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The microstructural evolution of fluid flow paths in semi-lithified sediments from subduction complexes

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The characterization of the fluid migration pathways is essential to an understanding of the hydrodynamics of accretionary wedges located in the high levels of subduction zones. Microstructural analysis of the fluid flow pathways can provide constraints on (*a*) the porosity/permeability evolution of different migration pathways, (*b*) the deformation mechanisms histories which promote different fluid flow characteristics, (*c*) the interconnectivity of migration pathways. Three important fluid migration pathways can be recognized in accretionary wedges; bulk flow through the sediment, localized flow through fracture networks and localized flow along fault zones. The recent progress made towards understanding the microfabric evolution in each of these pathways in semi-lithified sediments is reviewed. The analysis highlights the role of transient deformation events in these materials and the need to characterize the detailed deformation mechanism paths and syn-deformational (dynamic) properties associated with these events.

1. Introduction

An important aspect of understanding the fluid flow in any sediment/rock system is the assessment of the mechanical and physical processes which control the behaviour of potential fluid flow paths. In accretionary wedges the understanding of fluid flow in sediments is critical to unravelling the wedge dynamics (Moore 1989; Langseth & Moore 1990). However, such analysis is complicated by the range of burial, compaction and deformation histories possible in this tectonic situation where the sediments experience large and rapid changes in their physical (e.g. porosity and permeability) and mechanical properties (Shephard & Bryant 1983; Bray & Karig 1985; Karig 1986, 1990). Recent research has identified the need for integrated studies which assess the detailed interaction between dewatering, lithification and deformation processes during the burial and incorporation of sediment into accretionary wedges.

Fluid flow depends upon the complex interaction between permeability and fluid potential gradients. Permeability is controlled by the microstructure and pore geometry of the sediment, hence knowledge of the microstructural evolution of sediments during burial and deformation can help constrain on the physical and mechanical properties needed to model the fluid flow. Here we review the microstructural evolution of fluid flow paths in sediments undergoing lithification, the interaction between deformation processes and fluid flow and assess the role of microstructural analysis in future fluid flow. The discussion is based on analysis of

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Deep Sea or Ocean Drilling Program (DSDP/ODP) cores from active margins and of fabrics preserved in on-shore, exhumed subduction complexes where the depth of burial did not exceed 1–2 km.

2. Deformation processes and their recognition in partly lithified sediments

Data on the deformation behaviour of unlithified and partly lithified sediments is based upon experimental deformation programmes which have applied the methods developed for assessing the mechanical behaviour of soils (Lambe & Whitman 1969; Jones & Addis 1986; Maltman 1987; Karig 1990). These programmes have provided important data on the behaviour of 'soft' sediments during different stress histories and have highlighted the influence of the mean effective stress path, the differential stress magnitude, porosity and lithology in controlling the mechanical response.

The assessment of mechanical behaviour during natural deformation events in accretionary wedges requires experimental programmes designed specifically to reproduce the natural deformation conditions (Karig 1990) and confirmation that similar deformation processes have operated in the experimental and natural situations. Such a programme of comparison is still in its infancy as experiments using natural sediments are rare, and because the microstructural characterization of naturally and experimentally produced fabrics has only recently gained momentum (Knipe 1986*a*, *b*; Bennett & Hulbert 1987; Agar *et al.* 1989; Kemp 1990; Prior & Behrmann 1990). Recent developments in both the preparation techniques (Swartz & Lindsley-Griffin 1990) and in the improved performance of both transmission electron microscopes (TEMS) and scanning electron microscopes (SEMS) have considerably helped this research. The development of more efficient and higher resolution backscattered electron (BSE) images in SEMS (Lloyd 1985; Agar *et al.* 1989) have been particularly important. Backscattered images provide contrast between grains of different composition and when combined with careful preparation of polished specimens allow quantification of the microfabric elements (Prior & Behrmann 1990). The resolution of such images now provides a powerful companion to the more traditional TEM analysis (Smart & Tovey 1982; Knipe 1986*a*, *b*).

The detailed grain-scale deformation processes operating in semi-lithified sediments are still poorly understood. Thus while the general operation of particulate flow by grain-boundary (frictional) sliding is assumed to be the main mechanism of deformation (Knipe 1986*c*, 1989), whether the process is one of independent particulate flow (Borradaile 1981), where no grain deformation is involved, or whether dependent particulate flow, where grain (clay plate) deformation controls the strain accommodation in the aggregate needs to be resolved.

3. Deformation and fluid flow paths in accretionary prisms

Fluid flow paths available in the accretionary wedges include: (*a*) bulk flow through the grain framework of sediments, (*b*) flow through fracture networks (*c*) flow along fault arrays. The deformation processes which accompany the evolution of each of these paths will affect the fabric which develops and the fluid flow characteristics.

(*a*) *Bulk flow and compaction fabrics*

The pores in the grain framework of a sediment undergoing burial compaction and lithification provide a fluid flow pathway. The migration path characteristics are

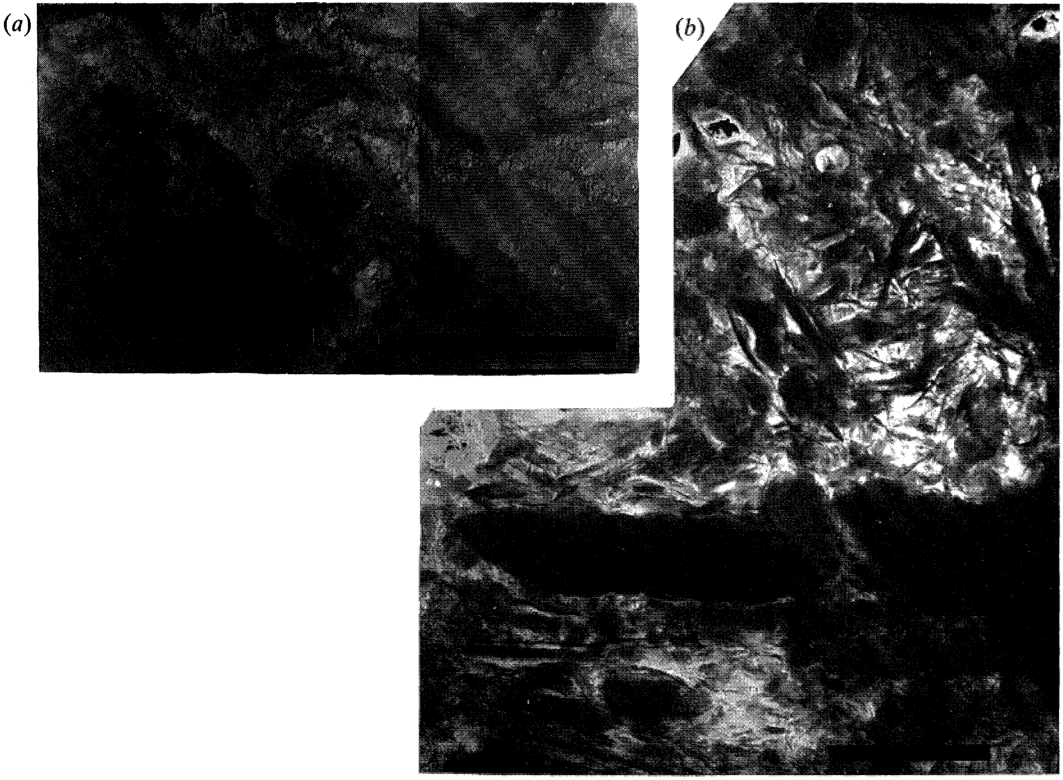

Figure 1. (*a*) Compaction fabric composed of domains of phyllosilicates aligned parallel to bedding and domains with more random and open grain framework. Scale bar 1 μm, TEM micrograph. Specimen from DSDP Leg 60 459B 46cc. (*b*) Compaction fabric containing wide domains of phyllosilicate aligned parallel to bedding (lower part of plate) and domains with a more open framework. Note the development of alignment domains at a high angle to bedding in upper part of plate. See text for discussion. Scale bar 5 μm TEM micrograph. Specimen from DSDP Leg 57.439.8.2.

known to change with time as porosity and permeability are reduced with time during burial (Bray & Karig 1985; Shephard & Byant 1983; Karig 1990). Grain collapse and cementation are known to be involved but the detailed mechanisms and the interaction of fabric collapse with fluid flow and expulsion are less well defined.

The microfabrics formed in fine-grained sediments at different stages of compaction are complex, often very heterogeneous and composed of a relatively rigid framework of grain aggregates or domains connected by weak links or chains (see review by Bennett & Hulbert 1987). The large variations in the microfabric geometries present create domains and chains with very different strengths. The complexity of the fabrics developed during compaction are illustrated in figure 1*a*, *b*. Both parts show the development of localized domains of aligned grains, in figure 1*a* they are subparallel to the mesoscopic bedding. If the alignment domains are considered to be collapse zones then the process of compaction will be heterogeneous and appears to arise from repeated, localized and transient deformation events. It is the frequency, distribution and size of these events which will control the porosity and permeability evolution. At present there is little information on these events. Analysis of the specimen shown in figure 1*a* suggests that in this case the collapse domains may involve volume losses of 25–50 μm³ per domain. To assess the fluid flow which may arise from such compaction some estimate of the rate of collapse in the domains is needed. Such rates are unknown at present as can be illustrated by a simple calculation of the likely range of volumetric strain-rates involved. Assuming that the porosity changes in this fine-grained sediment decreases by *ca.* 1% in *ca.* 1 Ma then the average volumetric strain rate is *ca.* 3×10^{-16} s^{-1}. However, if the volume loss per event is *ca.* 5–50 μm³ (based on the size and density of grains in the domains shown in figure 1*a*) and events are sequential then the local strain-rate within the collapse domain may be at least 10^{-5}–10^{-6} s^{-1}. Without more detailed information on the distribution and rate of collapse, processes associated with compaction, modelling of the fluid expulsion rates and permeability properties remain incomplete.

Figure 1*b* shows a more complex microfabric where in addition to the development of domains of aligned grains parallel to the mesoscopic bedding the domain with the more open grain framework has additional alignment zones at a high angle to the bedding. The alignment zones mark domains of reduced porosity and are permeability barriers which will induce a permeability anisotropy in the bedding plane. This specimen is from DSDP Leg 57 (Japan Trench) where down slope movement and extensional faulting is present in the core (Knipe 1986*b*) and suggests that the alignment zones may represent microscopic normal faults. The compaction processes and permeability characteristics of the sediment may be dependent upon evolution of the slope instabilities and the extensional faulting as well as on the burial history.

(*b*) *Flow through fracture networks*

Recent work on DSDP/ODP cores and onshore studies of accretionary prisms shows that a range of fracture types may be present. At shallow depths (less than 500 m) mud-filled veins are a common feature in fine-grained slope sediments (Lundberg & Moore 1986; Knipe 1986*b*; Kemp 1990; Pickering *et al.* 1990) while web structures (anastomosing networks of low displacement, cataclastic shear zones) are common in silts/sands (reviewed in Lundberg & Moore 1986). Carbonate filled vein arrays and open fracture networks have also been reported from some active margins (Brown & Behrmann 1990; Thornburg & Suess 1990). Studies of older on-shore prisms have also revealed the ubiquitous presence of fracture systems (Agar 1990). The microstructural evolution of the mud-filled veins and web structures and their involvement in fluid flow in the shallow sections of accretionary prisms is reviewed below.

(i) *Mud-filled vein structures in fine grained sediments*

Mud-filled vein arrays are composed of sets of planar/curviplanar, dark, clay rich structures usually less than 10 cm in length and less than 1 cm wide. These structures appear to represent a common mode of deformation in partly lithified slope sediments and occur in arrays (regular or anastomosing sets) orientated at a high angle to bedding and associated with bedding parallel movement or slip zones (Lundberg & Moore 1986). They have been described from a number of the active margins drilled during the ODP (see Lundberg & Moore 1986; Knipe 1986*b*; Lindsley-Griffin *et al.* 1990 for reviews) and from onshore studies in SE Central Japan (Pickering *et al.* 1990). Vein structures do not represent simple dilational features as they contain domains of external material and microfossils, and show evidence of new mineral growth (Knipe 1986*b*; Pickering *et al.* 1990). Two main models for the vein evolution involving a sequence of disaggregation/dilation-displacement and

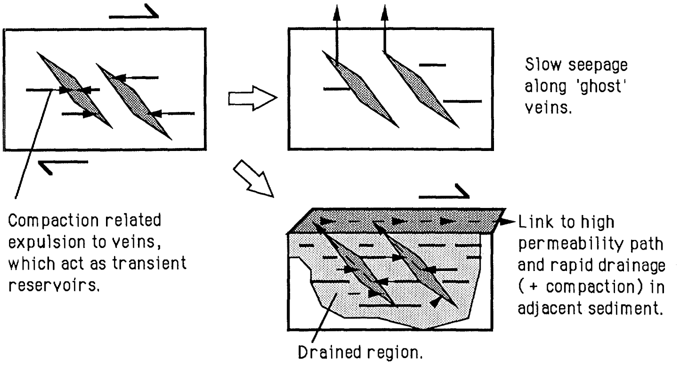

Figure 2. Review of possible interrelationships between fluid expulsion and vein evolution. The fluid ingress associated with the vein dilation may be linked to the collapse and compaction of the fabric adjacent to the vein. Fluid expulsion from the vein may either be by slow fluid flow along 'ghost' veins or by the propagation and linking of the veins to a more extensive migration pathway. Such a linking processes may induce a more extensive collapse and compaction in the adjacent sediment.

collapse were presented by Knipe (1986*b*): Model A, where the vein structures arise from fluid pressure exceeding the cohesion of the sediment and the alignment of clays within parts of the vein as the result of either rapid fluid flow or a late stage porosity collapse. Model B, where disaggregation producing the vein was associated with a shear or tensional failure not related to over-pressure but arising from slope instabilities or tectonic events. Veins described by Knipe (1986*b*) and Ritger (1985) did not show evidence of rapid dewatering. However, Kemp (1990) has reported evidence of upward fluid and mass transport in veins from Peru indicating that the model A is applicable in some cases.

The extensional geometry, evidence of disaggregation, dilation and mineral growth in veins all support the idea that fluid flow into the vein structures has occurred. The veins probably acted as small fluid reservoirs developed during deformation. There are two important aspects of vein evolution and fluid flow which require detailed assessment. Firstly, the affects of fluid movement into veins, as the disaggregation and dilation may induce enhanced compaction in the adjacent sediment (figure 2). The second important aspect of the vein evolution is the fluid escape from the veins. This escape may occur by one of two processes; (*a*) slow dewatering during continued compaction and cementation of the vein (i.e. the vein behaves in a similar fashion to the adjacent sediment), (*b*) fluid expulsion along localized channel-ways. Where vein arrays have propagated into, and are linked to, a more extensive fracture/fault network or more permeable horizons then dewatering may be rapid and a second wave of enhanced compaction may have been induced in the (over-pressured?) horizon containing the initial veins (figure 2). The magnitude of water pressure gradient in such zones and its decay rate (a function of the permeability) will control the amount of fluid released during such transient events. There are many examples of veins either connected to more extensive movement/slip surfaces or terminating at slightly different lithologies (see Lundberg & Moore 1986; Knipe 1986*b*). This simple separation of fluid expulsion implies that isolated veins with no obvious connection to high permeability pathways are confined to a slow diffuse dewatering history. However, the identification of 'ghost' veins (marked by regular to irregular networks containing a concentration of fine-

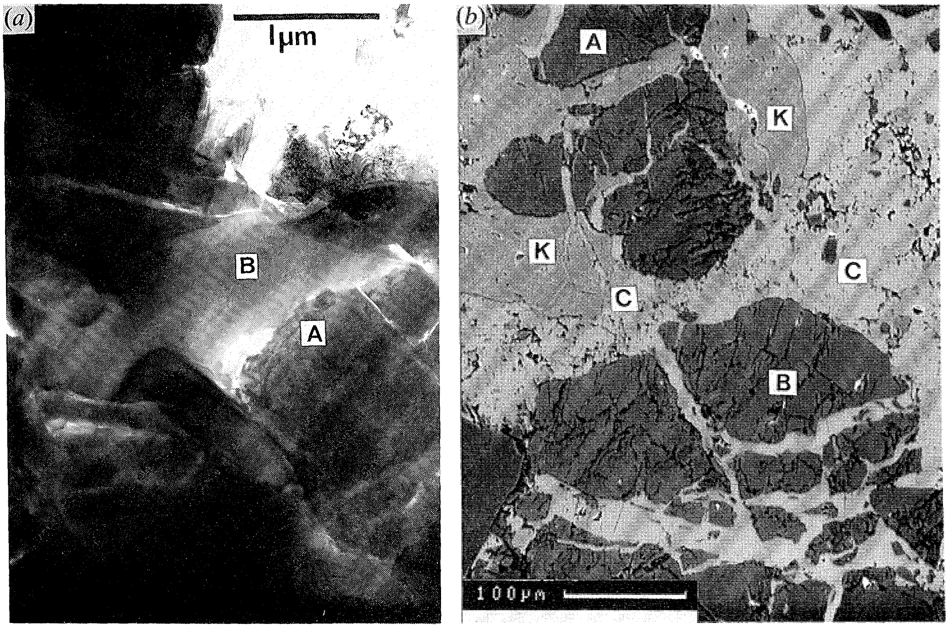

Figure 3. (*a*) Detail of multiple cementation in a web. An early pure calcite cement, A, has been fractured and a new Fe–Mn calcite cement, B, precipitated. Note the more complex defect structure in the older, deformed cement. TEM micrograph of Web from *Alvin* 2948-5V1. (*b*) Multiple fracture and cement events within a web structure. An early event has fractured Grain A and then sealed it with K-feldspar growth. K. A later event associated with calcite cementation has fractured both the original grain and the first cement. BSE image of specimen from Leg 66 493-1 100–105 cm.

grained material but not associated with a detectable modification of the sediment fabric) by Kemp (1990) during BSE analysis of sediments from the Peru forearc is extremely important as it suggests that localized fluid flow is far more extensive in sediments than previously considered.

(ii) *Web structures in silts and sands*

'Web' structures are arrays of irregular and localized cataclasite zones which commonly develop in partly cemented sandstones. The individual deformation zones are up to a few millimetres wide, usually show small displacements and form complex, intersecting arrays where the spacing is on a centimetre scale. (See reviews in Lundberg & Moore (1986) and Lucas & Moore (1986)). The zones are characterized by grain size reduction, fracture and brecciation. Lucas & Moore (1986) suggested that the process is associated with repeated strain hardening events linked to fluctuations in the pore pressure within the fractured material. Although webs are considered as important fluid migration pathways the processes involved in their evolution are poorly understood. Figure 3*a*, *b* presents evidence that the deformation in these structures is episodic and involves the introduction of fluids of different compositions. Both micrographs show the growth of cements of different compositions in dilation sites developed by different fracture events. The specimen shown in figure 3*b* is a web from a fault zone known to be an active vent and recovered by an *Alvin* dive in the frontal part of the Cascadia accretionary prism, Oregon (see Moore *et al.* (1990) for tectonic setting). The redistribution of deformation and fluid flow within the web network indicated by the multiple cements also emphasizes that different segments of the array may be active at different times during the array development and that fluid flow at any one time, or during a single deformation event, is not along all of the finite fractures preserved. This conclusion is important as the finite fracture density can not be used to estimate fluid fluxes. In addition the preferential growth of cements in and adjacent to the fracture zones leads to a change in the properties of the fracture from a transient high permeability pathway to a permeability barrier or seal.

(*c*) *Faulting and fluid flow*

The interaction between fluid flow and faults is well established (Carter *et al.* 1990; Sibson 1981, 1990) and a direct link between fluid flow and fault zones at active margins has been established by (*a*) the identification of biological communities and vents near faults (Suess *et al.* 1985; Carson *et al.* 1990; Moore *et al.* 1990), (*b*) the recognition of geochemical anomalies and thermal anomalies in fault zone fluids (Gieskes *et al.* 1990) and (*c*) the preferential growth of new mineral phases along fault zones (Knipe 1986*a*; Schoonmaker 1986). These associations render the assessment of the permeability properties of faults developed in semi-lithified sediment critical as these correspond to the zones where fluid expulsion is implied by calculations of heat flow and geochemical anomalies (Le Pichon *et al.* this symposium). Such an assessment requires an understanding of the mechanical properties and the relationship between fault zone fabric evolution and permeability characteristics during deformation (i.e. the dynamic properties). Experimental deformation studies of semi-lithified sediments have provided important data on the bulk mechanical behaviour of sediments with different initial physical properties and microstructural studies have already provided an insight into the deformation fabrics associated with faults.

The faults from active accretionary wedges which have been sampled by the DSDP/ODP and *Alvin* submersible operations provide an opportunity to study fabric development associated with faults in known tectonic locations within active margins where hydrogeological studies are also possible. However, only a small number of major fault zones have been sampled. Notable examples are the Barbados (Legs 78A and 110) and Nankai (Leg 131) wedges. In both cases the decollement associated with accretion was penetrated in addition to higher level faults present in the prisms. The mesoscale geometry associated with such faults range from arrays of thin (*ca.* 1 mm wide) zones to major zones (greater than 20 m wide) of scaly fabrics (defined by a mesoscopic set of anastomosing, polished and slickensided surfaces), breccias and stratal disruption/melange) (Lundberg & Moore 1986; Brown & Behrmann 1990; Lindsley-Griffin *et al.* 1990). The faults sampled exhibit a range of mesoscale fabrics and no single structure occurs on all faults.

Microstructural studies of the faults present in the semi-lithified sediments from active margins have revealed a large variety of deformation fabrics preserved. Many of the faults developed in clay rich sediments are composed of anastomosing micro-movement domains of finite porosity collapse enclosing domains/lenses of less well-aligned material (Knipe 1986*a*; Moore *et al.* 1986). The exact geometry and the spacing of the domains, varies from microscopic (less than 100 μm) in the case of mesoscopically discrete fault zones (see Knipe 1986*a*) to millimetre scale domains present in some scaly fabrics (see Moore *et al.* 1986). The deformation mechanisms involved in the fault zones are considered to be disaggregation and particulate flow

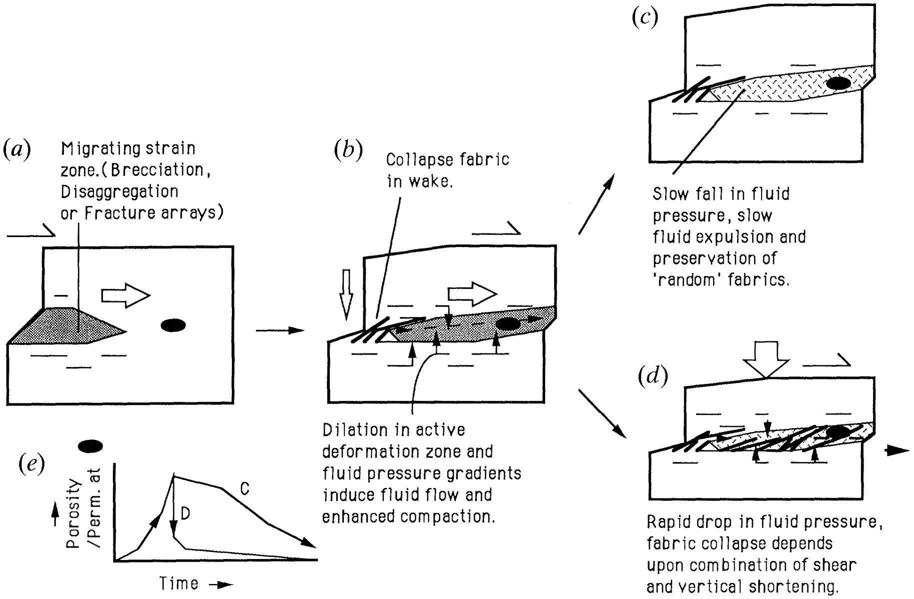

Figure 4. Review of the possible changes in the fabric and fluid flow during the migration of a strain wave in a fault zone. The diagram emphasizes the dynamic nature of the fabric, porosity and permeability associated with the migration of a strain wave and the potential influence of the decay rate of fluid pressure gradients on fabric stability and preservation.

with and without fracturing. The presence of numerous localized movement (alignment) zones suggests that new movement zones were generated during the deformation because existing ones were not able to accommodate the continuing deformation (Knipe 1986*a*). This situation may have developed either because of a hardening due to the increased coefficient of friction in alignment domains, a decrease in pore pressure or a reorientation of the slip surface relative to the stress field (Moore *et al.* 1986) or because the existing active deformation zones were incapable of accommodating an increasing strain/displacement rate (Knipe 1986*a*).

Not all the samples of fault zones studied from active margins exhibit the 'simple' two domain microfabric described above. Prior & Behrmann (1990) have reported that specimens from the decollement fault zone from Barbados (Leg 110) with a scaly clay appearance in hand specimen do not contain microdomains of aligned grains but are composed of randomly arranged aggregates less than 6 μm in size. These observations are important as they suggest that fault domains with random microfabrics do not always represent low-strain domains preserving the initial or external fabric; they may represent high strain zones where a pervasive disaggregation fabric is preserved. Prior & Behrmann (1990) emphasize the need to consider deformation by particulate flow where the grain boundary sliding is between aggregates not individual grains.

There are three aspects of the microfabric evolution in fault zones which are important to the future assessment of fluid flow (see figure 4).

(i) *Deformation mechanism paths and the transient changes in the physical properties associated with displacement*

The exact history of deformation processes, porosity, permeability and straining within the faults will control the fluid flow. Although the deformation mechanisms involved in both the experimental and the natural deformation are considered to be particulate flow and grain boundary sliding, the controls on the activity of (i) pervasive disaggregation and sliding by individual grains, or (ii) disaggregation by sliding between aggregates of grains, or (iii) by localized slip on discrete slip planes are unknown. The models of fault zone behaviour presented so far have concentrated on the fabrics where localized slip has occurred at some stage of the deformation history. Despite the lack of knowledge on the exact processes involved in fault zone fabric development the potential importance of cyclic and transient changes in the physical properties is recognized (see Karig 1986; Knipe 1986*a*–*c*; Moore *et al*. 1986; Moore 1989). Evaluation of the fluid flow during faulting requires knowledge of the dynamic properties (porosity and permeability) changes associated with the deformation events.

(ii) *Fabric stability*

The permeability characteristics of a material during deformation will depend upon the pore geometry and connectivity, which will be controlled by the mechanical response and deformation processes operating in the material. The changes in the effective stress, fluid pressure gradients, dilation, strain path and strain rate which accompany deformation in poorly consolidated material are likely to induce a series of changes in the microfabric and thus it is unlikely that one microfabric will be characteristic of an entire deformation event. Rather a series of microfabrics will develop during the deformation event and be modified during the late stages and/or between deformation events (Knipe 1986*a*). The fluid flow characteristics during the deformation event will be dependent on three interrelated factors of the deformation and fabric evolution.

1. *The dilation patterns induced during deformation.* A range of dilation patterns may be induced during deformation in the semi-consolidated material. The production of an interconnected fracture array which allows rapid expulsion of fluid during the production of scaly clay has been suggested by Moore (1989). At the other end of the spectrum is the pervasive disaggregation of the aggregate and dilation of the material in the fault zone during displacement under high fluid pressure, which would also enhance and increase permeability. Between these two end-member responses will be more complex patterns where dilation is linked to localized strain waves migrating through the material. The fluid flow in this case will depend upon the volume, dilation and migration velocity of these strain waves. Collapse of the material may occur in the wake of these migrating waves to produce domains of clay alignment (see figure 4). The migration of strain or creep events in over-pressured fine-grained gouges is known from the San Andres fault zones (see review by Wesson 1988) and is likely to be operational in the high level fault zones in accretionary wedges.

2. *The distribution of deformation within the fault zone.* The percentage of the fault zone volume active at different stages of the deformation event will affect the amount of dilation and the fluid flow possible. The controls on whether deformation is distributed or localized and how this pattern changes during strain/displacement

events is unknown. Initial TEM analysis of the scaly fabrics from the decollement under the Nankai wedge, sampled during ODP Leg 131, indicates that repeated localized deformation by brecciation of early fabrics has occurred.

3. *The duration of deformation activity.* This will control the time period when the different enhanced permeability paths can operate. Individual fault activity periods will depend upon the controls of fault array evolution (Platt 1990) but each fault may be associated with the generation, propagation and dissipation of large numbers of small strain events.

The above discussion raises the possibility that the variety of fabrics reported from individual fault zones may represent different types of deformation events or different stages of similar events preserved because of the exact history of conditions experienced. For example pervasive straining by disaggregation and particulate flow involving deformation throughout the entire shear zone may produce random fabrics and allow continuous and steady fluid flow. However, the stability of this fabric is low as adjustments and collapse are likely during the late stages of movement as the fluid is expelled and/or any fluid over-pressure decreased. The stability of fabric would be enhanced where collapse was prevented by a prolonged period of high fluid pressure (or a slow decay of fluid pressure) during which time cement bridges and/or a more open framework could form (figure 4*c*). The random fabrics (as described by Prior & Behrmann 1990) may be characteristic of such a situation and reflect one type of dynamic (syn-deformation) fabric. The development of domains of clay alignment may be more characteristic of the end of a deformation event where the displacement rate, fluid pressure and permeability changes induce localized grain-framework collapse (figure 4*d*). It is interesting to note that the production of such alignment zones may well change the material response to the next deformation event as a new pre-strain fabric is present. These points also emphasize that the fabrics preserved (and physical properties measured) are the finite features which are likely to have been modified during deformation.

(iii) *Cyclic versus continuous deformation to fluid flow*

Different fluid flow characteristics are likely to be associated with each of the deformation processes and fabrics discussed above. Three end-member modes of flow may be recognized:

(1) fluid flow associated with pervasive, continuous creep in fault zone;

(2) transient events of increased deformation and fluid flow;

(3) flow along faults during periods of low or no strain between deformation events where the permeability anisotropy of the grain alignment, generated during deformation, may create localized flow along the fault but act as a seal to cross fault flow. Arch & Maltman (1990) have discussed the possible role of permeability anisotropy in fault zones.

It is clear from the foregoing discussion that evidence for cyclic deformation is common in semi-lithified sediment. What is uncertain is the cause of the cyclic deformation and fluid flow. The possible causes which require future assessment may be divided into two groups: (1) *internally generated* events caused, for example by the linking of localized initial fabric failures, generated by fluid over-pressuring or by high differential stresses and (2) *externally imposed* cyclic straining caused by deformation events migrating into the volume considered. An example of the latter would be the seaward migration of the wedge deformation front (Platt 1990). A numerical analysis of the behaviour of event clustering applied to fluid flow along faults by Stark & Stark (1991) has demonstrated the important application of percolation theory to this problem. Establishing the exact nucleation, propagation and clustering processes as well as the size (volume affected), duration and migration distances of such events are all important to understanding the associated permeability and fluid flow characteristics and will require a combination of microstructural and numerical modelling studies.

4. Conclusions

The review of microstructural research presented above demonstrates the role that such studies have in assessing the migration of fluids in semi-lithified sediments. As permeability is controlled by the detailed microstructure of the grain framework characterizing the evolution of fabrics generated in experimental and natural deformation events can provide important information needed for understanding the hydrology of accretionary wedges. The discussion has identified a number of research areas where future analysis is particularly important. These include the assessment of; (*a*) the microfabrics associated with different fluid flow paths and their stability during deformation under different conditions, (*b*) the characterization of transient deformation events in terms of the deformation mechanisms paths, the volumes affected, the dilation histories and the propagation processes and (*c*) the interaction and interdependence of the different fluid migration paths.

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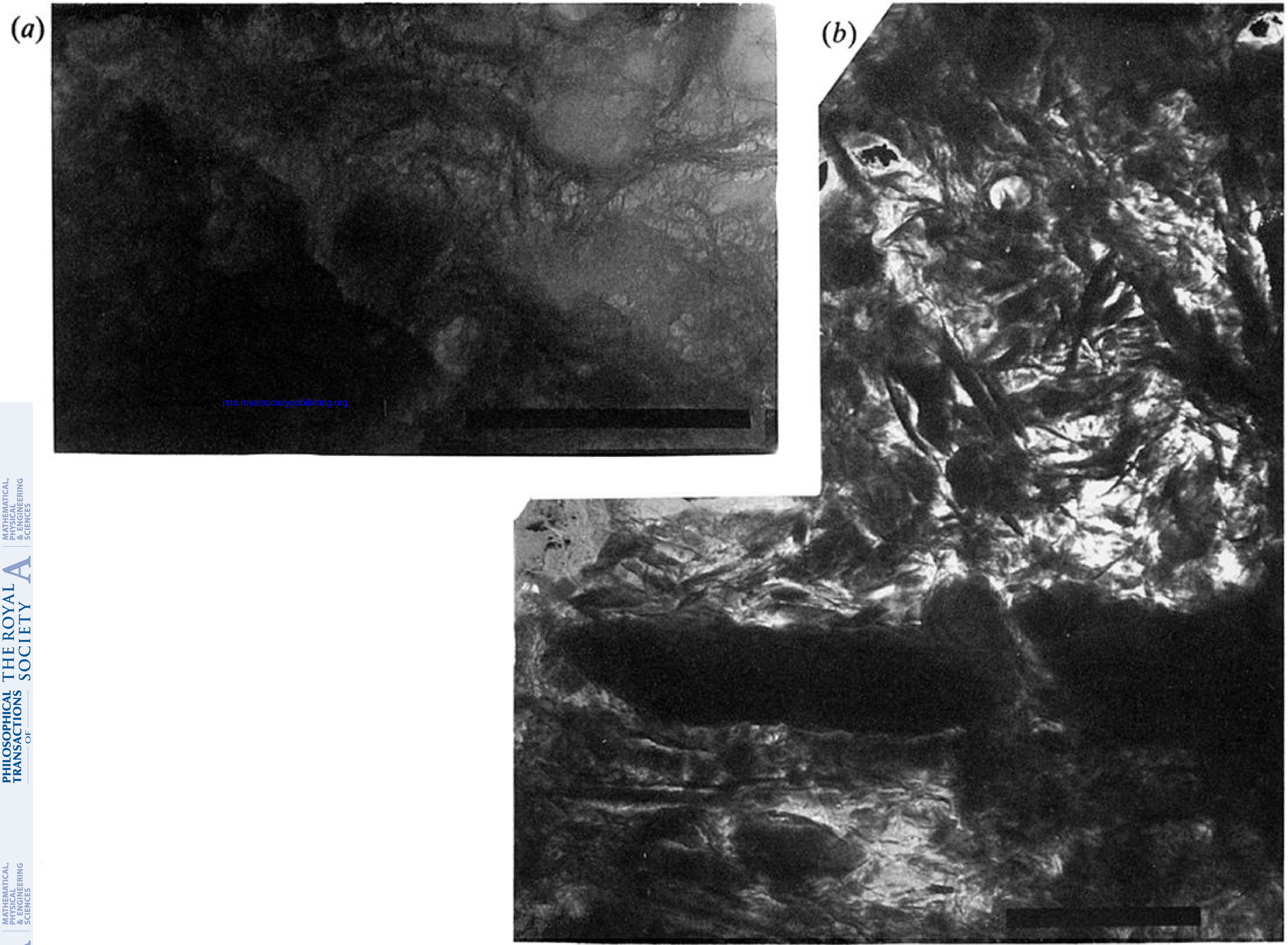
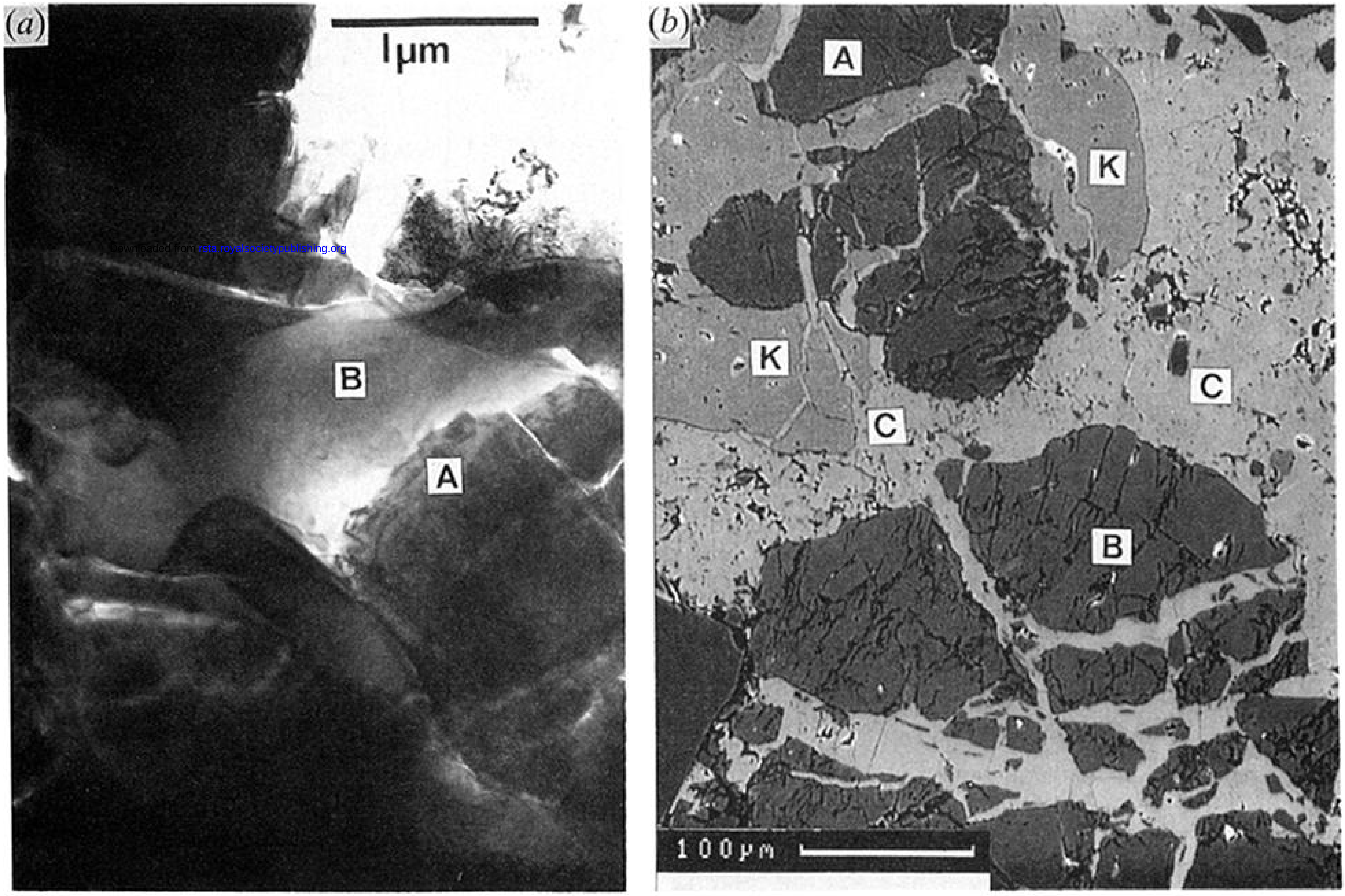


Figure 1. (*a*) Compaction fabric composed of domains of phyllosilicates aligned parallel to bedding and domains with more random and open grain framework. Scale bar 1 μm, TEM micrograph. Specimen from DSDP Leg 60 459B 46cc. (*b*) Compaction fabric containing wide domains of phyllosilicate aligned parallel to bedding (lower part of plate) and domains with a more open framework. Note the development of alignment domains at a high angle to bedding in upper part of plate. See text for discussion. Scale bar 5 μm TEM micrograph. Specimen from DSDP Leg 57.439.8.2.



gure 3. (*a*) Detail of multiple cementation in a web. An early pure calcite cement, A, has been actured and a new Fe–Mn calcite cement, B, precipitated. Note the more complex defect ructure in the older, deformed cement. TEM micrograph of Web from *Alvin* 2948-5V1. (*b*) Multiple acture and cement events within a web structure. An early event has fractured Grain A and then aled it with K-feldspar growth. K. A later event associated with calcite cementation has actured both the original grain and the first cement. BSE image of specimen from Leg 66 493-1 0–105 cm.