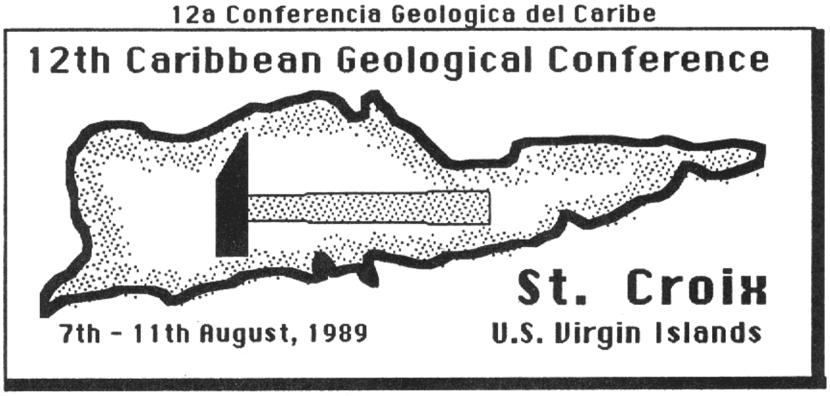
TRANSACTIONS OF THE 12TH CARIBBEAN GEOLOGICAL CONFERENCE

ST. CROIX, U.S. VIRGIN ISLANDS

August 7th - 11th, 1989

12a Conferencia Geologica del Caribe



12me Conference Geologique de Caraibes

Edited by

David K. Larue
Department of Geology, University of Puerto Rico
Mayagüez, PR 00708, Puerto Rico

and

Grenville Draper
Department of Geology, Florida International University
Miami, FL 33199
U.S.A.

Additional copies of this book may be purchased from

Miami Geological Society
P.O. Box 431552
South Miami, FL 33243, U.S.A.

December 1990

STRESS INDUCED MODIFICATION OF SEDIMENT MASS PHYSICAL PROPERTIES DURING ACCRETION: A RECONSTRUCTIONAL APPROACH

Warner Brückmann, GEOMAR–Research Center
for Marine Geosciences, Kiel, FRG

ABSTRACT

The impact of lateral stress on mechanical diagenesis of marine sediments can be estimated using sediment physical property data.

The depth dependent compactional behavior of a set of standard sediment types is described by a number of type curves developed in a statistical analysis of the Deep Sea Drilling Project (DSDP) sedimentological and mass physical property database (legs 1–96). The typecurves define compactional behaviour of mainly pelitic and psammitic sediments of low carbonate content. They are employed as a reference tool for the quantification of tectonically induced consolidation in a growing accretionary wedge.

Based largely on these typecurves and sediment physical property data from DSDP– and ODP–legs 78A and 110 (Barbados Ridge), a simple palinkinetic reconstruction procedure was employed to determine porosity changes during accretion. Palinspastically removing the compactional effects of burial diagenesis caused by imbricate stacking of wedge slices, a synthetic preaccretion porosity vs. depth profile could be modeled, which bears strong resemblence to characteristic profiles from 2 reference drill holes in front of the accretionary wedge (Sites 543 and 672). Comparison of synthetic and reference profiles reveals a lithologically controlled exponential relationship between depth and porosity divergence. Reevaluation of the reconstruction procedure in terms of involved stresses yielded a semiquantitative estimate of the relative and absolute impact of the lateral stress component on sediment consolidation in this part of the convergent plate margin.

This semiquantitative definition of compactional response to the lateral stress component provides an important constraint for further modeling of deformational behavior of accreted sediments.

INTRODUCTION

Convergent plate boundaries are in many instances characterized by the development of a wedge shaped accretionary superstructure, that derives from the process of continuous offscraping and subsequent addition of marine sediments from subducting oceanic plates to the overriding plate. Formulated by SEELY, VAIL & WALTON, 1974 the "trench slope model" postulated the development of submarine complexes of great lateral extension in the slope of trenches above subduction zones. It was based on earlier work and on seismic observations by SEYFERT, 1969, von HUENE, 1972, DICKINSON, 1973, and KARIG, 1969.

The popular subduction accretion model assumes the growth of such structural complexes by frontal accretion of imbricate thrust slices of sediments scraped off a downgoing oceanic plate (AOKI et al., 1982 BIJU-DUVAL et al., 1982, MOORE & BIJU-DUVAL, 1984, MOORE & SILVER, 1987).

Since the frontal accretion and imbrication of semilithified sediments constitutes a mechanical analogon to the tectonic style of fold and thrust belts on land (BOYER & ELLIOT, 1982), similar structural expressions are often inferred (MOORE & SILVER, 1987, SILVER et al., 1986, SAMPLE & FISCHER, 1986). Duplex structures, regular series of imbricately stacked thrust packages, which are a common feature in the frontal part of alpine nappes, are also believed to dominate the tectonic style of accretion. This rather regular mode of accretion constrains the style of deformation in the frontal zone of an accretionary wedge, often termed "wedge toe".

While a large part of the crustal convergence is compensated in the wedge toe (and beyond that) through imbrication, deformation and enhanced compaction of semilithified sediments during the process of accretion can also account for some degree of shortening.

Accreted sediments have experienced a multiphase deformational history that has a strong impact on their physical properties.

One of the most important factors in establishing a "steady state" accretionary wedge is the availability of pore fluids that are supplied by compaction, low grade metamorphic dehydration reactions and thermal expansion at depth. HUBBERT & RUBEY, 1959 and RUBEY & HUBBERT, 1959 were the first to point out the fundamental importance of overpressured pore fluids in the initiation of detachment zones and in the transport of thrust slices over long distances. The tectonic and geometrical analogy of accretionary imbrication zones with the frontal parts of alpine nappes suggests similar processes of mechanical decoupling along zones of overpressured pore fluids.

Assuming a Coulomb failure criterion CHAPPLE, 1978, WESTBROOK, 1982 and DAVIS et al., 1983 used the slope angle to estimate the basal shear stress of a sliding wedge. They calculated the relation of hydrostatic and lithostatic pressure necessary for mechanical decoupling along the basal décollement. In the case of the Barbados Ridge a relation of 0.92 is necessary for mechanical decoupling of subducted and accreted sediments. These calculations are supported by observations of overpressured pore fluids along

Larue, D.K., and Draper, G. (eds.),
Transactions of the 12th Caribbean Geological Conference, St. Croix, U.S.V.I., Miami Geological Society, P.O. Box 431552, South Miami, FL 33243, U.S.A

a number of convergent plate margins (von HUENE & LEE, 1983). Other indicators are mud volcanoes that are developing in many convergent settings, in some cases far away from the deformation front (WESTBROOK & SMITH, 1983). The oceanic reference Site 672 of ODP Leg 110 in front of the Barbados Ridge Complex penetrated a layer of sediments rich in methane which are derived from the accretionary prism indicating the existence of hydrologic preformation of a fore-runner for the future dcollement in the hitherto undeformed strata.

Deformation and mass physical properties of accreted sediments

Due to the unique structural and tectonic properties of accretionary wedges the constituting sediments are characterized by an anomalous development of their mass physical properties porosity, density and shear stress. The compressive tectonic setting of convergent plate margins can be treated as a natural laboratory, in which the deformational reaction of semilithified marine sediments to excessive lateral stress can be studied. The overall deformational behavior of accreted sediments and their soil mechanical properties are in close relationship with large scale geometry of an accretionary wedge.

Porosity as an important index parameter for the compaction is a function of lithology and burial depth as well as the orientation and magnitude of in situ total and shear stress. It is well known, that marine sediments undergoing accretion are developing a significantly lower porosity than those that are compacted in undisturbed basinal sequences (MOORE & KARIG, 1978, CARSON, 1977, WESTBROOK et al., 1982, FOWLER et al., 1985). This observation has not been quantitatively described, as was stated by BRAY & KARIG, 1985:

"However this conclusion has not been adequately documented, and neither the gradient with which porosity decreases with depth within an accretionary prism nor lateral changes in that gradient have yet been explored."

KARIG, 1985 proposed a rapid porosity decrease with depth and with distance from the wedge toe in the frontal parts of an accretionary wedge, leveling off gradually with increasing distance from the deformation front. Deformation and tectonic consolidation are concentrated in the upper part of the wedge toe. DAVIS & von HUENE, 1987 assumed that the bulk of active compressional deformation is concentrated in the first 5 to 15 km of the Barbados, Nankai and Middle America accretionary prisms.

Qualitative and quantitative modeling

During the late seventies to early eighties, when the basic concepts for the genesis of accretionary prisms were developed, these structures were relatively inaccessible to direct sampling by drilling, the only information available were derived from seismic profiles.

Based on seismic data a number of modeling attempts were made to gain a more thorough insight into the basic processes that shape and modify accretionary wedges.

Several physical modeling attempts succeeded in replicating the overall geometry of accretionary wedges in squeezze boxes and other mechanical devices in which artificially deposited clays were subjected to lateral compression (COWAN & SILLING, 1978, DAVIS, SUPPE & DAHLEN 1983, CARSON & BERGLUND, 1986). With poorly constrained boundary conditions and many problems of scaling, and through negligence of the hydrologic regime many of these models had only limited applicability to real world situations.

Aside of these techniques there have been several attempts of using FE/FD (finite element / finite difference) methods to model accretionary wedge deformation assuming viscous, plastic or, most successfully, Coulomb rheological behavior. Numerical methods were applied in a number of cases to define the overall geometry and gross deformational behavior of accretionary wedges in general. Early studies by WOODWARD, 1976, CHAPPLE, 1979, PARK, 1981 and STOCKMAL, 1983 attempted to model the stress field associated with accretionary wedges in general. NGOKWEY, 1984, 1985 developed a FE model that successfully incorporated data on Leg 78A to describe the framework of deformation in the Barbados Ridge Complex.

A common problem to all these models is the strong dependence on the type of assumed rheological properties of accreted sediments. There are three basic types of rheological behaviour that can be applied — Coulomb, plastic and viscous (MOORE & SILVER, 1987). Under the assumption of brittle deformation and constant rate of plate convergence Coulomb–type models predict the development of a stable continuum. In this "steady state trench"–situation the slope angle, internal pore pressures and the mass gain at the wedge toe are in equilibrium with the overall geometry of the wedge. STOCKMAL, 1983 using a plastic rheology to define a stress field around an idealized accretionary wedge proposed listric faults in the toe section. CLOOS, 1982 proposed mass transfer through convective return within the whole wedge assuming viscous material properties.

Nevertheless, realistic modeling of the deformational behavior of accreted sediments is still seriously hampered by the lack of good in situ data.

Apart from this, hydrological modeling mostly done by Shi and Wang has dominated the published work in recent years (WANG, 1984, SHI & WANG, 1985, 1987, 1988, and SHI, 1986).

Thermal modeling is another relatively new field, that has been developed in close relationship with the above mentioned techniques (DAVY & GILLET, 1978, SHI & WANG, 1987, and PEACOCK, 1987).

PALINSPASTIC RECONSTRUCTION OF PHYSICAL PROPERTIES

The problem that shall be adressed in this paper is the quantification of the magnitude of lateral stress in terms of its deformational impact on accreted sediments — as it can be deduced from compaction phenomena in these environments.

The concept that will be applied here, is to reconstruct a synthetic pre-accretionary porosity–depth profile from available drillhole data from an accretionary wedge taking into account all known parameters contributing to compaction and comparing it to a standard reference profile of comparable lithology.

This approach is somewhat different from the normally taken path: instead of relying on a set of functions relating the basic properties of the modeled structure, here only actually determined data points were used as a model input. As many as possible original data were incorporated to reconstruct a physical property profile such as additional gravitational loading due to imbrication.

By discounting the known processes it will be possible to define the magnitude of any additional process specific to the convergent accretionary environment.

DSDP Leg 78A and ODP Leg 110: BARBADOS RIDGE COMPLEX

An important drawback is the scarcity of actual data from accretionary wedges, since they are very inaccessible to direct sampling.

One of the main sources of information concerning sedimentological and sediment physical property data from accretionary wedges were the drilling operations of the Deep Sea Drilling Project (DSDP) and its successor Ocean Drilling Program (ODP).

Drilling the circumpacific forearc areas provided a wealth of data, yet only DSDP Leg 78A and ODP Leg 110 in the Barbados Ridge Complex succeded in reaching and penetrating the basal décollement zone, that is separating subducted and accreted sediments at the base of the prism. Both legs gained physical property data hitherto unavailable especially in the areas close to detachment planes and shear zones.

Regional setting

In the southern part of the Lesser Antilles island arc, continuing subduction of the North American plate under the Caribbean plate has produced an unusually broad accretionary prism varying in width from 80 to 300 km. Here the incoming sedimentary pile consists of up to 7 km of terrigenous material, derived mainly from the Orinoco Fan of the nearby South American continent.

The Leg 78A and 110 drilling area, located in the northernmost section of the Barbados Ridge Complex (Fig. 1, 2) is characterized by the input of 700 m of pelagic to hemipelagic clays. In this area the topographic high of the Tiburon Rise is shielding the subducted sedimentary sequence from the influx of terrigenous material. Drilling results as well as seismic profiles strongly suggest successive growth of the accretionary wedge by imbricate thrusting and stacking of offscraped sediment slices at the deformation front (Fig. 3). In the drilling area the upper 200 m of the incoming sedimentary sequence are scraped off from the subducting Atlantic plate and attached to the accretionary wedge. Shear and detachement zones in the wedge toe area are characterized by near lithostatic pore fluid pressures that are believed to facilitate the movement of large thrust slices.

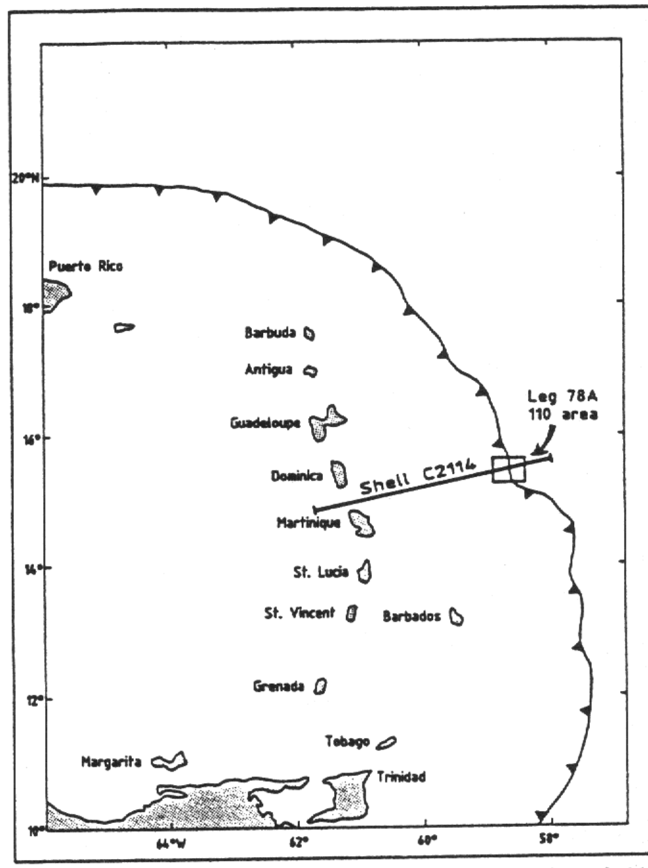


FIG. 1. Regional location map for the Leg 78A and 110 drilling area (from DAVIS & HUSSONG, 1984)

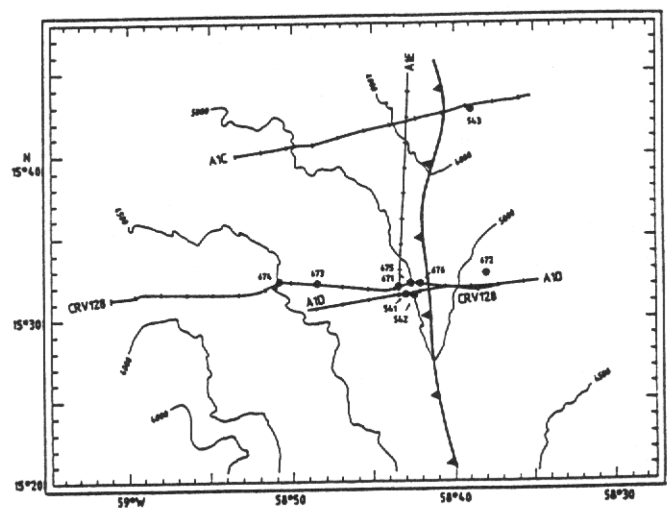


FIG. 2. Site location map for the Leg 78A and 110 drilling area (modified from MOORE & BIJU-DUVAL, 1984)

Sedimentological, stratigraphic and sediment physical property data on Legs 78A and 110 are utilized in this study to develop a palinspastic model to examine the compactional effects associated with initial deformation in imbricated thrust slices at the wedge toe.

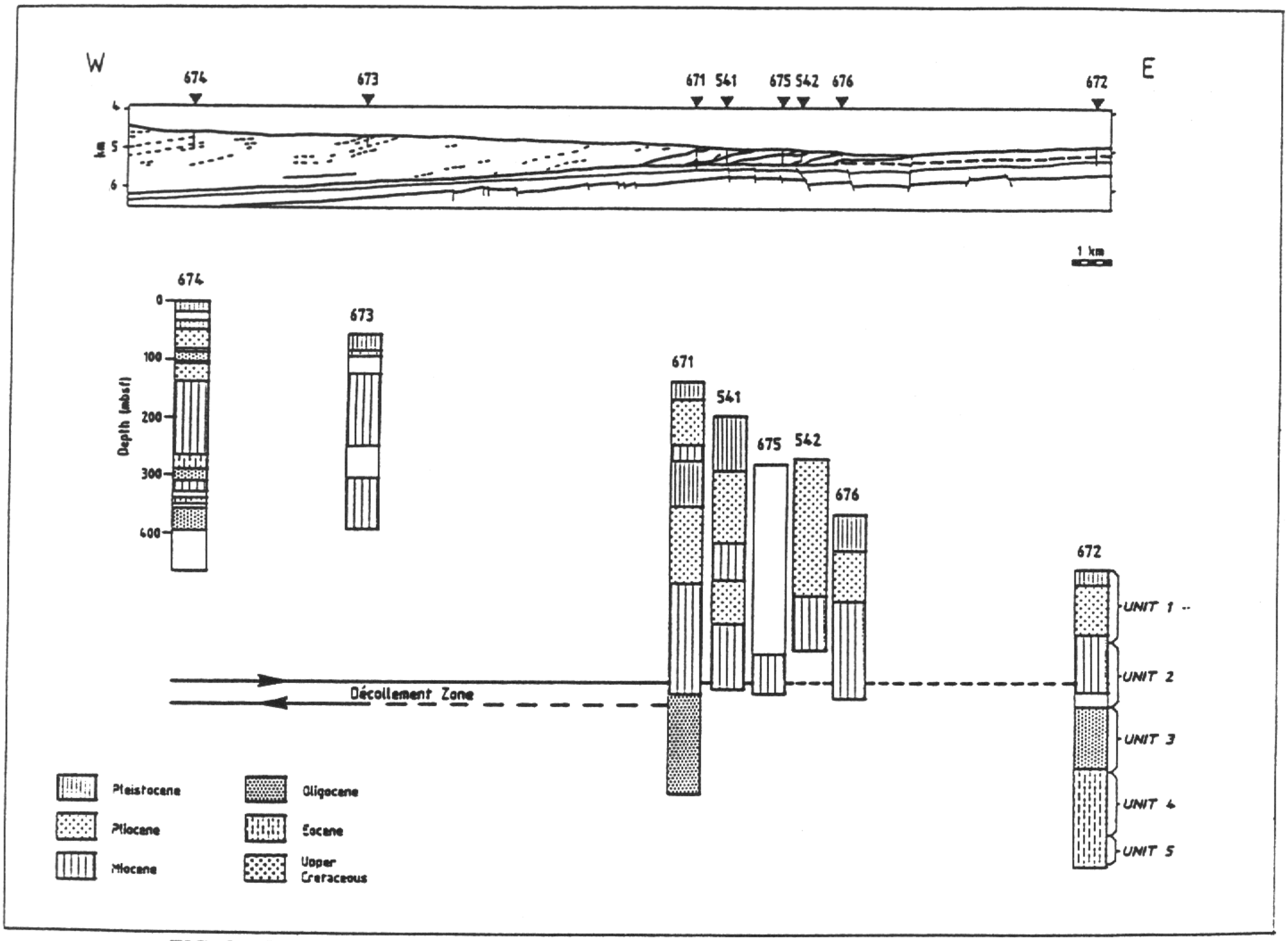


FIG. 3. Leg 78A and 110 sites projected onto an interpreted cross section along seismic Line C2114 (modified from MOORE, MASCLE et al, 1988)

The data fulfill a number of pre–requisites essential to the application of the reconstructional approach outlined above:

- all seven drill sites in the frontal part of the wedge toe as well as two reference sites in front of the deformation zone are located along one seismic line. There is good stratigraphic correlation among all sites, with the reference sections reaching stratigraphic levels below the lowermost sections recovered in the accreted sequences.
- Coring of holes was adequate to provide a good physical property data coverage of all sites.

There are four basic steps involved in the implementation of the proposed reconstruction procedure:

1. Data input
All physical property data that were routinely determined during Leg 78A were supplied through the DSDP database system; relevant physical property data on Leg 110 were made available by a shipboard scientist (J. Behrmann, Giessen). Error checking revealed only few serious data inconsistencies, that made correction or omission necessary.

2. Definition of correlation table
Using the biostratigraphic information given in MOORE & BIJU– DUVAL et al., 1984 and in the ODP–Preliminary–Report on Leg 110 a correlation table was defined to relate the position and vertical extension of the major lithological units in the wedge sites and the reference sites.

3. Resequencing
This information was utilized to carry out a resequencing procedure. All the data locations from the wedge sites were rearranged into the correct biostratigraphic order according to their original position in the reference section to establish a synthetic composite profile.

4. Decompaction
The decompaction procedure was carried out using a simple exponential compaction equation, the parameters of which were determined using the DSDP sediment physical property database of Legs 1–96.

5. Synthesis
The final steps of the reconstruction procedure involved the combination of all reassembled and decompacted data.

Implementation of proposed reconstruction procedure

Resequencing was carried out using the above defined correlation tables. Respective new data positions were calculated using the following scheme:

$$(1.1) \quad POS_{new} = LB_{act} + ((POS_{old} - UB_{act}) + \frac{UB_{act}-LB_{act}}{(UB_{ref}-LB_{ref}}$$

POS_{old}, POS_{new} represents the actual (old) and the calculated (new) positions in the hole (mbsf), LB_{ref} and UB_{ref} indicat the lower and upper boundary of the reconstructed unit in the reference drillhole. LB_{act} and UB_{act} represent the lower and upper boundary of the reconstructed unit (mbsf). The difference between POS_{new} and POS_{old} determines the amount of decompaction necessary to account for the difference in vertical gravitational loading.

Decompaction is accomplished using an exponential porosity vs. depth relation of the type:

$$(1.2) \quad n(z) = n(0) * e^{(\beta * z)}$$

were z represents depth in mbsf, n fractional porosity, $n(0)$ porosity at the seafloor (1 mbsf). This type of compaction equation was first proposed by ATHY, 1930, and is generally accepted as a good approximation for gravitational compaction. The value of the dimensionless constant β is lithology controlled. Using the old and reconstructed depth data calculated in (1.1), decompacted porosities can be calculated for the respective depths by:

$$(1.3) \quad n_{new} = n_{old} + ((n_0 - e^{(POS_{new} * \beta)}) - (n_0 - e^{(POS_{old} * \beta)})$$

Appropriate values for β were derived from a statistical analysis of the DSDP sedimentological and mass physical property database. Type curves were defined for the compactional behavior of pelitic and psammitic sediments of low carbonate content.

After completion of the resequencing and decompaction procedures the effects of additional gravitational loading due to imbrication alone have been removed. Reference curve and reconstructed partial curves should be congruent if the difference in loading were the only factor modifying porosity in an imbricated stack of accreted sediments. All resequenced and decompacted porosity vs. depth data were finally combined into a composite scattergram. In the following the reconstructed profile encompassing all sites is allways compared to the reference site 672.

Results of porosity reconstruction

Since most of the reconstructed data belong to either units 1 or 2 (Table 1), the reconstruction is well constrained by the large number of data from all sites in the uppermost 200 m.

Table 1: Site 672 : Lithology

UNIT 1 :	0 – 123 m	(Early Pleistocene to Late Miocene) Calcareous clay and mud, frequent ash layers, traces of biogenic siliceous components. $CaCO_3$: 20 to 45 %
UNIT 2 :	124 - 228 m	(Late Miocene to Late Oligocene) A: Mudstone, claystone, few ash-layers, $CaCO_3$ low B: Claystone, siliceous claystone, ash layers C: Claystone, mudstone, laminated silt intervals
UNIT 3 :	229 - 332 m	(Late Oligocene to Early Oligocene) Interbedded claystone, calcareous mudstone and marl; thin quartz–silt laminae, $CaCO_3$: 0–50 %
UNIT 4 :	333 - 446 m	(Early Oligocene to Middle Eocene) Interbedded claystone, laminated calcareous mudstone, micritic limestone and calcarenite; glauconitic sand layers; $CaCO_3$: 0 to 60 %
UNIT 5 :	447 - 494 m	(Middle Eocene to Early Eocene) Siliceous claystone, shaly in lower part, $CaCO_3$ nil

Visual comparison revealed some similarity in the data distributions of both reconstruction and reference scattergrams. To quantify this observation, the original as well as the reconstructed data sets were treated with a moving average (single pass) smoothing procedure. Comparison of the reference and reconstruction (Fig. 4) shows close correlation of both curves, that are following the same general trend with depth, the reconstruction being always a little lower than the reference. They are parallel even in the range between 100 and 200 m, were an anomalous pattern of lithologically controlled porosity increase with depth also marks the stratigraphic niveau of décollement. A closer look at the depth range from 0 to 250 mbsf which is best supported by data, suggests that the difference between both curves is not randomly distributed but closely correlated with lithological composition of the reference section (Fig. 5 A). A comparison with the table of lithological units (Tab. 1) shows that the divergence in porosity is regularly in– and decreasing from top to bottom being smallest close to unit boundaries. This effect is clearly visible in unit 1.

In yet another closeup encompassing mainly unit 1 (0 – 123 m) — porosity divergence again shown separately on the left — it is clearly visible, that the porosity gap is increasing with depth (Fig. 5 B). This divergence can very well be approximated by the simple exponential regression (Fig. 6).

$$(1.4) \quad \delta_{POR} = 3.783 * (1 - e^{(-0.02418 * z)})$$

This function is quantifying the modeled additional porosity reduction as a function of depth. This additional compaction compared to normal consolidation is due mainly to the stress conditions present in the accretionary wedge.

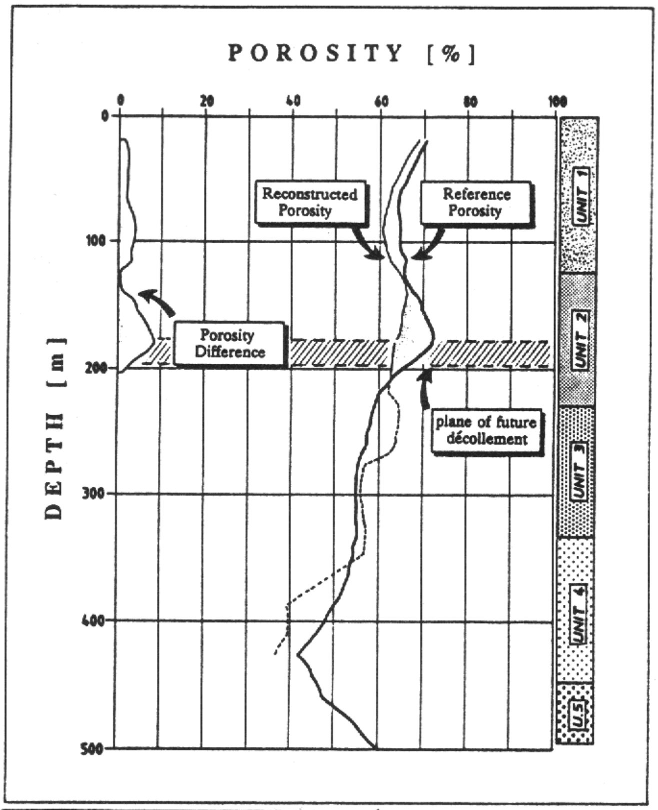


FIG. 4. Comparison of reconstructed and reference porosity–depth profiles. Stippled lines indicate areas of poorly constrained data. Porosity difference marked separately on the left.

Implications and applications

The next logical step in the analysis of the state of stress in the wedge is therefore the substitution of the parameter depth in the last equation with stress. This reassesment of the relation can be accomplished using site 672 data (MASCLE, MOORE et al, 1988, p. 242, fig. 42 – lithostatic stress) on the stress vs. depth relation. Assessment of the necessary amount of additional lateral loading is easiest accomplished by application of the same general reconstruction procedure again, using a stress vs. porosity instead of a depth vs. porosity relation. This was done by applying a linear relation between total stress and depth to (1.4) from which ultimately a homologous relation between porosity and stress can be defined. It presents the reconstruction–reference discrepancy with depth in a similar fashion.

(1.5) $\sigma_v = -3423 * (1 - e^{(0.1015 * \delta_{POR})})$

σ_v (effective vertical load) is expressed as a function of δ_{POR}, the appropriate regression curve (fig. 6 B) demonstrates the interrelationship of additional porosity reduction and the inferred total vertical loading. To understand

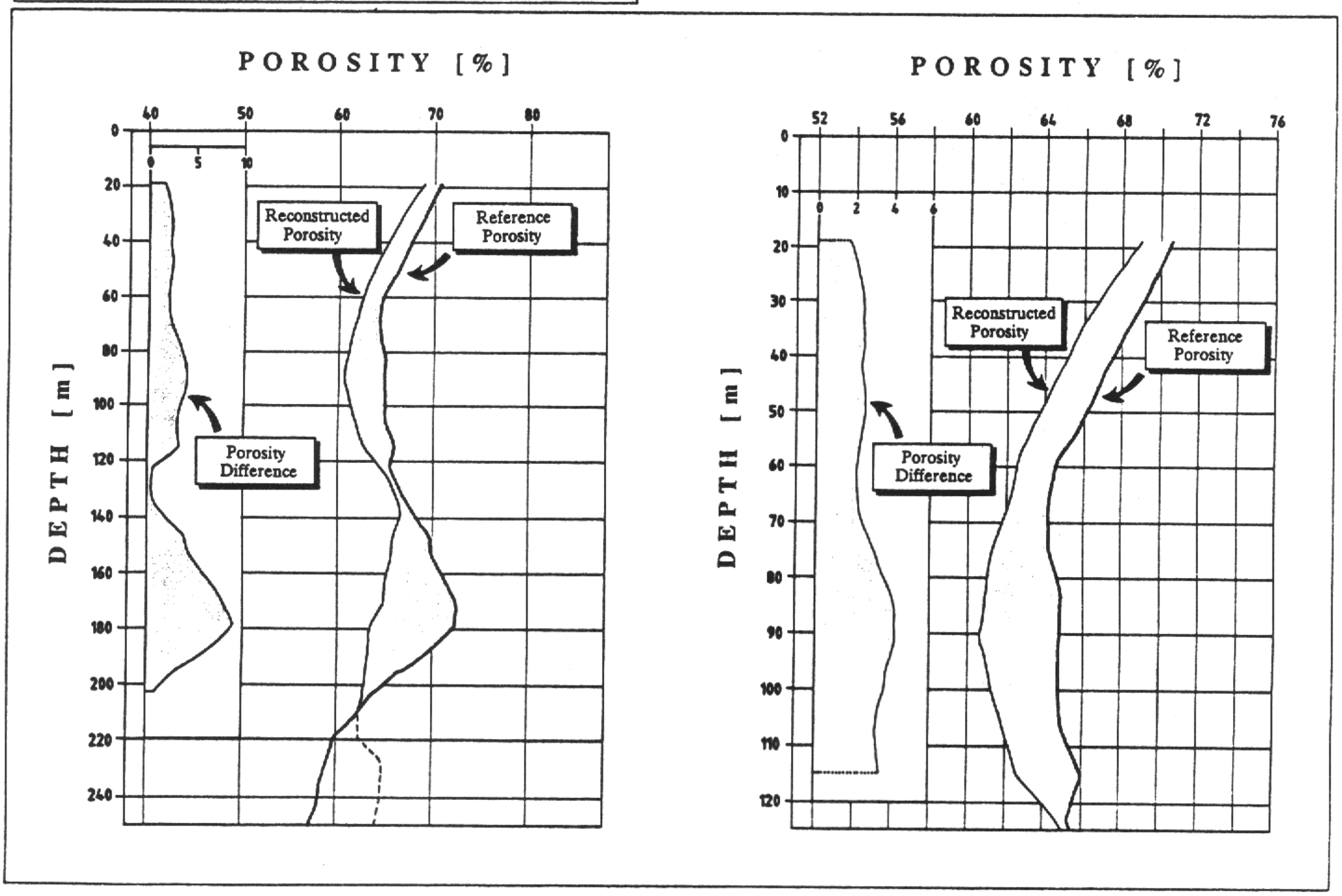


FIG. 5. Comparison of reconstructed and reference porosity–depth profiles
(A) Depth range 0 – 250 m (unit 1 and unit 2)
(B) Depth range 0 – 125 m (unit 1)

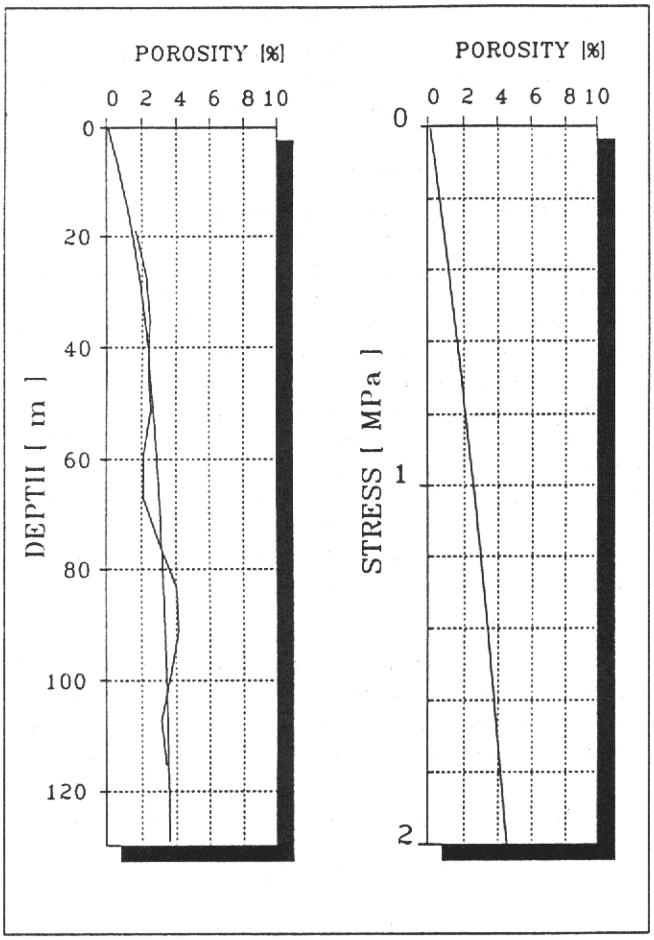


FIG. 6. (A) Regression of modeled porosity difference vs. depth
(B) Regression of modeled porosity difference vs. effective vertical stress

the relevance and possible implications pertinent to this function, some basic soil mechanical aspects of sediment compaction must be understood. During "normal" (uniaxial loading) gravitational consolidation a constant ratio K_0 of σ_v and lateral loads (σ_h) is maintained (eq. 1.6).

(1.6) $K_0 = (\sigma_v/\sigma_h)$

K_0 is a lithology dependent constant that is related to angle of internal friction by:

(1.7) $K_0 = (1 - \sin\Phi)$

This relation is valid for sediments under loading pressures of up to 100 MPa (LAMBE & WHITMAN, 1979). K_0 values of 0.6 are characteristic for marine sediments of the type discussed here (MOORE & BYRNE, 1986). Inserting this K_0-value into equation (1.6) the following relative amount of σ_v can be inferred for a normal uniaxial loading situation:

(1.8) $\sigma_v = 1.67 * \sigma_h$

This relative estimate of σ_v is valid for normal K_0 consolidation. It can be applied to determine the proportion of the lateral stress component in the convergent setting of the Barbados Ridge Complex. Redefining the modeled relation of additional porosity reduction and necessary additional vertical loading (eq. 1.5) using eq. (1.8) the following new equation holds:

(1.9) $\sigma_{h+} = (-3423 * (1 - e^{(0.1015 * \delta_{POR})})/1.67)$

were σ_{h+} expresses the amount of lateral stress necessary to cause the additional porosity reduction modeled for unit 1 sediments in the wedge. Comparison of the relative proportions of normal vertical, normal horizontal and additional horizontal stresses acting on unit 1 sediments facilitates the analysis of in situ stress conditions in the frontal on the wedge (Fig. 7). The relative impact of the modeled additional (or excess) stress on the observed compaction of unit 1 sediments is largest near the surface. Normal vertical and normal horizontal stress exceed the impact of additional lateral stress around 15 m and 75 m respectively.

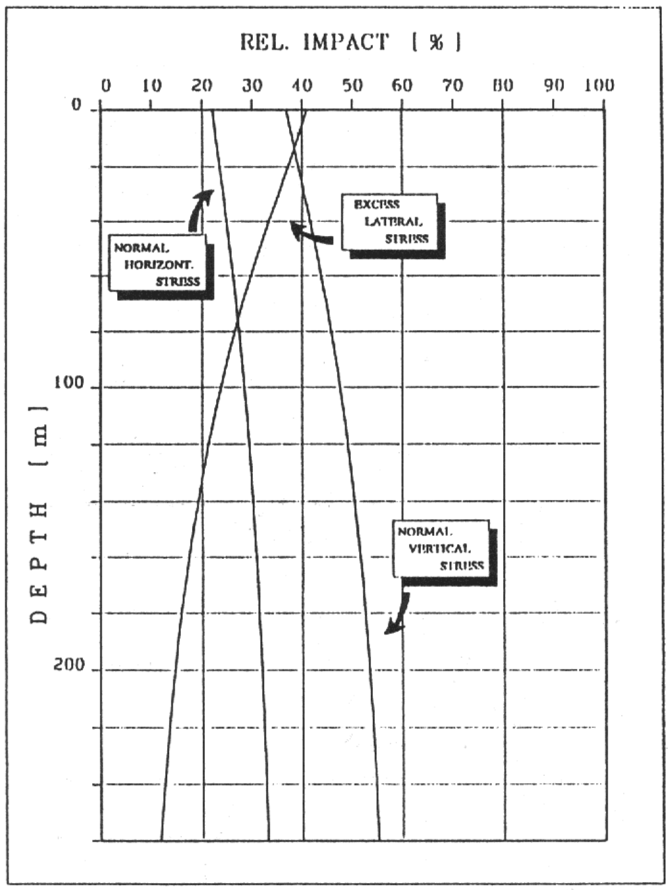


FIG. 7. Relative contribution of excess lateral, normal horizontal and vertical stress to total deformation

In a diagram of mean normal effective stress vs. shear stress — commonly termed σ–τ–diagram — the rest state consolidation path is identified by a straight line (Fig. 8).

(1.10) $\tau = (\sigma_v - \sigma_h)/2$

(1.11) $\sigma = (\sigma_v + \sigma_h)/2$

Stress paths that extend into the field of negative shear stress values are indicative of horizontal shortening and thrust faulting, in soil mechanics called passive state and passive failure respectively (LAMBE & WHITMAN, 1969). During normal undisturbed consolidation sediments will follow a straight K_0–deformation path with σ and τ increasing with a constant ratio. Upon approaching a subduction zone sediments will deviate from the normal K_0–path. With horizontal stress here exceeding the vertical stress, the stress path is departing from the normal consolidation path, until shearing and detachment of a new wedge slice occurs (Fig. 8). This process has been described only qualitatively, since boundary conditions for sediment compaction in this tectonic setting are poorly known and physical properties of the involved sediments were rarely determined. Several stress path configurations previous to sediment failure are possible, depending on the type rheological properties assumed (in Fig. 8 indicated by E–T, E–O, E–P).

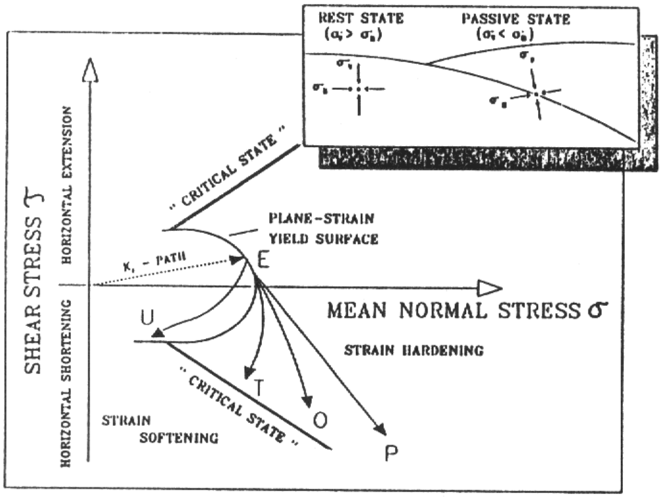


FIG. 8 Possible stress paths during accretion (modified from BRANDON, 1984)

Expressing the modeled and inferred vertical and horizontal stresses in terms of shear stress and mean normal effective stress it is possible to determine the state of stress for reconstructed unit 1 sediments. To do so, σ_{h+} has to be included in eq. (1.10) and (1.11):

(1.12) $\tau = (\sigma_v - (\sigma_h + \sigma_{h+}))/2$

(1.13) $\sigma = (\sigma_v + (\sigma_h + \sigma_{h+}))/2$

Thereby it is possible to present the in situ state of stress of unit 1 sediments as it can be inferred from the modeled additional lateral stress (Fig. 9).

DISCUSSION

The curve representing all reconstructed shear stress values for unit 1 sediments lies completely in the negative field of the diagram. The distribution of negative τ–values with depth is asymetric towards the upper part of unit 1. The obvious conclusion, that convergence–related lateral stress was compensated most intensively in the middle part of unit 1 is misleading. A realistic assessment of the compactional response of unit 1 sediments has to be based on a comparison of K_0–deformation path and the reconstructed in situ path, as indicated in Fig. 9. The strongest deviation from the normal isotropic consolidation path occurs at the base of unit 1, not in the middle part. This is indicated by a set of parallel stress vectors at random depths, that are connecting corresponding depths on the K_0–curve and the in situ–curve. The inclination of the stress vectors is in good agreement with a stress–path E–O (Fig. 8), which BRANDON, 1984 assumed to be typical for ductile deformation without failure in normally to underconsolidated sediments.

This result is supported by the observation, that few mayor shear zones or detachement planes or located in unit 1 sediments.

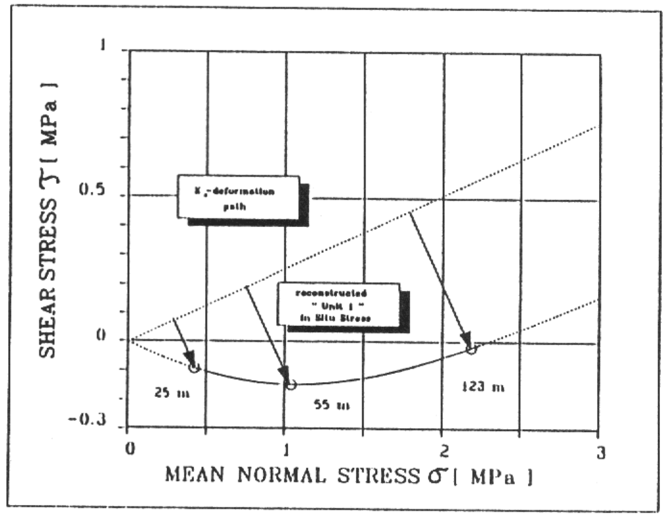


FIG. 9. State of stress during normal consolidation and during accretion (unit 1 sediments). Solid curve indicates reconstructed unit 1 data, the stippeled part their extrapolation. The straight line identifies normal K_0–consolidation path. See text for explanation.

CONCLUSIONS

A palinspastic reconstruction scheme, developed to study porosity changes in marine sediments during accretion was sucessfully applied to sediment mass physical property data from the accretionary Barbados Ridge Complex. From the results the following conclusions can be drawn:

- A restored composite porosity vs. depth profile exhibits strong similarity to an original profile from undeformed strata prior to accretion.
- After accounting for the effects of structural disruption and differential loading during accretion, porosity differences between undeformed sediments and their accreted counterparts remain significant, ranging from 2% to 9%.
- This phenomenon, which is best seen for the uppermost section of the reference site, can be approximated by an exponential function that relates the mode-

led additional porosity reduction to additional lateral loading.

- This quantification of the excess lateral stress can be employed in the analysis of the stress pathways sediments take during the process of accretion.

- Sediments of unit 1 in the oceanic reference section experienced strong lateral deformation during accretion, causing them to depart from the normal isotropic consolidation path. The prevailing consolidational process during accretion in this unit is ductile deformation without failure.

REFERENCES

AOKI, Y., TAMANI, T. & KATO, S., Detailled structure of the Nankai Trough from migrated seismic sections, In: Studies in Continental Margin Geology, Watkins, J.S., & Drake, C.L.(ed.), Am. Ass. Pet. Geol. Memoir, 34: 309–322, 1982.

ATHY, L. F., Density, porosity, and compaction of sedimentary rocks, Am. Ass. Pet. Geol., 14 (1): 24.

BALDWIN, B., & BUTLER, C.O., Compaction curves, Am. Ass. Pet. Geol. Bull., 69 (4): 622–626, 1985.

BIJU-DUVAL, B., LE QUELLEC, P., MASCLE, A., RENARD, V., & VALERY, P., Multibeam bathymetric survey and high resolution seismic investigations on the Barbados Ridge Complex (Eastern Caribbean): A key to the knowledge and interpretation of an accretionary wedge, Tectonophysics, 86: 275–304, 1982.

BOYER, S. E., & ELLIOT, D., Thrust systems, Am. Ass. Pet. Geol. Bull., 66, (9): 1196–1230, 1982.

BRANDON, M.T., A study of deformational processes affecting un- lithified sediments at active margins, Unpubl. PhD thesis, University of Washington, Seattle, Washington. 159 p., 1984.

BRAY, C.J., & KARIG, D.E., Porosity of sediments in accretionary wedges and some implications for dewatering processes, J. Geophys. Res., 90 (B1): 768–778, 1985.

BRÜCKMANN, W., Typical modes of sediment compaction and their modification in an active accretionary wedge (Barbados Ridge), PhD thesis (in German), Beitr. Geol. Inst. Univ. Tübingen, Rh. A, 6: 1–135. 1989.

CARSON, B., Tectonically induced deformation of deep-sea sediments off Washington and Northern Oregon: Mechanical consolidation, Marine Geol., 24: 289–307, 1977.

CARSON, B., VON HUENE, R., & ARTHUR, M., Small-scale deformation structures and physical properties related to convergence in Japan Trench slope sediments, Tectonics 1 (3): 277–302, 1982.

CARSON, B., & BERGLUND, P.L., Sediment deformation and dewatering under horizontal compression: Experimental results, In: MOORE J.C.(Ed.): Structural fabric in Deep Sea Drilling Project cores from forearcs, Geol. Soc. Am. Mem., 166: 135–150, 1986.

CHAPPLE, W.M., Mechanics of thin-skinned fold-and-thrust belts, Geol. Soc. Am. Bull., 89: 1189–1198, 1978.

COWAN, D.S., & SILLING, R.M., A dynamic, scaled model of accretion at trenches and its implications for the tectonic evolution of subduction complexes, J. Geophys. Res., 83 (B11): 5389–5397, 1978.

DAVIS, D. M., & VON HUENE, R., Inferences on sediment strength and fault friction from structures at the Aleutian Trench, Geology, 15: 517–522, 1987.

DAVIS, D. M., & HUSSONG, D. M., Geothermal observations during Deep Sea Drilling Project Leg 78A, In: BIJU-DUVAL, B. MOORE, J.C. et al., Init. Repts. DSDP, 78: 593–598, 1984.

DAVIS, D.M., The compressive mechanics of accretionary wedges applied to the Leg 78A study area near Barbados, In: BIJU- DUVAL, B. MOORE, J.C. et al., Init. Repts. DSDP, 78: 569–579, 1984.

DEMARS, K.R., & NACCI, V.A., Significance of Deep Sea Drilling Project sediment physical property data, Marine Geotechn., 3: 151–170, 1977.

DICKINSON, W.R. & SEELY, D.R., Structure and stratigraphy of forearc regions, Am. Ass. Pet. Geol. Bull., 63 (1): 2–31, 1979.

FOWLER, S.R., WHITE, R.S., & LOUDEN, K.E., Sediment dewatering in the Makran accretionary prism, Earth and Planetary Science Letters, 75: 427–438, 1985.

GRETENER, P.E., Pore pressure, discontinuities, isostasy and overthrusts, In: LEGGET, J.K.: Thrust and Nappe Tectonics, Geol. Soc. Spec. Publ., 9: 33–39, 1981.

HAMILTON, E.L., Prediction of deep-sea sediment properties: state of the art, In: INDERBITZEN, A.L.: Deep-sea sediments, physical and mechanical properties . Plenum Press, New York. 1–43., 1974.

HAMILTON, E.L., Variations of density and porosity with depth in deep sea sediments, J. Sed. Petr., 46 (2): 280–300, 1976.

JONES, M.E., & ADDIS, M.A., The application of stress path and critical state analysis to sediment deformation, J. Struct. Geol. 8, (5): 575–580, 1986.

KARIG, D.E., & SHERMANN III, G.F., Subduction and accretion in trenches, Geol. Soc. Am. Bull., 86: 377–389, 1975.

KARIG, D.E., Physical properties and mechanical state of accreted sediments in the Nankai Trough, Southwest Japan Arc, In: Moore, J.C.: Structural fabric in Deep Sea Drilling Project cores from forearcs, Geol. Soc. Am. Mem., 166: 117–133, 1986.

KNIPE, R.J., & NEEDHAM, D.T., Deformation processes in accretionary wedges — examples from the SW margin of the Southern Uplands, Scotland, In: COWARD, M.P., & RIES, A.C.(eds.): Collision Tectonics, Geol. Soc. Spec. Publ., 19: 51–65, 1986.

LAMBE, T.W., & WHITMAN, R.V., Soil mechanics, New York, John Wiley & Sons, 553 p., 1969.

LUCAS, S.E., & MOORE, J.C., Cataclastic deformation in accretio– nary wedges: Deep Sea Drilling Project Leg 66, southern Mexico, and on–land examples from Barbados and Kodiak Islands, In: MOORE, J.C.: Structural fabric in Deep Sea Drilling Project cores from forearcs, Geol. Soc. Am. Mem. 166: 89–104, 1986.

MAGARA, K., Water expulsion from clastic sediments during compaction – directions and volumes, Am. Ass. Pet. Geol. Bull. 60 (4): 543–553, 1976.

MAGARA, K., Compaction and fluid migration. Developments in Petroleum Science, Amsterdam (Elsevier), 319 p., 1978.

MARLOW, M.S., LEE, H.J., & WRIGHT, A.W., Physical properties of sediments from the Lesser Antilles Margin along the Barbados Ridge: Results from Deep Sea Drilling Leg 78A, In: BIJU–DUVAL, B. MOORE, J.C. et al., Init. Repts. DSDP, 78: 548–558, 1984.

MASCLE, A., BIJU–DUVAL, B., LETOUZEY, J., MONTANDERT, L., & RAVENNE,C., Sediments and their deformation in active margins off different geological settings, In: International Symposion on Geodynamics in the Southwest Pacific, Noumea, 1976. Paris (Ed. Technip), 327–344, 1976.

MASCLE, A., MOORE, J.C. and shipboard scientific party, Site 672, Proc. ODP, Part A, Init. Repts., Leg 110, 205–310, 1988.

MASCLE, A., MOORE, J.C. et al., Accretionary complex penetrated, defined, Geotimes, 32: 13–16, 1987.

MOORE, J.C, ROESKE, S., LUNDBERG, N., SCHOONMAKER, J., COWAN, D.S., & GONZALES, E., Scaly fabrics from Deep Sea Drilling Project cores from forearcs, Geol. Soc. Am. Mem., 166: 55–74, 1986.

MOORE, J.C., & BIJU–DUVAL, B., Offscraping and underthrusting of sediment at the deformation front of the Barbados Ridge: Deep Sea Drilling Project Leg 78A, Geol. Soc. Am. Bull., 93: 1065–1077, 1982.

MOORE, J.C., & BIJU–DUVAL, B., Tectonic Synthesis, Deep Sea Drilling Projekt Leg 78A: Structural evolution of offscraped and underthrust sediment, Northern Barbados Ridge Complex, In: BIJU–DUVAL, B. MOORE, J.C. et al., Init. Repts. DSDP, 78: 601–621, 1984.

MOORE, J.C., & BYRNE T., Thickening of fault zones: A mechanism of melange formation in accreting sediments, Geology, 15: 1040–1043, 1987.

MOORE, J. C, & MASCLE, A. et al., Tectonics and hydrology of the northern Barbados Ridge: Results from Ocean Drilling Program Leg 110, Geol. Soc. Am. Bull., 100: 1578–1593, 1988.

MOORE, J.C., & SILVER, E.A., Continental margin tectonics: submarine accretionary prisms, Reviews of Geophysics, 25 (6): 1305–1312, 1987.

NGOKWEY, K., Numerical modeling of sediment deformation linked to subduction: Mechanical model and comparison with Barbados ridge complex, In: BIJU–DUVAL, B. MOORE, J.C. et al., Init. Repts. DSDP, 78: 559–568, 1984.

PARK, M.J.M., Numerical analysis of deformation in the upper part of subduction zones. Unpubl. PhD thesis, University of Durham, Durham, England ,165 p., 1981.

SHI, Y., & WANG, C.Y., High pore pressure generation in sediments in front of the Barbados Ridge complex, Geophys. Res. Letters, 12 (11): 773 –776, 1985.

SHI, Y. & WANG, C.Y., Two dimensional modeling of the P–T–t paths of regional metamorphism in simple overthrust terrains, Geology, 15: 1048–1051, 1987.

SEELY, D.R., VAIL, P.R. & WALTON, G.G., Trench slope model, In: BURK, C.A. & DRAKE, C.L. (Eds.): The geology of continental margins. Springer (New York), 249–260, 1974.

SEYFERT, C.K., Undeformed sediments in oceanic trenches with sea floor spreading, Nature, 222: 70, 1969.

SILVER, E.A., ELLIS, M.J., BREEN, N.E., & SHIPLEY, T.H., Comments on the growth of accretionary wedges, Geology, 13: 6–9, 1985.

SPEED, R.C., Geology of Barbados: implications for an accretionary origin, Oceanologica Acta, 28: 259–265, 1981.

STOCKMAL, G.S., Modeling of large scale accretionary wedge deformation, J. Geophys. Res., 88 (B10): 8271–8287, 1983.

SUESS, E., KULM, L.D., CARSON, B. & WHITICAR, M.J., Fluid flow and methane fluxes from vent sites at the Oregon subduction zone, EOS, 68 (44): 1486, 1987.

TORRINI, R., SPEED, R.C., & MATTIOLI, G.S., Tectonic relations between forearc basin strata and the accretionary complex at Bath, Barbados, Geol. Soc. Am. Bull., 96: 861–874, 1985.

VON HUENE, R., Long décollements and mud volcanoes: Evidence from the Barbados ridge complex for the role of high pore fluid pressure in the development of an accretionary complex, Geology, 2: 279–283, 1983.

VON HUENE, R., Structural diversity along modern convergent margins and the role of overpressured pore fluids in subduction zones, Bull. Soc. Geol. France, XXVI (2): 207–219, 1984.

VON HUENE, R., & LEE, H.J., The possible significance of pore fluid pressure in subduction zones, Am. Ass. Pet. Geol. Memoir, 34: 781–791, 1983.

WESTBROOK, G.K., SMITH, M.J., PEACOCK, J.H. & POULTER, M.J., Extensive underthrusting of undeformed sediment beneath the accretionary complex of the Lesser Antilles subduction zone, Nature, 300: 625–628, 1982.

WOODWARD, D.J. Viscoelastic Finite Element analysis of subduction zones, Unpubl. PhD. thesis, University of Durham, Durham, England, 1976.

WRIGHT, A.W., Sediment distribution and depositional processes operating in the Lesser Antilles Island Arc, Eastern Caribbean, In:BIJU-DUVAL, B. MOORE, J.C. et al., Init. Repts. DSDP, 78A: 301–324, 1984.

ZHAO, W.L., DAVIS, D.M., DAHLEN, F.A., & SUPPE, J., Origin of convex accretionary wedges: Evidence from Barbados, J. Geophys. Res., 91 (B10): 10,246–10,258, 1986.