrites should be located low within the turbidite sandstone. Away from the slope there is time to deposit a thicker sand sequence before debrite emplacement, so debrites may be located higher within the turbidite sandstone. Some field evidence supports this interpretation. The debrite illustrated in Figure 12A is from the Braux pinch-out section, at a position relatively close to the confining slope (some 225 m), and is located relatively low within the turbidite. The debrite illustrated in Figure 12B is from the Peira Cava lap section, at a relatively distant position from the slope (some 2.8 km) (Laurence Amy, 2000, personal communication), and is located at a relatively higher position within the sandstone. The relative height of the debrite within the turbidite sandstone is also a function of current longevity, however, and the debrite is overlain by thicker turbidite sandstones where triggered by relatively long-lived currents. Thus this analysis is most reliably applied to sections deposited by flows of similar character, such as a series of surge-type turbidity currents of comparable magnitude.

DATA FROM OTHER PINCH-OUT MARGINS: THE SORBAS PINCH-OUT

The Sorbas basin (Almeria Province, southeast Spain) is a small, fault-controlled basin that has its long axis oriented east-west, flanked by contemporaneous mountain ranges to the north and south (Haughton, 1994b). During the Tortonian, turbidity currents derived from the northern massif entered the basin laterally and were deflected against the southern margin to run axially toward the east (Haughton, 1994b); turbidites deposited along this margin can be correlated basinward in an oblique 5 km section from the west-southwest to the east-northeast.

Haughton (1994b) identified five distinct bed types, of which types I to III are of principal interest here. Type I beds have a bipartite structure, in which a basal parallel-laminated and/or cross-laminated fine-grained to medium-grained sandstone (the α division) is abruptly overlain by an upper, coarser unit of massive sandstone (the β division), which commonly loads downward into the basal unit. The upper massive sandstone is commonly transitional upward, via a parallel-laminated unit, into a mudstone cap (commonly without an intervening silt interval). The mud cap is absent, however, in areas interpreted to have been high on the southern confining structure. Overall sandstone bed thicknesses range from 0.1 to 0.8 m, of which some 10–50% comprises the β division. Type II beds are similar to those of type I but have a more complex internal structure, commonly containing more than one massive sandstone, each developed above a finer grained parallel-laminated or cross-laminated unit. Type III beds are generally thicker than those of types I and II, ranging in thickness from 2 to 5 m, and tend to grade progressively upward, via a thick siltstone interval, into a mudstone cap. Bed types I and II are characteristic of the pinch-out itself and were shown to be transitional into type III beds in the basin.

In broad terms, the southern Sorbas pinch-out margin comprises a type A pinch-out, in which individual beds thin onto the confining surface. In his analysis of this pinch-out, Haughton (1994b) concluded that beds of types I, II, and III must be produced by single events. He postulated that as northerly and northwesterly derived flows impacted the southern massif, the front parts of each flow ran up the confining slope. Meanwhile, the bodies were deflected to run down the basin axis, where they deposited α divisions of types I or II. The head regions of the flows turned back into the basin to deposit β divisions. Haughton (1994b) interpreted the presence of thick mud caps in basinal areas to indicate ponding of the flows by confining topography; their absence in some type I beds indicates that in these areas the flows rode up the confining topography above the height to which the mud cloud was ponded.

Comparison of the Sorbas, Braux, and Peira Cava Pinch-Outs

The laminated facies that comprise type A pinch-outs at Braux and Peira Cava bear some similarity to type I and (particularly) type II beds of Haughton (1994b), but they do not tend to have as pronounced a development of a β division. The differences may be due, in part, to different angles of turbidity current incidence. At Sorbas, incidence angles were between 45 and 90° (Haughton, 1994b). The turbidites at Braux were point-sourced and thus struck the confining slope at a range of incidence angles. At the point where the pinch-out facies are best exposed (sections 1 and 2 of Figure 6), however, incidence angles were 45° or less. At Peira Cava, incidence angles of the incoming flows were negligible. At higher incidence angles, a greater part of the momentum of the incoming flow is likely directed up the slope, allowing the turbidity current head to run up the confining slope (e.g., Siegenthaler et al., 1984; Muck and Underwood, 1990) before deflecting back into the basin. Recognition of well-developed β divisions in core may thus indicate proximity to a confining slope in an area where the turbidity currents struck the slope at high angles of incidence.

INDUSTRIAL APPLICATIONS

Pinch-Out Characterization

Where turbidite-hosted fields exploit stratigraphic traps along confining margins, pinch-out characterization is a key appraisal issue. This is especially the case where exploration wells have been placed conservatively, away from the pinch-out margins. Because pinch-out character depends on flow magnitude, as described previously, core or high-quality downhole image data collected from wells in a relatively basinal position can be used indirectly to make a first order assessment of sandstone geometries at confining slopes. Type A configurations are likely produced by small-magnitude, steady or quasi-steady turbidity currents and, we infer, by small-magnitude surge-type turbidity currents. Under such conditions, individual beds thin toward the slope and tend not to erode into earlier deposits. Thus vertical seal integrity is likely to be good, but vertical connectivity poor (Figure 13A). In this scenario, if targeted production wells are to be drilled, they are best oriented parallel or subparallel with the confining surface to sweep the reservoir effectively (although this production strategy requires that the position of the confining slope is adequately constrained; see the discussion in the following section).

Type B pinch-out configurations are likely produced by large magnitude turbidity currents. Individual beds thicken toward the confining slope and may incise into earlier deposits. Thus, there is likely to be enhanced reservoir volume at the pinch-out. Furthermore, vertical connectivity likely is enhanced between

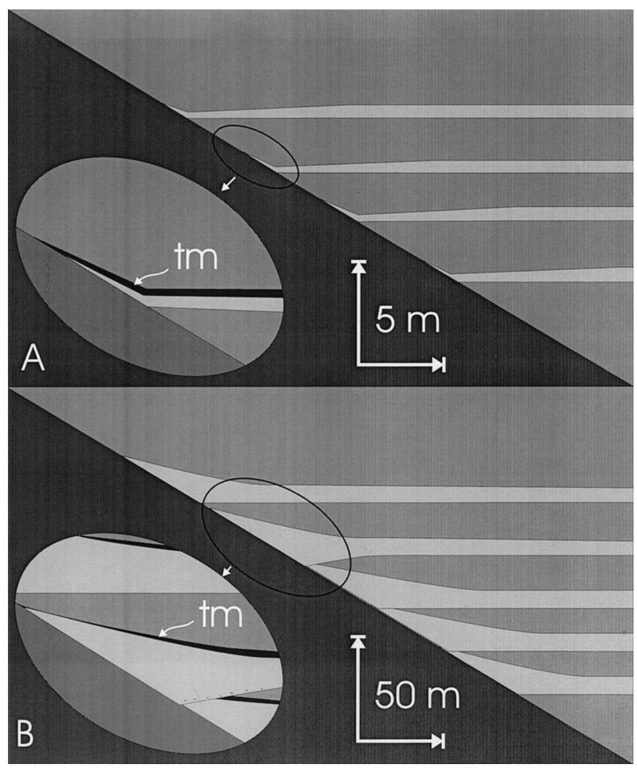

Figure 13. Schematic diagrams illustrating pinch-outs of (A) type A geometry and (B) type B geometry (slope dip not to scale). Note that as modeled, turbidite mudstones (tm) act to vertically seal their associated underlying sandstones.

adjacent sandstones, undermining the effectiveness of stratigraphic trapping. Therefore the presence and integrity of the top seals may become a development issue (Figure 13B). It is worth bearing in mind, however, that in mixed type A/B successions, packets of type A beds may act to seal underlying packets of type B beds.

In ponded basins, turbidite muds may act to vertically seal their associated turbidite sandstones (e.g., the Braux system; see previous discussion). In systems where turbidity currents strike the confining slope at high angles, however, sand may be deposited on the slope above the mud pinch-out level (e.g., the Sorbas system) (Haughton, 1994b). This raises the possibility that updip hydrocarbon leakage may occur in such systems (although this is less likely in reservoirs in which hemipelagic drape also acts to seal the sandstones).

Constraining the Position of Confining Slopes

Systematic facies and paleoflow variations commonly can be identified in individual turbidite sandstones as they approach the slope. Analysis of bed thickness variations and paleoflow trends in vertical successions can be used to assess proximity to confining surfaces. Analysis of the field data described previously suggests that slope effects cannot be detected at distances greater than about 500 m into the basin in beds of type A geometry and about 300 m in beds of type B geometry.

Analysis of Bed Thickness Trends

At pinch-out margins of type A, analysis of the vertical succession shows a trend of bed thicknesses diminishing downward toward the confining slope. At pinch-out margins of type B, there is a trend of bed thicknesses increasing downward toward the confining slope. In addition, in confined sheet systems characterized by relatively high incidence angles, the presence of beds of type I and II (Haughton, 1994b), in which massive sandstones abruptly overlie and load into finer grained horizontally laminated or cross-laminated sandstones, may also indicate the presence of the confining slope. We note that thinning- or thickening-upward cycles may also be produced by systematic changes in turbidity current magnitude driven by extrabasinal controls. In practice it may be difficult to differentiate between such cyclicity and the bed thickness trends described previously without seismic evidence of a confining slope. Analysis of paleoflow trends and/or the presence of sandwich beds, however, may provide independent evidence of a confining slope (see the next section).

Analysis of Paleoflow Trends

Where there is any obliquity between the dispersal direction of incoming turbidity currents and the strike of a confining surface, turbidity currents will likely be deflected parallel with the confining topography. Because the position of the base of slope effectively retreats as the basin fill aggrades, vertical section analysis should show a progressive rotation of measured paleoflow azimuths into parallelism with the strike of the confining slope with increasing depth (using erosional sole structures or primary grain fabrics measured from the basal parts of turbidite sandstones). Paleoflow trends may be more complex, however, around zones where turbidity currents strike slope zones at high angles of incidence (e.g., see Haughton, 1994b).

Paleoflow determinations from ripple cross-laminated units within basinwide sheet-form sandstone bodies also can be used to locate the position of lateral slopes (Kneller et al., 1991: Kneller, 1995; Kneller and McCaffrey, 1995). Furthermore, in confined subsurface systems characterized by large magnitude flows, the ripple-derived paleoflow data may also indicate the possible location and orientation of type B base-of-slope sandstones.

Analysis of Debrite Location and Frequency

The presence of locally derived debrites preserved as sandwich beds provides complimentary evidence of the presence of confining slopes of some type. In a vertical succession the observed frequency of such debrites should initially increase downward with increasing proximity to the slope but may decrease before the slope is intersected. Additionally, there may be a tendency for debrites deposited close to the confining slope to be located relatively lower within the turbidite sandstones that encase them than those deposited in relatively more basinal settings.

Applications in the Subsurface

Insights gained at outcrop into the processes affecting pinch-out styles of individual turbidite systems can potentially be applied to subsurface systems. Within confined systems, flow magnitude appears to control which of two end-member pinch-out geometries is developed. Smaller flows produce type A geometries, in which turbidites progressively thin toward the confining slope before pinching out abruptly against it; there is little bed amalgamation. Large flows produce type B geometries in which turbidites progressively thicken toward the slope, terminating in relatively thick base-of-slope sand accumulations; in this scenario, turbidites are amalgamation-prone. Assessment of pinch-out geometry may be made through estimating paleoflow magnitude. This can be done via assessing the thickness and grading patterns of individual beds in basinal positions. In type B, turbidite sandstones typically thicken toward the confining slope, producing thickening and coarsening downward vertical successions; individual events may erode into earlier deposits (Figure 13B). This article shows that a combined assessment of flow magnitude, together with vertical trends in bed thickness, paleoflow, and frequency of debrite occurrence, can yield information on the character and proximity of confining slopes.

In core, paleoflow directions can be determined either by direct measurement of sedimentary structures such as ripple cross-lamination or by measurement of grain fabrics using petrographic or magnetic techniques (e.g., Hailwood and Ding, 1995). In deviated wells, establishing the true orientation of core is generally straightforward if the structural dip is known. These techniques, however, may also be applied to unoriented core from vertical wells, using the remanent magnetization to establish the original core orientation.

Potential areas of application include the following:

1. Mature plays in systems that have abundant wireline log and core databases, such as the Paleocene–Eocene of the central North Sea, where, for example, unswept volumes of hydrocarbons may exist at the margins of existing fields
2. New plays in areas such as the Gulf of Mexico, where stratigraphic trapping enhanced by halokinesis may provide the dominant play type, and especially where seismic resolution is poor (e.g., because the field is subsalt)

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