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ACCRETION AND LATERAL VARIATIONS IN TECTONIC STRUCTURE ALONG THE PERU–CHILE TRENCH

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ABSTRACT

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Extensive marine geophysical data sets on the deformational characteristics of the oceanic crust and of sediments in and near the Peru–Chile Trench (notably those presented by Schweller, Kulm and co-workers) have established the presence of significant north–south variations along the trench. In this paper we investigate the physical basis for these variations by studying the stress field in the Nazca plate with emphasis on the region near the trench. Finite element methods were employed to calculate the stress distribution. The resulting regional stress field near the trench is characterized by compression normal to the trench at latitudes between 1°S and approximately 16°S, tension in the range 16°S–27°S and again compression from 27°S to 45°S. Many conspicuous and hitherto unexplained variations along the trench system can be understood by taking into account these lateral changes. A close correlation appears to exist between the latitude ranges with compression and tension normal to the trench and the accreting and non-accreting provinces of the Peru–Chile Trench, respectively. The basis for this correlation must be sought in the role which grabens in the seaward trench slope play in the subduction (or accretion) of sediments. Deep grabens can trap the sediments and carry them down into the subduction zone, leaving little or no material to be accreted onto the margin. The regional stress field is superimposed on the stresses generated in bending the Nazca plate prior to subduction. Tension in the direction normal to the trench, as inferred for the Nazca plate off southern Peru and northern Chile (16°S–27°S), lowers the neutral plane in the bending plate and increases the tensional stresses near the surface. This promotes the formation of grabens and, consequently, the subduction of sediments. Similarly, compression normal to the trench counteracts the formation of deep grabens in the latitude ranges 1°S–16°S and 27°S–45°S, thus favouring accretion of sediments.

From this study we infer that the regional stress field may have a significant effect on the topography of the seaward trench slope. Taking into account the role of regional stress in graben formation not only explains first-order latitudinal variations in accretion and subduction of sediments along the Peru–Chile Trench, but it is also expected to contribute significantly to understanding similar variations observed in other subduction zones.

INTRODUCTION

Since the mid-1970's the tectonic evolution of active margins and more specifically the structure and tectonics of trench regions has received continuously increasing attention from earth scientists of various disciplines. Excellent reviews and compilations of recent work in many different regions, both offshore and onshore, are given by Leggett (1982) and Watkins and Drake (1983). A very conspicuous and puzzling feature is the extremely wide variety of structures and processes encountered in the trench regions, not only among different regions but also, and sometimes with great intensity, within one single trench system.

In this paper we focus on a prominent example of these non-uniform trench systems, the Peru–Chile Trench. Several authors have described segments of the Peru–Chile Trench in considerable detail (Hussong et al., 1976; Coulbourn, 1981, and many other studies of the Nazca Plate Project, see Kulm et al., 1981; and recently, Warsi and Hilde, 1983). Here, in this study, we especially refer to the results obtained and compiled by the School of Oceanography of Oregon State University (e.g. Kulm et al., 1977; Schweller and Kulm, 1978; Schweller et al., 1981), because they provide great overall insight into the trench structure along its entire length, from about 5°S to 45°S. Significant lateral variations in structure and tectonics of the Peru–Chile Trench, implying variations in sediment accretion and sediment subduction, were recognized. In a first-order description Kulm et al. (1977) used the morphology and the structure of the continental slope and shelf to divide the Peru–Chile Trench into three provinces, comprising the latitude ranges 6°–19.5°S, 19.5°–27°S and 27°–45°S. In two provinces, Peru 6°–19.5°S and Central-South Chile 27°–45°S, accretion takes place. In the third province, North Chile 19.5°–27°S, no significant accretion occurs; hence, nearly all sediments are subducted and, possibly, even the process of tectonic erosion of the continental margin is active in this province. Later work (Schweller et al., 1981) on the shallow structure of the trench axis and the seaward trench slope led to a five-fold division of the trench system (see also Fig. 3): Peru (4°–12°S), Nazca (12°–17°S), North Chile (17°–28°S), Central Chile (28°–33°S) and South Chile (33°–45°S). The refinement relative to the earlier three-fold division essentially consists of a division of each of the two accreting provinces (off Peru and off Chile, south of 27°–28°S) into two separate provinces. The most notable feature on the seaward trench slope is the variability of the graben structures (see Fig. 1). Deep grabens (with offsets of 500–1000 m) are mainly limited to and best developed in the North Chile province (17°–28°S).

Apart from the rather complex region of the Arica Bight (latitude range 17°–19.5°S), where some ambiguity exists with respect to the role of accretion and subduction, there appears to be a distinct correlation between the way in which graben structures are developed on the seaward trench slope and the fate of the

Fig. 1. Schematic cross section of a trench at a convergent plate boundary. Sediments in the trench region are either carried down along with the subducting plate or accrete onto the continental margin, depending on the depth of the grabens on the seaward trench slope (after Schweller et al., 1981).

sediments. The depth of the grabens is significantly deeper in those segments of the trench where no sediments are accreted (or tectonic erosion of the margin takes place) than where accretion occurs. Throughout this paper "depth" of grabens refers to the depth below the top of the lithosphere. Focusing on the process of tectonic erosion Schweller et al. (1981) implicitly postulated the following mechanism (see also Schweller and Kulm, 1978): If the grabens are well-developed, the trench sediments can be trapped in them and are carried down into the subduction zone along with the descending lithospheric plate. If the grabens are shallow or absent not all (or no) sediments can be accommodated; they are not (all) carried down but they accrete onto the continental margin. Similar suggestions as to the role of grabens in the tectonics of the trench region were made by Jones et al. (1978). Clearly, this mechanism can also explain the correlation between graben development on the seaward trench slope and accretion or subduction in the Peru–Chile Trench.

Much work has been directed towards deciphering the details of sediment accretion, with off-scraping and, presumably, underplating as the main processes involved (Seely et al., 1974; Karig and Sharman, 1975; Watkins et al., 1981; Leggett, 1982; Watkins and Drake, 1983). In this study, however, we will concentrate on a hitherto largely unexplained first-order variation; accretion and no accretion (that is subduction) of the sediments in the trench regions. In view of the observed correlation between graben development and accretion, and the sound nature of the trapping mechanism, understanding the non-uniformity in graben formation may be vital to elucidate the variations in trench tectonics. Therefore, we investigated the physical background of graben formation, that is the stress distribution in the downbending lithospheric plate just prior to subduction. This stress distribution is

dominated by two contributions:

- (1) the stress distribution associated with the bending of the lithosphere,
- (2) the regional stress field in the lithosphere.

The first contribution is calculated by modelling the flexure of the lithosphere, using a plate with the appropriate thickness and rheology (Goetze and Evans, 1979). The second contribution is calculated from the system of forces acting on the plate, using the same procedure as in Wortel and Cloetingh (1981). Together, this provides a unique opportunity to quantitatively relate the observed patterns of graben formation and sediment accretion (or subduction) to the stress field in the lithosphere.

In our earlier work on lithospheric stress fields presented at the Hollis Hedberg Conference on Continental Margin Geology (Galveston, January 1981, see Wortel and Cloetingh, 1983) we have drawn attention to the possible significance of regional stress fields in the context of trench tectonics. The results of finite element modelling presented in this paper demonstrate that the regional stress field in the Nazca plate varies significantly along the trench, comprising transitions from compression to tension (normal to the trench). These stress variations strongly affect the extent to which grabens are developed on the seaward trench slope and, hence, via the above-mentioned trapping mechanism, the fate of the sediments in the trench region.

REGIONAL STRESS FIELD

Modelling

In calculating the regional stress field in the Nazca plate we apply the same procedure as in Wortel and Cloetingh (1981, 1983). In these studies we employed finite element methods and incorporated plate tectonic forces dependent on lithospheric age and pertinent kinematic parameters.

We calculated the regional stress field using a uniform elastic plate with Young's modulus $E = 7 \cdot 10^{10} \text{ N m}^{-2}$ and Poisson's ratio $\nu = 0.25$, and a plate thickness of 100 km. This thickness is only a reference value. As we use a plane stress approximation, stress in an elastic plate with a thickness different from this reference value can be derived directly from the stress obtained for the model plate: for all thicknesses for which the plane stress approximation is valid, the product of stress and plate thickness is constant. The boundaries of the Nazca plate model are shown in Fig. 2. In view of its complex structure a small part in the northeastern corner of the Nazca plate (off Panama) was omitted. Using these boundaries the geometry of the Nazca plate was modelled as a part of spherical shell, approximated by an assembly of 338 triangular membrane elements, with a thickness of 100 km and a grid point spacing of 3° . The stress calculations were made with the ASKA package of finite element routines (Argyris, 1979), in which we employed a quadratic representation of the displacement field (linear strain).

Fig. 2. Regional stress field in the Nazca plate, based on force model A (see text). The solid line indicates the boundaries of the Nazca plate. The scale is indicated in upper right-hand corner. The stress values are given for a uniform elastic plate with a thickness of 100 km.

The regional stress field in the Nazca plate is assumed to be determined by plate tectonic forces. The forces considered to act on the plate are the driving forces F_{sp} (slab pull) and F_{rp} (ridge push), and the resistive forces F_{tr} (resistance at the trench and in the subduction zone) and F_{dr} (drag or shear stress σ_b at the base of the plate, integrated over the area of the base of the plate). F_{tr} consists of two parts: One part (F_{cb} , compositional buoyancy) is associated with the buoyancy of the stable petrological stratification of the oceanic lithosphere created at the spreading centre. This compositional buoyancy counteracts the slab pull. The other part (F_{sh}) represents shearing forces acting along the contact between the downgoing plate and the overriding plate and along the boundaries of the subducted slab in the upper mantle.

The slab pull and ridge push were calculated according to Richter and McKenzie (1978) and Wortel (1980). It can be shown that per unit width along the trench the

slab pull, resulting from the density contrast between the cold descending slab and the surrounding upper mantle, depends on the thickness L of the subducted slab according to $F_{sp} \propto L^3$. It is generally agreed upon that L depends on the square root of the age (t) of the lithosphere for $t < 70$ Ma (e.g., Parsons and McKenzie, 1978).

Hence for these ages, $F_{sp} \propto t^{3/2}$. Owing to the reduced rate of thickening of L for $t > 70$ Ma, the age-dependence is somewhat weaker for old lithosphere. Similarly it was found (Richter and McKenzie, 1978; England and Wortel, 1980) that for $t < 70$ Ma, the ridge push F_{rp} (per unit width parallel to the ridge) depends linearly on the lithospheric age near the trench. The ridge push, acting on the oceanic lithosphere in the trench region, should be considered to be the integrated (over the distance from ridge to trench) value of a horizontal pressure gradient (Lister, 1975). Thus, like in Wortel and Cloetingh (1981), we distributed the total ridge push over the area of the plate.

The lithospheric ages needed to calculate F_{sp} and F_{rp} were taken from Herron (1972) and Handschumacher (1976). Because we are mainly interested in the stress field near the trench we refrained from modelling details of the complex age-pattern which has been established in the western part of the Nazca plate (e.g. Herron, 1972).

The slab pull F_{sp} depends on the convergence rate v_c (Richter and McKenzie, 1978) and the dip angle ϕ of the descending slab as $F_{sp} \propto v_c \sin \phi$. Hence, F_{sp} varies linearly with v_z , the vertical velocity of the sinking slab. Values for v_z were determined from convergence rates and dip angles published by Minster et al. (1974) and Barazangi and Isacks (1976), respectively.

The resistive forces F_{tr} acting at a convergent plate boundary were incorporated after England and Wortel (1980), who found a total resistive force per unit width along the trench of $-8 \cdot 10^{12} \text{ N m}^{-1}$. Using a more internally consistent set of parameters we found that a modified value of $-7 \cdot 10^{12} \text{ N m}^{-1}$ gives a slightly more satisfactory fit to the observations compiled by England and Wortel (1980). The buoyancy effect of the stable petrological stratification of the oceanic lithosphere (F_{cb}), according to Oxburgh and Parmentier's (1977) model, accounts for $-4 \cdot 10^{12} \text{ N m}^{-1}$. The remaining resistance of $-3 \cdot 10^{12} \text{ N m}^{-1}$ is attributed to shearing forces F_{sh} acting along the plate contact and the interfaces between the slab and the surrounding upper mantle.

To ensure mechanical equilibrium the torque on the plate is required to vanish. The drag at the base of the plate (σ_b) is determined from the torque balance.

To explore the effect of different *distributions* of the resistive forces we considered three different distributions (model A, B and C) representing various modes of coupling between the lithosphere and the asthenosphere. In model A the resistive shearing forces (F_{sh}) in the trench region and along the slab are taken to be $F_{sh} = -3 \cdot 10^{12} \text{ N m}^{-1}$. From the requirement of mechanical equilibrium it follows that the shear stress at the base of the lithosphere is negligibly small. Model B differs from model A in the sense that one third of the total shear resistance is not assumed

to act in the trench region or along the subducted slab but at the base of the plate between the spreading ridge and the trench. This yields a basal shear stress $\sigma_b = -4$ bar (minus sign indicating resistance). In model C, the basal shear stress is assumed to have the opposite sign. The lithosphere is taken to be dragged *along* by motions in the underlying asthenosphere: consequently, in this case the integrated shear stress is not a resistive force but a driving force. If, in model C, we take $\sigma_b = +4$ bar, the shearing force F_{sh} at the trench must be changed (to $F_{sh} = -4 \cdot 10^{12} \text{ N m}^{-1}$), relative to the value of $-3 \cdot 10^{12} \text{ N m}^{-1}$ in model A. In terms of the σ_b -values which are -4 , 0 and $+4$ bar for the models B, A and C, respectively, model A is the intermediate model.

Results

The resulting stress field in the Nazca plate for force model A is displayed in Fig. 2. The results exhibit an interesting feature, which confirms preliminary model results reported in Wortel and Cloetingh (1983), namely a transition from compression normal to the trench off Peru, to tension off North Chile and again compression along the southern part of the trench system.

In order to bring out the stress situation along the Peru–Chile Trench more clearly we show in Fig. 3 two stress components for the near-trench region of the Nazca plate: $\sigma_{\perp}$ is a normal stress component in the direction normal to the trench; as a normal component it acts on a vertical plane parallel to the trench-axis, $\sigma_{\parallel}$ is a normal stress component in the direction parallel to the trench, it acts on a vertical plane normal to the trench axis. The $\sigma_{\perp}$ - and $\sigma_{\parallel}$ -curves for models A, B and C are shown in Fig. 3. It is clear that the overall pattern is the same for all three models; essentially the latitudes where the transitions from compression to tension take place are insensitive to the differences in force modelling. For this reason the complete stress field is only shown for model A (in Fig. 2). In combining the regional stress field with the bending stresses (in the following section) we will use the results of model A, which are intermediate between those of models B and C (see Fig. 3).

Of the two stress components shown in Fig. 3 the component normal to the trench, $\sigma_{\perp}$, is the one which is of most interest to the analysis of tectonic style in the trench region.

The right-hand side of Fig. 3 shows the recent division of the Peru–Chile Trench into five provinces after Schweller et al. (1981), based on the shallow structure of the trench axis and the seaward trench slope.

In Fig. 3, we note that the latitude range with tension normal to the trench (positive $\sigma_{\perp}$), that is between about 16°S and 27°S , coincides remarkably well with Schweller et al.'s (1981) province 3 (17° – 28°S) where the formation of grabens is most prominent.

For all stress values in Figs. 2 and 3 it should be kept in mind that they represent the non-hydrostatic stress in a uniform elastic plate with a thickness of 100 km. A

Fig. 3. $\sigma_{\perp}$ - and $\sigma_{\parallel}$ -values for the region near the eastern boundary of the Nazca plate along the Peru–Chile Trench. Positive stress values indicate tension, negative values compression. $\sigma_{\perp}$ is the normal stress acting in the direction perpendicular to the trench axis on a vertical plane parallel to the trench axis. $\sigma_{\parallel}$ is the normal stress acting in the direction parallel to the trench axis on a vertical plane perpendicular to the trench axis. Values are given for a uniform elastic plate with a reference thickness of 100 km. The curves are labelled A, B and C, according to the force model used in the calculation (see text). The right-hand side of the figure shows the division of the Peru–Chile Trench into five provinces, as made by Schweller et al. (1981). The thick black line schematically indicates the trench axis. Extensional faulting and formation of grabens (on the seaward trench slope) are most prominent in province 3.

somewhat better idea of the real stresses can be obtained if we utilize the concept of effective elastic thickness of the lithosphere. According to Caldwell and Turcotte (1979) and Bodine et al. (1981) the effective thickness of the elastic upper part of the lithosphere, which is presumably temperature-dependent, ranges from a few kilometres for very young lithosphere to about 40 km for lithosphere older than about 80 Ma. This implies that the stress values in Fig. 2 (not too close to the ridge) and Fig. 3 should be multiplied by a factor of about 3 to get the values appropriate for the elastic upper part of the lithosphere. A more realistic incorporation of rheological properties in the model is not required in the calculation of the regional stress field. It will be, however, in the analysis of bending (next section).

The other stress component, $\sigma_{\parallel}$, bears on the problem of plate fragmentation as studied for the Farallon plate by Wortel and Cloetingh (1981, 1983). As in the Farallon plate about 25 Ma ago the tensional stresses parallel to the Peru–Chile

Trench are considerable. In this paper we do not wish to elaborate on the implications of tensional stresses in terms of lithospheric plate fragmentation. It is interesting to note, however, that recent work by Hilde and Warsi (1983) and Warsi and Hilde (1983) has provided data which convincingly show incipient fragmentation of the Nazca plate along the Mendana Fracture Zone off Lima, Peru.

BENDING STRESSES

The second major contribution to the stress field in the Nazca plate near the Peru–Chile Trench arises from the downbending of the lithosphere in the trench. Apart from being a function of the curvature, the bending stresses depend on the plate's thickness and rheology. Both these properties vary with lithospheric age. Along the Peru–Chile Trench neither the curvature (see Schweller et al., 1981) nor the age of the oceanic lithosphere (Herron, 1972; Wortel and Vlaar, 1978) is constant.

To obtain the total stress field, the regional stress field investigated in the previous section must be superimposed on the bending stresses.

Variations in lithospheric age and dip of the seaward trench slope

We adequately cover the age variations along the trench by selecting three representative cross sections in which oceanic lithosphere of 15, 40 and 70 Ma is involved, respectively. The inset in Fig. 4 (lower left corner) indicates the latitudes where these ages are encountered. Along the trench segment off North-Central Peru the lithospheric age is practically constant. Hence, the age of 40 Ma stands for all of this segment. Off North-Chile/southernmost Peru the age of the Nazca plate at the trench is not known. From the orientation of the magnetic anomalies farther to the west and the half-spreading rates involved a maximum age of 70 Ma may be inferred for the lithosphere at the trench (Wortel, 1984). Furthermore, along the Chilean part of the trench the lithospheric age decreases almost continuously down to 42°–45°S, where lithosphere of about 15 Ma approaches the trench (Herron et al., 1981).

An extensive set of bathymetric profiles across the Peru–Chile Trench, showing a variation in dip of the seaward trench slope, is given by Schweller et al. (1981): off Peru and off Central Chile south of 28°S the seaward trench slope dips between 2° and 3° near the axis of the trench, whereas off North Chile between 18° and 28°S dip angles of 5°–8° are typical.

Modelling

In calculating the regional stress field we were essentially interested in the stress integrated over the plate's thickness. For this purpose a uniform elastic plate was adequate. Also in studies of deflection of the lithosphere and of the corresponding

Fig. 4. Strength envelopes and stress distributions in cross sections through lithosphere of 70 Ma (top), 40 Ma (middle) and 15 Ma (bottom), respectively. Sign convention: positive values indicate tension, negative values compression. Stress (and also strength) refers to differential stress. Solid lines indicate strength envelopes. Where the stress is less than the strength the dots represent the calculated stress values. At depths shallower and deeper than the zone with dots the stress equals the strength in tension and in compression, respectively. The regional stress field is taken from Fig. 3, $\sigma_{\perp}$, model A. In addition, results for a tensional regional stress field are shown for the 40 Ma case (for comparison only). D_{BF} (see text) is indicated only for bending of 70 Ma old lithosphere without regional stress field. The inset shows where lithosphere of the selected ages is encountered along the Peru-Chile Trench.

gravity anomalies the concept of an effective (uniform) elastic thickness of the lithosphere (Caldwell and Turcotte, 1979; Watts et al., 1980; Bodine et al., 1981) is appropriate. If one is interested, however, in the stress variation with depth, such as generated in bending processes, the concept fails. Bending of a uniform elastic plate generates stress maxima at the top and the bottom of the plate which are quite unrealistic in view of limited strength of the lithosphere near the surface and also in the lower part of the lithosphere (Goetze and Evans, 1979). In the present study we do need to know the stress variation with depth to be able to relate graben formation to the stress distribution. This means that a realistic depth-dependent rheology must be incorporated in the models. Data on the depth-dependence of the lithosphere's rheology were taken from Goetze (1978) and Goetze and Evans (1979).

These authors show that three deformation zones are present in the bending lithosphere (see also Fig. 4).

(a) Brittle deformation zone. In the upper part of the lithosphere the deformation is in the brittle regime and the (Coulomb) strength increases strongly with depth. The deformation is not sensitive to variation in temperature and strain-rate, and the strength does not depend on rock type. We denote the maximum depth down to which brittle failure takes place by D_{BF} (see Fig. 4, top).

(b) Elastic deformation zone. Below the brittle deformation zone (depth greater than D_{BF}) near the central plane of the bending lithosphere, the stresses do not reach the depth-dependent strength. Thus, the stresses are supported elastically.

(c) Ductile deformation zone. In the lower part of the plate the effects of temperature become dominant and the stresses are limited by ductile flow. The ductile deformation is relatively insensitive to pressure, but very sensitive to temperature, to differential stress and to a far lesser extent to strain rate. At high stresses dislocation glide is the dominant creep process. The ductile flow is described by the Dorn-creep equation (Goetze, 1978) which holds for stresses above 2 kbar:

$$\dot{\epsilon} = \dot{\epsilon}_1 \exp\left\{-Q_1(1 - \sigma/\sigma_p)^2/RT\right\}$$

where $\dot{\epsilon}$ is the strain-rate (s^{-1}), σ is the differential stress, Q the activation energy ($Q_1 = 128$ kcal/mol) for dry olivine, R is the universal gas constant and T is the temperature (K). $\dot{\epsilon}_1 = 5.7 \cdot 10^{11} s^{-1}$ and $\sigma_p = 85$ kbar are constants. At stresses below 2 kbar creep by thermally activated climb of dislocations becomes effective. This process is described by a power-law creep equation (Goetze, 1978):

$$\dot{\epsilon} = \dot{\epsilon}_2 \sigma^3 \exp(-Q_2/RT)$$

with $Q_2 = 122$ kcal/mol and, for σ in bar, $\dot{\epsilon}_2 = 70 \text{ bar}^{-3} s^{-1}$.

The age-dependent temperature distribution in the lithosphere, which enters the rheological flow laws, was calculated on the basis of Crough's (1975) model for the thermal evolution of oceanic lithosphere.

The depth-dependence of the lithospheric differential strength is shown in Fig. 4

for the selected ages of 15, 40 and 70 Ma. *Note the dependence of the strength curve on lithospheric age.* The linear dependence of the brittle strength on depth is probably stronger in compression (negative stress values) than in tension (positive stress values). Because (with a very small exception in the 15 Ma case) the bending process considered here does not imply compression in the upper pressure-dependent part of the lithosphere, the depth-dependence of the differential brittle strength in compression was taken to be equal to the one in tension without affecting the results.

The calculations were carried out with a modified version of the MARC finite element program (MARC, 1980). The depth-dependent rheology was implemented in the bending models by specifying yield strengths at the integration points of the elements, following a technique previously developed by Cloetingh et al. (1982) (see also Cloetingh, 1982). We adopted a strain-rate of 10^{-14} s^{-1} characteristic for lithospheric bending at trenches. The bending of the lithosphere is counteracted by hydrostatic restoring forces, which were incorporated into the analysis by modifying the stiffness matrix at the basal nodes of the model. This was accomplished by the implementation of an elastic foundation with a stiffness equal to $(\rho_m - \rho_w)g$ in the model, where $\rho_m - \rho_w$ is the density difference between the mantle (density ρ_m) and the medium overlying the plate (usually water with density ρ_w), g is the acceleration due to gravity.

For analysis of bending, constant strain elements are inadequate and an element is required with linearly varying strain over its surface. For this reason, the displacement field has to be at least quadratic and, hence, an eight-node quadrilateral element was chosen. The use of linear strain elements also allows an accurate representation of variations of material properties with depth, since material properties are allowed to vary linearly within a separate element. A secant stiffness procedure was used to solve the plane strain equations. The results of the analysis were checked and confirmed by convergence tests and an analysis of the internal reaction forces of the model. It should be noted that the finite element approach followed here is not hampered by the limitations and the assumptions of the classical thin plate theory, encountered in other methods of bending analysis (Bodine et al., 1981). In particular, the assumption of a zero shear neutral surface and of zero shear forces in the vertical plane are avoided.

The curvature of the plate was modelled after the bathymetric profiles (smoothed in order to reduce the effects of local topographic anomalies) as given by Schweller et al. (1981).

Results

The resulting bending stresses in lithosphere of 15, 40 and 70 Ma old are displayed in Fig. 4. The stresses are shown for the case of pure bending and for bending in combination with the regional stress field as calculated in the previous

section (Fig. 3). Thus, we have 70 Ma old lithosphere bending in regional tension (denoted as case 70BT where B and T stand for Bending and Tension, respectively), and 40 and 15 Ma old lithosphere bending in regional compression (40BC and 15BC; C stands for Compression).

Of the regional stress field it is the $\sigma_{\perp}$ -component which affects the bending process. Values taken for $\sigma_{\perp}$ are based on the preferred force model, which resulted in curve A in Fig. 3. For the 70 Ma cross section (off North Chile) we take the maximum value of province 3 (see Fig. 3): $\sigma_{\perp} = +800$ bar. For the 40 Ma and 15 Ma cross sections (representing provinces 1, 2, 4 and 5) $\sigma_{\perp} = -300$ bar is adopted as a characteristic value. These values correspond with a stress integrated over the plate thickness (100 km in the model plate used in the calculations for Fig. 3) of $+8 \cdot 10^{12}$ N m $^{-1}$ and -3×10^{12} N m $^{-1}$, respectively. For comparison, the stress distribution on 40 Ma old lithosphere in regional tension (40BT), with $\sigma_{\perp} = +300$ bar, is also included in Fig. 4.

Next, we want to relate the characteristics of graben formation to the stress distribution in the bending plate. From the stress distributions in Fig. 4, we can determine two parameters which undoubtedly are of interest to the formation of grabens. These are the depth of the neutral plane (denoted by D_{NP}) and the maximum depth down to which brittle failure takes place (D_{BF}). For the purpose of illustration, D_{BF} is indicated in Fig. 4 (top) for the case of bending of 70 Ma old lithosphere, without regional stress field. Values for D_{NP} and D_{BF} indicate depth below upper surface of the lithosphere. The depth of the neutral plane (D_{NP}) gives the thickness of the upper part of the lithosphere which is in tension. Extensional faulting, however, is not expected to extend all the way down to this depth, because just above the neutral plane the stress does not reach the strength (see Fig. 4). In the depth range between D_{BF} and D_{NP} the stress is supported elastically, without faulting. In a given state of stress D_{BF} represents the deepest level where extensional faulting occurs, which makes it a parameter pertinent to analyses of graben depths.

Table 1 displays the values of D_{NP} and D_{BF} , both for the cases of pure bending (70B, 40B, 15B) and for bending in combination with the regional stress field (70BT, 40BC, 15BC).

TABLE 1

Stress parameters for bending lithosphere of 70, 40 and 15 Ma, with and without regional stress field

	70B *	40B	15B	70BT *	40BC	15BC
$D_{BF}(\text{km})$ **	20	15	10	26	12	5
$D_{NP}(\text{km})$ ***	27	22	14	34	18	8

* 70B denotes bending of 70 Ma old lithosphere, without regional stress; similar for 40B and 15B.

BT = bending in regional tension, BC = bending in regional compression; regional stress after Fig. 3.

** Maximum depth down to which stress reaches brittle strength; all depth values refer to depth below top of the lithosphere.

*** Depth of neutral plane.

Fig. 5. *Upper part:* Surface geometry of the model for 40 Ma old lithosphere bending in the trench region. Cross section normal to the trench. Displacement is given relative to the standard age-dependent ocean depth. Zero on the horizontal scale corresponds with the point of zero vertical displacement. Since the maximum depth in the Peru–Chile Trench is less than 2 km deeper than the standard depth, only the distances less than 65 km correspond with the seaward slope of the Peru–Chile Trench. *Lower part:* D_{BF} -values in bending lithosphere (40 Ma) as a function of distance normal to the trench, corresponding with geometry in upper part of the figure. D_{BF} is the maximum depth at which the stress reaches the strength in tension. The compressive regional stress field is taken from Fig. 3: $\sigma_{\perp} = -300$ bar (appropriate for 40 Ma old lithosphere). For comparison the results for a regional tensional stress field ($\sigma_{\perp} = +300$ bar) are shown as well.

40BC, 15BC). Considering the fact that the 15 Ma cross section represents only a small part of the total trench, we are especially interested in the differences between the 70 Ma and 40 Ma cross sections. The values for D_{BF} and D_{NP} in the case 70B are only about 25–30% greater than in the case 40B. The compressive regional stress in the 40BC (and also in the 15BC) cross section elevates the neutral plane resulting in a decrease in both D_{NP} and D_{BF} , relative to the 40B case. On the other hand, the tensional regional stress in the 70BT cross section lowers the neutral plane and causes an increase in D_{NP} and D_{BF} . The net effect of the regional stress field is such that for the 70BT case the values of D_{BF} and D_{NP} outweigh those for 40BC by about 100%. Thus the regional stress field in the Nazca plate strongly amplifies the relatively small differences which are introduced by variations in curvature and thermo-mechanical structure of the downbending plate.

Variation in stress and graben depth across the trench. The stress distribution in the bending lithosphere varies in the direction normal to the trench. A representation of this stress variation, in terms of variation of D_{BF} in the direction normal to the trench axis, is graphed in Fig. 5 for 40 Ma old lithosphere. The upper part of Fig. 5 shows the (modelled) displacement of the bending lithosphere, or equivalently, the depth of the ocean floor relative to the standard age-dependent depth (Parsons and Sclater, 1977). Since the maximum depth in the Peru–Chile Trench exceeds the standard age-dependent depth of the adjacent oceanic lithosphere by less than 2 km, it follows from the upper part of Fig. 5 that the seaward trench slope covers the distances less than about 65 km on the horizontal scale. The lower part of Fig. 5 contains three D_{BF} -curves pertaining to the seaward trench slope: one in the middle for pure bending of 40 Ma old lithosphere, a second one (top) for bending in a regional compressive stress field as we found (see Fig. 3) for the latitudes where the age of the lithosphere at the trench is around 40 Ma. A third curve (bottom) is shown for bending in a regional *tensional* stress field (the same magnitude of $\sigma_{\perp}$, but with opposite sign); this situation does not correspond with any real situation along the Peru–Chile Trench, but it is included to demonstrate the relevance of a regional stress field more completely. The stress values previously shown in Fig. 4 refer to the state of stress at the point of maximum bending, represented by the left-hand ends of the D_{BF} -curves of Fig. 5.

Figure 5 clearly shows that at the upper part of the seaward trench slope (where the plate starts to bend down) the presence of a regional compressive or tensional stress field strongly affects the D_{BF} -values. Here, the relative changes in D_{BF} caused by the regional stress field are even greater than already could be inferred from the results displayed in Fig. 4 (which refer to 65 km on the horizontal distance axis). Thus, especially the first development of grabens in a lithospheric plate approaching the trench (see also Fig. 1) is controlled by the regional stress field.

Characteristic features of the D_{BF} -curves across the trench, also in those for 15 Ma and 70 Ma not shown here, are the strong increase in D_{BF} at the beginning of the seaward trench slope (right side in Fig. 5) and the flattening near the trench axis

(left side in Fig. 5). A seismic reflection profile across the trench at 23°S published by Schweller and Kulm (1978) provides a clear example of graben development from the outer trench slope break towards the trench axis. Schweller and Kulm (1978) note that the magnitude of the offset increases sharply as the plate begins to curve downward, reaching its maximum extent by approximately the 5000 m depth contour, *with minimal additional offset developing below this depth*. The latter depth range corresponds with the last 20–30 km up to the trench axis. These observations are in excellent agreement with the shape of the D_{BF} -curves (see Fig. 5). This is especially the case for the flattening in the last 20 km (left side of curves in Fig. 5), because this flattening indicates that the depth range in which brittle failure occurs does not increase in depth. We consider the agreement between our calculated results and the observations to be strong evidence for our contention that D_{BF} is a very pertinent parameter in the context of graben formation.

DISCUSSION

According to Schweller et al. (1981) graben development on the seaward slope of the Peru–Chile Trench is mainly limited to and best developed in province 3 (North Chile, see Fig. 3). The fact that the boundaries of this province coincide with the latitudes where the regional stress field changes sign strongly indicates that the regional stress constitutes an important factor in the tectonics of the Peru–Chile Trench. Characteristics of another type of structure described by Schweller et al. (1981), step faults on the seaward slope, point into the same direction: whereas step faults are found along the entire length of the trench system, the offset on a single step fault is greater in province 3 (up to a kilometre) than in the other provinces (average offset ≤ 100 m).

Hussong et al. (1976) have presented seismic evidence for thrust faults in the oceanic crust of the Nazca plate. The approximate location of these faults is at about 200 km from the trench axis in the latitude range 8°–12°S (off Peru). At such a distance from the trench axis, bending stresses do not play a role; the regional stress field (Figs. 2 and 3) represents the total non-hydrostatic stress field in the plate. It appears that our results are in very good agreement with the deformation observed by Hussong et al. (1976).

For two small regions our calculated stresses should be considered with caution. We anticipate that the calculated regional stress field off Ecuador is affected by our exclusion of the Panama Basin in the modelling procedure (see Fig. 2). For the Arica Bight region ($\sim 17^\circ$ – 19.5° S) our plane strain calculations of bending stresses may not be warranted in view of the three dimensional character of the plate bending process.

Sediment supply and convergence rate

Sofar we have approached the problem of variable accretion and subduction of sediments via the process of the graben formation on the seaward trench slope.

Whether a certain topography of the seaward trench slope eventually results in sediment accretion or in sediment subduction depends on the amount of sediments in the trench region. This in turn is dependent on many factors such as nature of adjacent margin (island arc or continent), climate and ocean currents. The absence or presence of grabens should be considered as an independent basic condition on which the volume of supplied sediments has to be superimposed, before the net outcome can be predicted.

As both graben development and sediment supply are subject to large variations, it is evident that the combination of these factors may lead to an extremely variable result. Two extreme combinations are: (1) deep grabens without sediment supply and (2) no grabens with ample sediment supply. The first combination may lead to tectonic erosion of the adjacent continental margin as suggested by Kulm et al. (1977) for province 3 (Fig. 3). The second combination favours abundant sediment accretion (like in province 5, South Chile).

In principle the relation between volume of grabens and the amount of sediment in the trench region should be considered per unit time or averaged over a certain period. Thus, on the one hand, the supply *rate* of sediments enters the process and, on the other hand, the volume of the grabens per unit time. The latter quantity depends linearly on the normal component of the convergence rate of the two plates involved, which acts as the conveyor belt velocity of the system. Along the Nazca–South America plate boundary the normal component of the convergence rate is practically uniform (Minster et al., 1974), with a small exception near the Arica Bight. Therefore, this kinematic parameter does not introduce significant lateral variations. In many other trench systems, however, for example the Java–Sumatra Trench, it should be taken into account.

Correlation between segmentation of the downgoing slab and the accreting and non-accreting provinces of the Peru–Chile Trench

From the distribution of hypocentres of intermediate earthquakes it is known that the slab descending beneath the Andes is segmented, with the various segments exhibiting different dip angles (Barazangi and Isacks, 1976). In the latitude range 16° – 27° S the dip angle is about 30° whereas to the north and to the south the slab segments dip at only about 10° . Kulm et al. (1977) have noticed an apparent correlation between the pattern of segmentation in the downgoing slab and the boundaries of accreting and non-accreting provinces of the Peru–Chile Trench. Our study throws light on the mechanism underlying this correlation. The differences in dip angle of the slab segments cause differences in the slab pull forces. The forces acting on the Nazca plate result in a regional stress field. The northern and southern boundaries of the trench area with regional tension normal to the trench (16° S and 27° S, see Fig. 3) coincide with boundaries between the main slab segments. As we have seen, the regional stress field controls graben formation which in turn, affects

the accretion or subduction of sediments. We have incorporated dip variations of slab segments in our force models and we may conclude that, via the dip angle $\rightarrow$ slab pull $\rightarrow$ stress field $\rightarrow$ graben depth $\rightarrow$ accretion/subduction relation, our study offers a physical explanation for the above-mentioned correlation.

Temporal variations

In our earlier study of the break-up of the Farallon plate (Wortel and Cloetingh, 1981, 1983) we have drawn attention to the fact that lithospheric stress fields are subject to temporal variations. Underlying causes are changes in plate geometry and changes in the age of the oceanic lithosphere at convergent plate boundaries. The latter changes affect the geometry of the downgoing slab (see Wortel, 1984; for the South American zone), and the most important forces driving the plates, namely the ridge push and slab pull (England and Wortel, 1980).

In the present study we have assessed the role of regional stress in trench tectonics to be potentially very significant. Therefore, the above-mentioned temporal variations in regional stress field should be considered to be a likely cause of temporal variations in trench tectonics, as well. Such changes have been documented by Watkins et al. (1981) for the Middle America Trench. The very complex Cenozoic history of the East-Central Pacific region (Herron, 1972; Handschumacher, 1976; Hey, 1977; Mammerrickx et al., 1980) has implied changes in plate geometry and lithospheric age at the trenches off Central and South America, which may well have led to be observed variations in trench tectonics.

CONCLUSION

The incorporation of depth-dependent lithospheric rheology allows for a quantitative analysis of the relation between stress distribution and graben formation. From this study we conclude that the regional stress field in the downbending Nazca plate has a significant effect on the topography of the seaward trench slope. Taking into account the role of regional stress in graben formation (on the trench slope) not only explains first-order latitudinal variations in accretion and subduction of sediments along the Peru–Chile Trench, but it also expected to contribute significantly to understanding similar variations observed in other subduction zones.

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