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Tectonics and hydrogeology of accretionary prisms: role of the décollement zone

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Abstract—At convergent margins the décollement zone comprises the plate boundary and is marked by profound structural disharmony, by changes in stress orientation and by a discontinuity in plate velocity. The décollement zone initiates in a weak sediment layer, typically a low-permeability hemipelagic mud lying below a more rapidly deposited, stronger, more permeable trench turbidite sequence. At the deformation front, trench turbidites tend to be offscraped, whereas the finer-grained hemipelagic and pelagic sediments are more likely to be underthrust. Offscraped materials may undergo only limited burial whereas underthrust deposits can be deeply buried, undergo high-pressure metamorphism, and are more likely to be preserved in the stratigraphic record. Burial rates associated with underthrusting are high, exceeding 20 km/my.

With high rates of underthrusting, sediment descending below the décollement zone is probably buried faster than it can dewater, resulting in emplacement of relatively high porosity deposits at depth. Fluids flowing from modern décollement zones have migrated substantial distances laterally and tapped deep sources. The episodicity of flow suggests pumping of fluid by cycles of dilation and flow to the décollement zone followed by failure and fluid expansion along the décollement zone. Possible pressure gradients below the décollement zone allow flow upward into it while maintaining minimum effective stress along it.

The thickness of sediment underthrust beneath the décollement zone determines whether these deposits are emplaced by diffusive underplating with stratal disruption and efficient dewatering, or by coherent underplating with the formation of macroscopic duplexes and transfer of fluid to the base of the accretionary prism. Deformation mechanisms affecting accreted sediment depend on depth of entrainment into the décollement zone and duration of residence.

INTRODUCTION

THE hydrologic system developed at subduction zones influences nearly every aspect of tectonic evolution in this environment. Effects include: generation of extensive thrust surfaces (Hubbert & Rubey 1959, Gretner 1981, Westbrook *et al.* 1982); control of wedge geometry (Davis *et al.* 1983); heat transport (Reck 1987); transport of solutes and control of water sediment–rock interactions (Schoonmaker 1986); alteration of physical properties and constitutive relations of sediments (Karig 1986a, Ritger *et al.* 1987); and spawning of unique biological communities on the surface at sites of fluid expulsion (Kulm *et al.* 1986, Le Pichon *et al.* 1987).

This paper describes structural and hydrogeologic features of one element of a convergent margin, the décollement zone. This feature is unquestionably maintained by high fluid pressure, acts as a major conduit for fluid expulsion, and has a major impact on structural development in the accretionary prism. The inception and evolution of the décollement zone exemplifies the mutually interactive nature of tectonic and hydrologic processes in subduction zones.

Sediment columns entering subduction zones initially have porosities of at least 50%, whereas rocks preserved in subaerially exposed equivalents typically have less than 10% pore space (Bray & Karig 1985). In addition to water produced during this porosity collapse, that produced by mineral dehydration and hydrocarbon generation also create significant volumes of water that must be expelled. In addition to fluid from sediments, the oceanic crust may release large volumes of water (Peacock 1987) that can also influence accretionary prism tectonics.

Rapid tectonic burial, mineral dehydration, hydrocarbon generation, aquathermal pressuring and other processes generate high pore pressures (e.g. Gretner 1981) that drive fluids out of subduction zones. Fluid flow out of subduction zones may occur in a diffusive manner, along faults, along permeable sedimentary layers, or with the enclosing solids, for example, as pore fluid incorporated mud diapirs. Accretionary systems may be subdivided into those dominated by fine-grained sediments with low intergranular permeability vs those with significant quantities of sandy sediments with much higher intergranular permeability. Fluid expulsion in the fine-grained prisms is predominantly via fracture permeability associated with faults, even at an early stage of structural evolution (Moore *et al.* 1987). Fluid loss from the coarser grained accretionary systems should at least be initially dominated by flow through layers with high intergranular permeability (Kulm *et al.* 1986). Extensive stratigraphically controlled conduits of fluid transport are probably rapidly destroyed by early structural and diagenetic processes. Fracture permeability more than likely becomes the dominant conduit of fluid migration as accreted sediments become buried, cemented, and deformed (Cloos 1984).

DECOLLEMENT ZONE: FACTS AND REASONABLE INFERENCES

Nature of the décollement zone

A décollement is by definition a surface or zone of structural disharmony. At subduction zones the struc-

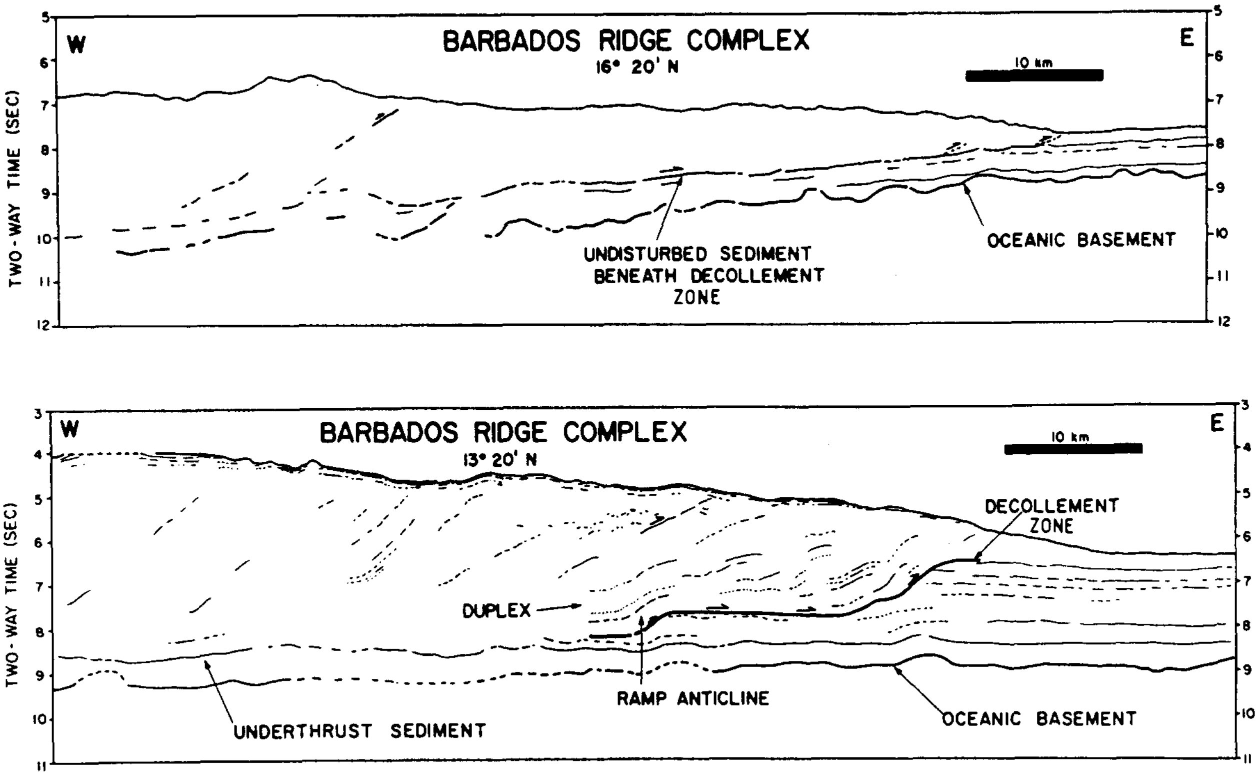

Fig. 1. Examples of extensive décollement zones. Note down-stepping of décollement in lower section forming an underplated duplex. Both line drawings are from migrated seismic lines (Westbrook *et al.* 1984).

tural disharmony is demonstrated most commonly in seismic reflection data (Fig. 1), but also has been confirmed by drilling along the northern Barbados Ridge, where the décollement zone consists of a 40 m-thick interval of scaly mudstone separating an imbricate thrust complex, above, from essentially undeformed sediments below (Behrmann *et al.* 1988). Melanges apparently formed along ancient décollement zones show: (1) layer-parallel shear that has caused their characteristic stratal disruption, and (2) cross-cutting ductile shear bands (Agar 1987, Fisher & Byrne 1988). Extensive vein networks in these melanges attest to concentrated fluid flow along fractures (Vrolijk 1987). In the northern Barbados Ridge area these extensive décollement zones developed in sediments apparently can only be maintained by high fluid pressures (Westbrook & Smith 1983, Biju-Duval *et al.* 1984 Site 542).

Décollement zone as a plate boundary

At the deformation front, sediment riding on the oceanic plate is bifurcated along the décollement zone into a component that is offscraped at the front of the accretionary prism and another component that is thrust beneath it, to be underplated at depth or perhaps truly subducted; the décollement marks the boundary between the two tectonic plates. Because of continuing deformation within the accretionary wedge, sediment offscraped at the deformation front has only a component of the velocity of the overthrusting plate. As deformation in the accretionary complex decreases landward the incorporated sediment moves at a velocity approximating to that of the overthrusting plate. For example, the Nankai accretionary prism of southwestern Japan apparently has acquired about 75% of the velocity of the overthrusting plate 15 km landward of the deformation front (Karig 1986a). Sediment underthrust beneath décollement zones moves at the velocity of the underlying plate with a consequent increase in the velocity difference across the décollement zone in a landward direction. Thrusting of the accretionary complex landward on to the forearc basin (Westbrook *et al.* 1984, Silver & Reed 1988) also accounts for a component of the total convergence motion of the overthrusting and underthrusting plates.

State of stress across the décollement zone

In passing from the oceanic plate to the accretionary prism, sediments change from a gravitational state of stress to that characteristic of a thrust belt. The maximum principal stress is oriented vertically in the oceanic basin setting and becomes gently inclined as the sediment is incorporated into the accretionary thrust belt (Davis *et al.* 1983). At shallow depth in the accretionary prism, the geometry of the thrust surfaces allows the orientations of stresses to be approximated using Coulomb failure criteria; for example, in the Eastern Aleutian forearc the maximum principal stress is inclined 11° in a seaward direction (Davis & von Huene 1987). The magnitude of effective stress along the décollement is likely to be low in sedimentary accretionary prisms because of the low density of the overburden and the inherently high pore pressures. The sharp change in

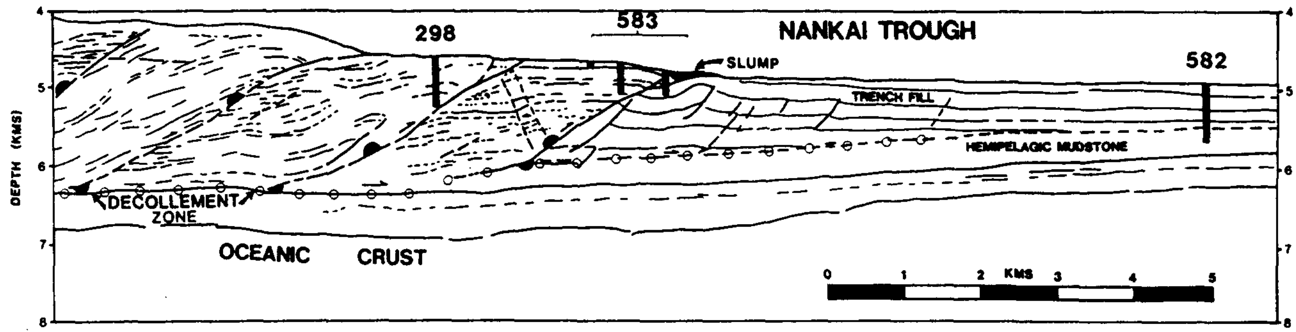

Fig. 2. Décollement zone development beneath Nankai accretionary prism, southwest Japan. Décollement zone (open circles) initiates along the boundary between trench-filled turbidites and hemipelagic muds. Solid half-circles represent offset of truncated reflectors along imbricate thrusts. Numbers are DSDP drill sites from Legs 31 and 87. Line drawings from a migrated depth section (after Karig 1986b).

structural style across the décollement zone suggests that this surface marks the major shift in the orientation of the stresses. In underplated coherent sequences, quartz and calcite extensional veins, interpreted as hydrofractures, suggest a near vertical orientation of the maximum principal stress during underthrusting (Fisher & Byrne 1988).

Sedimentary inheritance: genesis of the décollement zone

The décollement zone is initiated along a layer of low strength originating from the depositional regime of convergent plate boundaries. The oceanic crust typically accumulates a pelagic sedimentary sequence that is covered by a more rapidly deposited layer of muddy hemipelagic sediment as it approaches the trench, and finally it is topped by a rapidly accumulated trench fill. Where penetrated by drilling the sedimentary section increases in porosity from the trench fill to the underlying hemipelagic layer (Figs. 2 and 3). This increase in porosity is correlated with reduced strength (see fig. 8 in Karig 1986a) and probable underconsolidation and excess pore pressure, and a propensity for localized failure. The higher porosity of the hemipelagic layer results from its uniformly finer grained nature relative to the trench muds and its rapid loading (and overpressuring) by the trench fill (Table 1). Finally the sand component of the trench sediment causes it to have a higher coefficient of friction than the underlying hemipelagic muds (Lambe & Whitman 1969), favouring failure in the latter (Table 1).

The foregoing example of décollement formation in the hemipelagic sediments underlying the trench wedge represents the most typical situation; however, exceptions occur such as the development of the décollement in an incoming hemipelagic layer where trench sediments are absent (Moore & Shipley 1988, Moore *et al.* 1988) or the initiation of the décollement within the trench wedge (McCarthy & Scholl 1985, Moore & Shipley 1988); the central requirement is a weak sedimentary layer. In a gradually accumulated incoming sedimentary section of uniform lithology, consolidation theory predicts highest pore pressure and décollement development at an intermediate depth (Wang & Shi 1984).

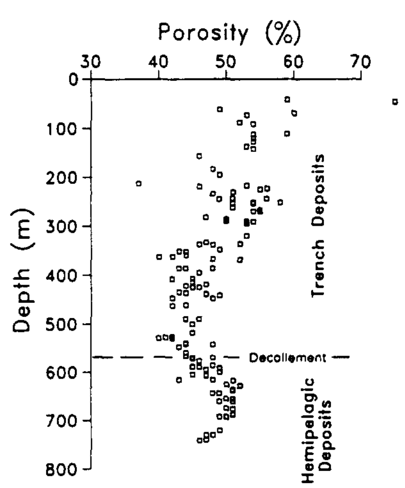

Fig. 3. Porosity–depth plot and generalized stratigraphy of Site 582 (Fig. 2) showing porosity inversion in hemipelagic sediments immediately below trench deposits.

EFFECTS OF THE DECOLLEMENT ZONE: SEDIMENT PRESERVATION AND METAMORPHISM

Sediments offscraped above the décollement zone have limited burial potential whereas underthrust sediments can be sub-crustally subducted. Imbrication at the deformation front may produce several kilometers of burial which might be doubled or tripled through out-of-sequence thrusting, pervasive deformation (Karig 1983, Behrmann *et al.* 1988) and accumulation of slope sediments. Excepting the case of covering by a major forearc basin, burial depth of offscraped sediments would be unlikely to be beyond about 10 km, that is not exceeding the transition between zeolite and blueschist facies metamorphism (Fig. 4). With higher thermal gradients and the development of prehnite–pumpellyite facies metamorphism, the offscraped sediment could be buried into the top of this facies interval. Because of their shallow burial, offscraped deposits are susceptible to erosion or tectonic denudation (Platt *et al.* 1986) and recycling.

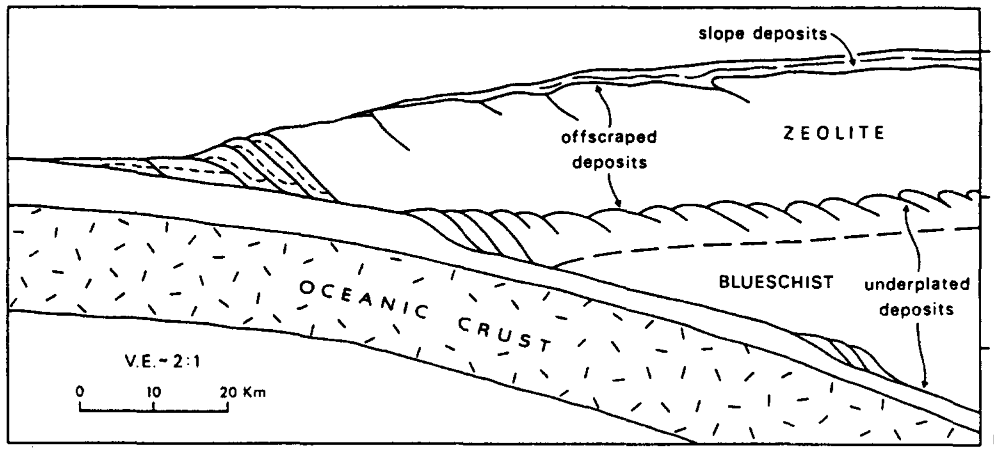

Fig. 4. Metamorphic facies in an idealized accretionary wedge relative to levels of offscraping and underplating. Note that the transition to blueschist facies occurs below the level of underplating. The boundary between zeolite and blueschist facies is defined by the transition from laumontite to lawsonite bearing rocks and occurs at about 3 kb over a temperature range of about 150–300° (Liou *et al.* 1987). This diagram makes a generous allowance for the ultimate structural thickness of the offscraped material. At many convergent margins, underplating initiates at shallower depths and therefore accreted rocks of blueschist facies most certainly are underplated. At higher geothermal gradients, prehnite–pumpellyite facies metamorphism develops at pressures of 1.5–3 kb (about 6–12 km) (Liou *et al.* 1987). Rocks of this metamorphic grade could occur in the lower portion of a thickened offscraped package, but would most likely have been underplated.

Any significant degree of metamorphism of sediments in accretionary prisms requires that they be underthrust below the décollement zone. Blueschists and eclogites of exposed accretionary prisms commonly indicate burial depth of 30 km or greater (Liou *et al.* 1987). Seismic reflection profiles traversing the subduction zone off Vancouver Island, western North America, directly image sediments being underthrust between 30 and 40 km. Given the geometry of the down-going slab and the rate of convergence, calculated burial rates for several representative subduction zones range from 3 to 24 km/my (Fig. 5). These burial rates track sediment riding just above the oceanic crust and were determined from modern plate velocities and subduction zone geometries established by both seismic reflection and refraction data. Because the seaward portion of accretionary prisms are not moving at the full velocity of the overthrusting plate, the plot overestimates rates of burial at shallow depths (about 0–5 km), but is probably only slightly in error at greater depths. The essential conclusion is that burial rates are very rapid, exceeding those associated with sedimentation and probably representing the fastest burial rates anywhere. Although metamorphic reactions would occur in these rapidly buried sediments, it is unlikely that fluid could completely escape perhaps resulting in the underplating of a relatively fluid-rich material or 'metamorphic mush' at depth.

EFFECTS OF THE DECOLLEMENT ZONE: FLUIDS

Although it has been long argued that extensive décollements require high fluid pressures (Hubbert & Rubey 1959, Westbrook & Smith 1983), the effect of the décollement on controlling the input and outflow of fluid in the subduction system has only recently become appreciated. Factors leading to the key hydrogeological role include the state of stress across the décollement zone, the nature of the adjacent sediments and the rapidity of the burial process.

Fluid input to the accretionary prism

Accretionary prisms may obtain fluid from a multiplicity of sources. Fluid can be supplied to the accretionary prism through sediment accretion either at the front or

Table 1. Lithology and physical properties of sediments flanking décollement at initiation

	Above décollement zone	Below décollement zone
Lithology	Turbidites, interbedded sand and mud	Hemipelagic and pelagic muds
Strength:* coefficient of friction	Higher due to sand layers and increased silt content in mud	Lower in mud
Intergranular permeability	Moderate to high depending on sand percentage	Uniformly low

*Cohesion of trench sediments and hemipelagic muds is low; therefore the coefficient of friction is the most important strength parameter. References: Marlow *et al.* 1984, Davis & von Huene 1987.

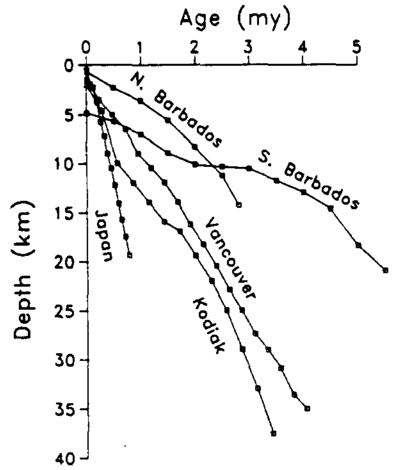

Fig. 5. Rate of burial of underthrust sediment. Burial rates were constructed from plate convergence velocities beneath upper plates of known geometries. Subduction zone geometries were estimated from seismic reflection and refraction data (von Heune *et al.* 1982, 1985, Speed *et al.* 1984, Clowes *et al.* 1987). Convergence velocities (Engebretson *et al.* 1985, Stein *et al.* 1988) were adjusted to reflect convergence along line of sections utilized to constrain geometry. Although the overthrust plate near the deformation front is not moving at the full velocity of the overthrust plate (Karig 1986a), no adjustment was possible because of ignorance of the velocity variation at the margins investigated. The calculated burial rate probably initially exceeds the real burial rate, but is only slightly in error at depths greater than 5 km.

the base of the prism. This sediment contains pore water, structurally bound water and organic matter that can be transformed to hydrocarbons at depth (von Huene & Lee 1983). Additionally, hydrous oceanic crust provides a substantial reservoir of fluid that can be liberated upon heating and stream up along the décollement zone and perhaps into the accretionary prism (Peacock 1987). Discussion here is limited to fluid derived from pore-volume reduction, and specifically to how the décollement zone may separate fluid reservoirs with differing consolidation histories.

Expulsion of pore fluids from a consolidating sediment depends on its lithology and loading history. Consolidation theory predicts that, after application of an arbitrary load, the consolidation time (t) for a sedimentary layer is directly proportional to the square of its thickness (H) and compressibility of its mineral skeleton (m), and inversely proportional to its permeability (k) or,

$$t \approx mH^2/k$$

(Lambe & Whitman 1969). The permeability, which may vary in sediments by orders of magnitude, controls how quickly the fluid can migrate. The thickness controls the distance to the drainage surface. The compressibility controls the amount of consolidation of the mineral skeleton for a given load, and hence the amount of fluid that can be produced. The time of consolidation is independent of load because the greater the load the larger the degree of consolidation. The partitioning of sediment during the initiation of the décollement surface typically separates materials with contrasting hydrologic properties. The sandier offscraped section is significantly more permeable and less compressible than the underlying underthrust muddy section (Lambe & Whitman 1969). Moreover, imbricate thrusting of the offscraped section provides numerous drainage surfaces through which this sediment can dewater; in the simplest case the underthrust sediment can only dewater along the bounding upper surface; although some sequences include sandy layers that might provide additional conduits for dewatering. Overall consolidation theory suggests that there is substantial retardation in the dewatering of the underthrust sediment package relative to the offscraped deposits (Fig. 6). As this sediment is underthrust beneath the accretionary prism at a high rate (Fig. 5), this down-going layer may constitute a significant source of water at depth.

An example of the retarded consolidation of sediments underthrust below the décollement level is illustrated by comparative physical property data from sediments on the ocean floor and those that have just passed landward of the deformation front of the northern Barbados Ridge (Fig. 7; Table 2). Sediments underthrust beneath the décollement have lost but a fraction of the fluid in comparison to offscraped deposits. Sediments lying in the décollement zone show the most dramatic water loss because they were initially of anomalously high porosity and lie directly in a drainage surface. The measurements are entirely from hemipelagic sediments;

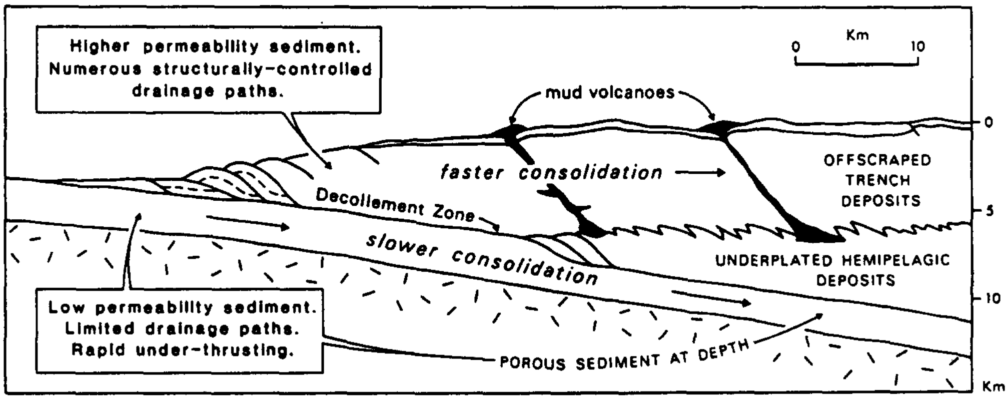

Fig. 6. Schematic cross-section showing how less consolidated underthrust material could serve as a source for mud volcanoes and diapirs. After Brown & Westbrook (1988).

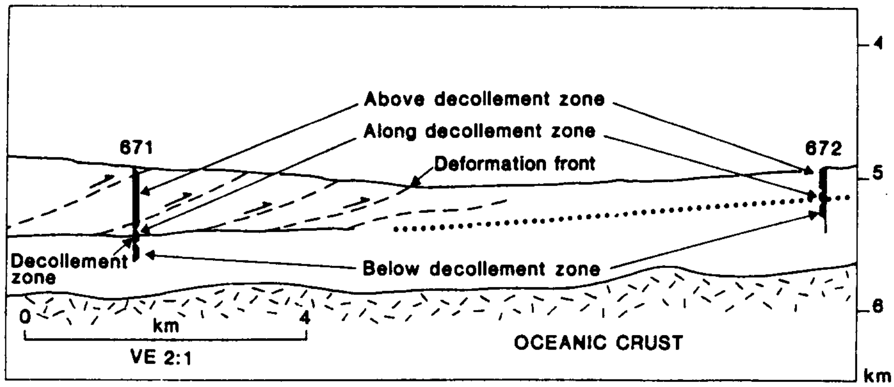

Fig. 7. Cross-section of northern Barbados Ridge showing time correlative sedimentary sections used to examine volume reduction during offscraping and underthrusting (listed in Table 2; after Moore *et al.* 1988).

therefore permeability differences due to changes in grain size are less important than in the example of a sandy trench wedge overlying an underthrust hemipelagic mud sequence. Numerical simulations of the porosity variations along the Leg 110 drilling transect suggest a porosity inversion at depth across the décollement (Screaton *et al.* in press). Similarly, velocity data from another cross-section of the northern Barbados Ridge suggests a porosity inversion downward from the accretionary prism through the décollement to the underthrust section (Bangs *et al.* 1986).

Evidence from the modern subduction zones also suggests fluid may be effectively transported to depth beneath the décollement. Magnetotelluric sounding along the Lithoprobe transect of Vancouver Island suggests that sediment above the oceanic crust at depths more than 30 km contains saline pore fluid (Kurtz *et al.* 1986, Clowes *et al.* 1987). According to Brown & Westbrook (1987), the occurrence of mud diapirism above the zone of significant underplating beneath the southern Barbados Ridge suggests derivation of the mud and fluid from the underthrust sediment package (Fig. 6).

At one subduction zone, however, relatively rapid fluid loss is inferred during underthrusting beneath the décollement. Thickness of underthrust sediment determined from seismic reflection data indicate a 27% volume loss during underthrusting at a distance of 4 km beneath the accretionary prism off Costa Rica (Shipley & Moore 1986). Conversely, direct measurements of porosity change during underthrusting 4 km beneath the northern Barbados Ridge indicates only a slight loss in volume during the same distance of underthrusting (Fig. 7; Table 2). The difference between these estimates might lie in the assumption of constant original layer thickness in the Costa Rican example; if real, the relatively large volume reduction off Costa Rica might be explained by a somewhat higher sediment permeability or by dewatering along the normal faults that cut the underthrust section. At the very least the Costa Rica data caution one in application of the generalized arguments outlined above and behove individual evaluation of subduction zone hydrogeology.

Fluid flow out of the subduction zone

Observations in both modern and ancient accretionary prisms suggest that faults, particularly the décollement zone, may be important loci of fluid flow. Along the décollement zone beneath the northern Barbados Ridge, anomalies in pore water composition suggest active fluid flow through this surface (Fig. 8) (Moore *et al.* 1987, Gieskes *et al.* in press). The methane bearing fluids of the décollement zone and subjacent underthrust sediments vs the methane free fluids of the accretionary prism define two fluid reservoirs. Thermogenic methane in the fluids within and below the décollement argues for derivation of the fluids from at least 45 km landward of

Table 2. Comparisons of porosity and volume changes with deformation path

Sections compared	Porosity change* (%)	Water loss (%)	Time (my)	Burial increment (m)	Comments on deformation path
Site 672 and 671 Recent to Lower Miocene	68–59	32	0.75	200	Entire offscraped section deformed above décollement
Site 672 and 671 Lower Miocene	69–55	46	0.25	300	Sediment being deformed in décollement zone
Site 672 and 671 Lower Oligocene	53–52	4	0.25	300	Sediment underthrust beneath décollement zone

*Changes in porosity determined from averages of 10 to more than 100 values evenly distributed through sections compared. Water loss refers to percentage of total water or void space loss from initial state at Site 672. Time represents estimated time since sedimentary sequence was either incorporated in the accretionary prism or underthrust beneath it. Data from Moore *et al.* (1988).

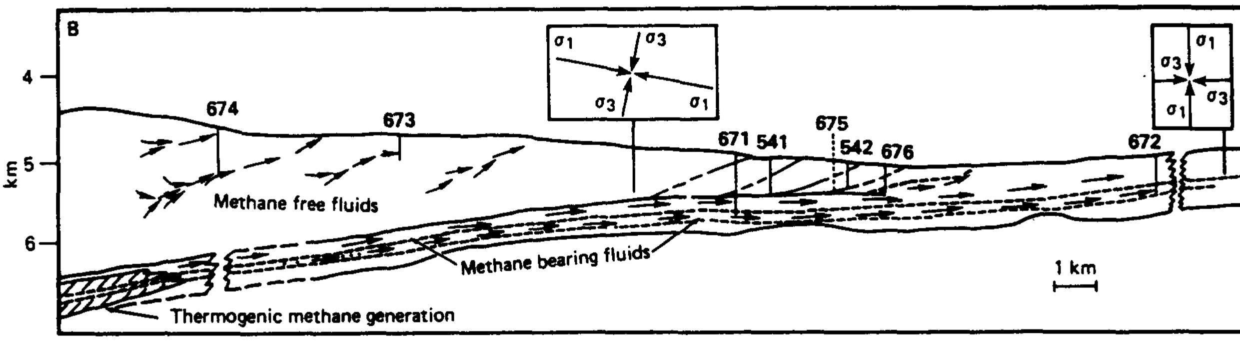

Fig. 8. Hydrogeologic summary of northern Barbados Ridge in Leg 110 area (Moore *et al.* 1987). Note methane-bearing fluids occur only below décollement zone whereas methane-free fluids characterize the accretionary prism.

the deformation front of the accretionary prism. In the Barbados example, fluid flow is localized along the décollement zone apparently because of its high fracture permeability. Here, the trapping of the methane-bearing fluids below the accretionary prism probably is due to the gentle inclination of the maximum principal stress in the prism which discourages high-angle hydrofractures and venting of the fluids directly to the surface (Fig. 8). Similarly, the expulsion of thermogenically-derived hydrocarbons at the frontal thrust of the Nankai accretionary prism indicates a deep source for the fluids (Le Pichon *et al.* 1987) with the décollement zone as the probable conduit. Even in accretionary prisms with significant quantities of coarse-grained, initially permeable sediments, fault zones, and by inference the décollement zone are localized zones of fluid flow (Cloos 1984, Vrolijk 1987).

The episodicity of fluid flow and deformational pumping along the décollement zone

Geochemical and thermal signatures indicate that fluid flow along décollement zones and related faults is episodic, perhaps on the time-scale of large thrust earthquakes in subduction zones (Moore *et al.* 1988). A model associating deformation with fluid flow involves (Fig. 9): (1) a relatively protracted interval of strain accumulation allowing fluid flow to dilate fractures formed in the décollement zone; (2) increasing fluid pressure as dilated fractures coalesce leading to failure and slip on along the décollement zone with fluid expulsion along the décollement zone due to the high permeability interconnection of dilatant fractures, and the in ability of the fluid to flow back through the low intergranular permeability of the source sediment; and (3) an interval of recovery in which continuing deformation of the source sediment again elevates their pore pressure, finally leading to a renewed phase of dilation. Basically this deformational pumping mechanism builds on previous models of Sibson *et al.* (1975), Sibson (1981), Etheridge *et al.* (1984) and Vrolijk (1987). The model presented here relies on a high fracture permeability to allow flow along the décollement; recent data indicating that shear zones in muds have enhanced permeability parallel to the shear surface may also encourage flow along the décollement zone and not back into the source sediment (Arch 1987). The mineral- and mud-filled veins in the modern décollement zone of the northern Barbados Ridge indicate a phase of dilation (Behrmann *et al.* 1988). The fluid pressure variation inferred by Vrolijk (1987) from veins in melange and by Agar (1987) from melange microstructures also suggest cyclical fluid pressure variation in ancient accretionary environments.

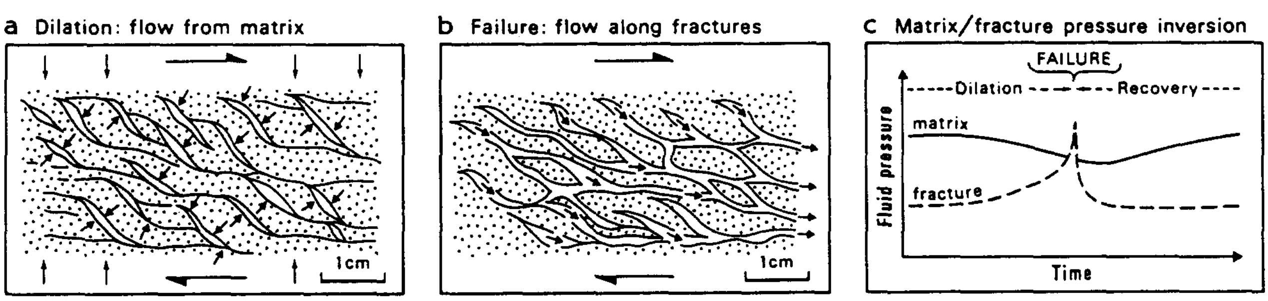

Fig. 9. Fluid movement during décollement zone displacement. (a) Dilation of scaly fabric with fluid flow to zones of localized fluid pressure minima within dilatant fractures. (b) Fluid movement at the instant of failure. The density of dilated fractures has weakened sediment with consequent failure. During failure, fluid pressure briefly approximates lithostatic with opening of and fluid flow *along* interconnected network. Because the fracture permeability and directional matrix permeability parallel to the décollement zone (Arch 1987) are much higher than the matrix permeability of the sediment adjacent to the décollement zone, fluid cannot flow back to its source region and is pumped along the décollement zone. (c) Comparison of fluid pressure in fractures of the décollement zone and sediment matrix of adjacent source regions. During dilation, flow from the matrix reduces its fluid pressure. The pressure in fractures exceeds that in the source matrix during collapse of dilatant fabric. The matrix does not record this brief increase in pressure and its pressure minima follows the pressure peak in the fractures because of the hydraulic lag of the low permeability mud. During the 'recovery' phase, deviatoric stress increases again, causing an increase in pore pressure in the matrix and ultimately leading to a subsequent dilation of fractures in the décollement zone.

Maintenance of minimum effective stress along and fluid flow into the décollement zone

Data from the northern Barbados Ridge indicate that fluids, probably sourced from the underthrust sediments, flow out of the décollement zone (Moore *et al.* 1988). This flow path requires a decrease in head from the underthrust sediments into the décollement zone. In order for the décollement zone to be a failure surface in sediments of uniform strength, minimum effective stress is required. At first glance, the requirement of minimum effective stress and flow into the décollement zone is paradoxical.

Fluid flow may occur from the underthrust sediments to the décollement zone while maintaining minimum effective stress at the décollement zone because of the divergence of hydrostatic and lithostatic pressure gradients with depth (Fig. 10). Head is determined at any point along the pressure gradient curve by its difference above the hydrostatic gradient. Similarly, effective stress along the pressure gradient curve is defined by its value below the lithostatic gradient. As long as the slope of the pressure gradient curve in the sediments below the décollement zone does not exceed that of the hydrostatic gradient and is not less than that of the lithostatic gradient the condition of minimum effective stress and minimum head will occur at the décollement (Fig. 10, inset).

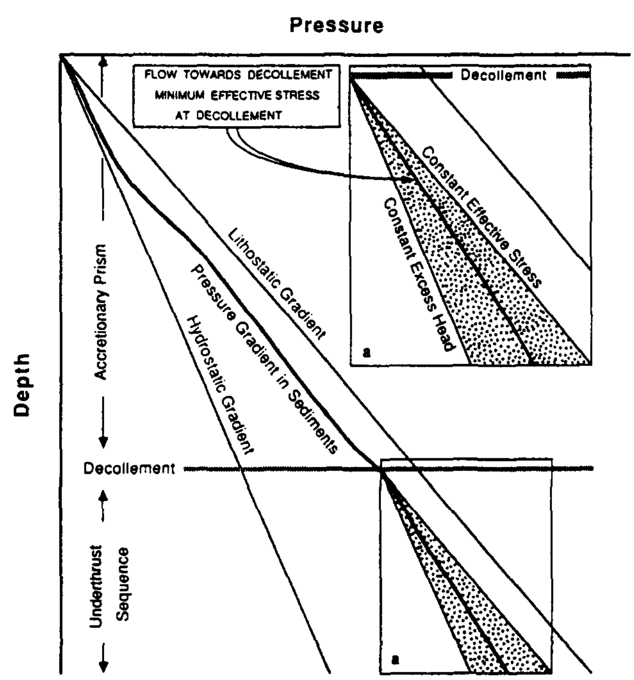

Fig. 10. Pressure distribution through an accretionary prism and underthrust sequence that allows both fluid flow to, and minimum effective stress in, the décollement zone. Maintenance of fluid flow from underthrust sediments to décollement zone with minimum effective stress in the zone occurs if the slope of the pressure curve is greater than that of a line of excess head but less than that of a line of constant effective stress.

EFFECTS OF THE DECOLLEMENT: STRUCTURAL GEOLOGY

All underplated sediment must transect the décollement zone. The effect of the décollement zone on the underplated sediment depends on structural thickness of the duplexes or thrust packages transferred and on the depth of underplating. Because the décollement zone effectively protects underthrust sediment from deformation these materials can begin their substantive structural history under a variety of conditions depending on their depth of passage.

Role of underthrust sediment thickness

The structural thickness of underplated packages appears to be proportional to underthrust sediment thickness. Where thick sequences of sediment are underthrust the décollement zone cuts down through the lower plate in discrete large steps; for example, along a seismic line crossing the southern Barbados Ridge where the underthrust sequence is about 4 km thick, the steps in the décollement are several hundred meters to more than a kilometer thick (Fig. 1). Where the underthrust sediments are thin (less than several hundred meters) the down-stepping of the seismic décollement can be near or below the limit of resolution by seismic reflection (Shipley 1982, Shipley & Moore 1986).

Coherent vs diffusive underplating

Two end-member accretionary styles are probably a function of underthrust sediment thickness (Moore & Sample in press) (Fig. 11). At any distance of underthrusting the thickness of the décollement zone probably does not increase proportionally with the thickness of sediment entering the subduction zone. Accordingly, the underplating of thicker underthrust sequences would result in a relatively lower ratio of disrupted to coherent units because coherency would be maintained in the larger duplexes; underplating of thin underthrust sequences would be characterized by a higher ratio of disrupted to coherent units. The Kodiak slate belt is a probable example of the former where the underplating of a thick sedimentary sequence resulted in a unit characterized by coherent macroscopic duplexes with subsidiary (20%) zones of stratal disruption (Sample & Fisher 1986, Sample & Moore 1987). Conversely, the Uyak Complex also of the Kodiak Islands, shows similar burial depths and presumably distance of underthrusting, and is virtually 100% disrupted (Moore & Wheeler 1978). The Uyak complex contains mostly hemipelagic and pelagic sediments and oceanic crust (Connelly 1978), and is inferred to have been a much thinner underthrust sequence than that preserved in the Kodiak slate belt.

Because the décollement zone is a dewatering conduit and underplated sediment must transect it, the volume of accretionary packages should affect fluid transfer to the base of the accretionary prism. The larger volume of

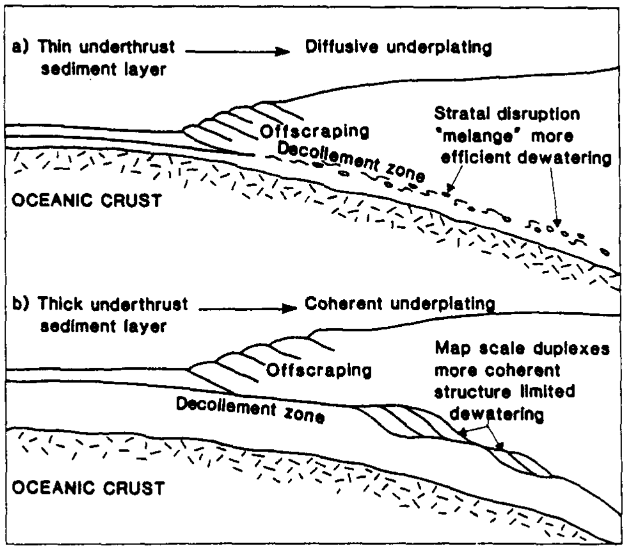

Fig. 11. Contrasts in structural and hydrologic development of underplated sediment. (a) Underthrusting of thin sediment layer with stratal disruption along décollement zone. Thin underthrust layer tends to transfer smaller underplated packages leading to their more efficient dewatering because of closer proximity on any given sediment element to dewatering path or bounding fault. (b) Underplating of thicker sediment layer with emplacement of macroscopically (seismically resolvable and mappable) duplexes. Even though disruption along décollement zone (not shown for graphical clarity) is of similar thickness as in (a) proportion of disrupted material is less because of thicker incoming sediment fill. Overall, underplated section is more coherent and is less dewatered because smaller volumetric percentage of disruption zones which are also drainage paths.

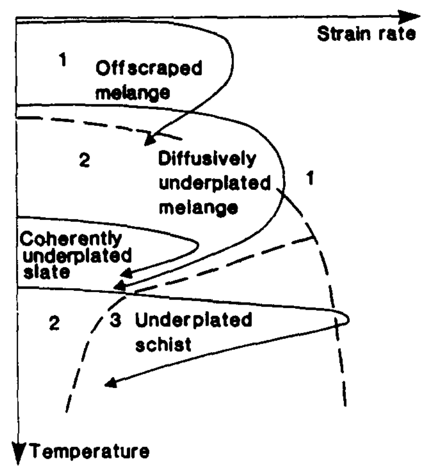

Fig. 12. Accretion and deformation mechanisms. Examples of paths of accreted material are plotted through a deformation mechanism map. In each case highest strain rate represents passage through a décollement zone. Offscraped melange remains almost entirely in the particulate and cataclastic flow field because of limited burial. Diffusively underplated melange resides in a décollement zone for relatively long time interval. Curve for coherently underplated slate represents a sample of the interior of a duplex that is never subjected to brittle faulting. Underplated schist deforms mostly in crystal plastic field except for a brief interval of brittle faulting during passage through a décollement zone. Deformation mechanisms after Knipe (1986).

individual underplated packages associated with thick underthrust sediment packages would retard dewatering because of the larger average distance of any sediment element from drainage paths, the enveloping fault surfaces. Conversely, the sediment in smaller fault-bounded blocks of a diffusively underplated sequence would have easier access to dewatering paths. Since the consolidation time varies by the square of the distance to the dewatering path, the underplating of larger duplexes could substantially increase fluid transfer to the accretionary prism with consequent effects on structural and metamorphic processes.

Variation in deformation mechanisms

Seismic data (Clowes *et al.* 1987, Westbrook *et al.* in press) and geological data (Fisher & Byrne 1988) indicate that little-deformed sediments are underthrust and available for accretion at depths locally exceeding 30 km. Therefore, deformation of these deposits may be initiated at a variety of pressure and temperature conditions with consequent variation in deformation mechanisms.

Materials in accretionary prisms deform by particulate and cataclastic flow, diffusional mass transfer, and crystal plasticity (Knipe 1986). As used here, particulate flow refers to sliding of grains over and past one another without any deformation of the particles. Particulate flow occurs under low effective stresses and produces ductile deformation on the aggregate level. Cataclastic flow involves grain breakage coupled with grain-boundary sliding and develops under higher effective stresses than particulate flow. Cataclastic deformation may produce distributed grain breakage in sands and, with lithification, discrete cataclastic shear zones or web structure (e.g. Cowan 1982, Byrne 1984). The diffusional mass transfer mechanism is active during the development of solution phenomena of all types including pervasive cleavages. Crystal plasticity forms microstructures characterized by undulatory extinction, sub-grains and dynamic recrystallization textures.

These deformation mechanisms are mapped on to a plot of temperature and strain rate (Fig. 12). Strain rates on the plot vary from those expected during faulting (Price 1975) to a 'geological' strain rate which might be the background deformation rate in an accretionary prism. The persistence of large thrust-mechanism earthquakes to depths of 50 km or more provides justification for extending the field of particulate and cataclastic flow to the region of higher temperatures and strain rate. Absent in Fig. 12 is an axis representing the variation in fluid pressure. Fluid pressures are likely to be high but cyclical during most deformation in accretionary prisms. Any increase could move the deforming material from diffusional mass transfer or crystal plasticity into the particulate or cataclastic flow field, or into the realm of fracture (Knipe 1986). Hence the effect is similar to increasing strain rate. Additionally, deformation mechanisms may influence boundary conditions; for instance, deformation by particulate or cataclastic flow may reduce fluid pressures and cause movement into the field of diffusional mass transfer or crystal plasticity

(Knipe 1986, Agar 1987). Only the dominant deformation mechanisms under any given temperature and strain-rate conditions are depicted in Fig. 12, but this representation is probably sufficient to interpret the evolution of the major features of accreted materials. Knipe (1986) treats deformation mechanisms more completely, addressing shallow levels of structural evolution in accretionary prisms.

The plot of deformation mechanisms (Fig. 12) allows use of the microstructures and the overall structural setting of a rock to interpret its path through the subduction zone. Because sediments may either begin to deform immediately upon entering the subduction zone or be protected and transported to depth below the décollement zone, many scenarios of deformation mechanism development are possible. Material being accreted at the deformation front along one of the imbricate thrusts would be deformed nearly completely in the realm of particulate and cataclastic flow, reaching a peak in strain rate during maximum rate of fault movement and perhaps finally developing some solution phenomena as it becomes buried. The product would be an offscraped melange. Conversely, the interior of a coherently underplated slaty duplex would deform completely in the diffusional mass transfer field. During deep underthrusting sediment may pass momentarily through the diffusional mass transfer field but then on to crystal plasticity, and into the particulate and cataclastic flow field when it passes through the décollement and is subjected to the fracture process associated with earthquakes. Finally, with accretion, this sediment element would settle into the field of crystal plasticity forming a schist.

CONCLUSIONS AND FUTURE PERSPECTIVES

Conclusions

At convergent plate boundaries the décollement zone is the plate boundary and an interval of profound structural disharmony. The décollement zone forms typically along an underconsolidated interval or 'weak link' in the incoming sedimentary section, most commonly in the hemipelagic apron beneath the trench fill. In contrast to offscraping at the deformation front, deep underthrusting beneath the accretionary prism allows the development of high metamorphic grade, increases the chance of preservation of accreted material, and can occur at rates of more than 20 km/my. Such rapid burial may be able to emplace the fine-grained underthrust sediment before it can dewater. Episodic fluid flow along décollement zones may be explained by a deformational pumping mechanism. Fluid flow may occur from the underthrust sediments upwards to the décollement zone while maintaining minimum effective stress along the décollement zone because of the divergence of hydrostatic and lithostatic pressure gradients with depth. Variations from thin to thick underthrust sediment result in structural styles ranging from virtually complete stratal disruption (melange) to relatively coherent duplexes, respectively. For a constant volume of sediment accreted, fluid transfer increases with the size of the thrust-bound packages. Since the décollement zone can protect underthrust sediment from substantial deformation until emplacement at a range of depths, a variety of possible deformation mechanisms may develop.

The future perspective

This paper only treats one aspect of the tectonics and hydrogeology of accretionary prisms; hopefully it demonstrates the fundamental connection between structural and fluid evolution. A range of other features and processes also show this intimate interaction between fluids and solids. Structural studies of accretionary prisms ignoring fluids are likely to be myopic because of the enormous impact of fluid as both a physical parameter and a chemical messenger. Future analyses of ancient deformed rock sequences require careful field work to be coupled with comprehensive microstructural investigations, plus thorough geochemical and fluid inclusion studies. Ancient rock sequences provide the only practical means of studying the deep-level, protracted evolution of fluids in accretionary environments.

Comprehensive understanding of the tectonics and hydrogeology of accretionary prisms will require measurements of temperature, fluid pressure, fluid flow rates, *in situ* permeabilities and stresses in modern environments. Evaluation of rates of fluid expulsion in active accretionary prisms provides a means of constraining their fluid budget as inputs can be easily estimated. Geophysical and hydrological measurements in modern environments must be closely coupled with studies of the physical properties, structural geology, diagenesis and sedimentology of the prism.

Investigations of the hydrogeology and tectonics of modern and ancient accretionary prisms must be coupled with modelling. Appropriate analytical and numerical models provide guidance on the critical measurements. Conversely, models unconstrained by data are of little use.

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