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Opening of the Okinawa basin and collision in Taiwan: a retreating trench model with lateral anchoring

C. Viallon [1], P. Huchon [1] and E. Barrier [2]

[1] *CNRS UA 215 et Département de Géologie, Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris Cedex 05 (France)*
[2] *18 rue des Boulangers, 75005 Paris (France)*

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Using a two-dimensional finite element model with an elasto-plastic behavior, we show that the opening of the Okinawa basin behind the Ryukyu trench since about 6 Ma can be explained by a retreating trench model with lateral anchoring due to the collision in Taiwan. We assume that a suction force is applied to the edge of the overriding plate. This force corresponds to the difference between the mean lithospheric pressure in the overriding lithosphere and the normal pressure applied to its edge. It results in an outward motion of the edge of the continental margin (retreating trench) and in the opening of the Okinawa basin. If, on the contrary, no suction force is applied, the collision in Taiwan does not result in any extension in the Okinawa area. On both extremities of the Ryukyu trench, this outward motion is locked by the collision in Taiwan and the buoyant subduction of the Palau-Kyushu ridge. It results in the arcuate shape of the Ryukyu arc. In order to explain the actual amount of extension in the Okinawa basin, it is however necessary to take into account the presence of the Miocene volcanic arc which results in a weakened lithosphere. In our model, this weak zone is simulated by a lower yield condition. Finally, the dissymmetry of the Ryukyu arc and Okinawa basin can be explained by a lateral variation of the suction force related to the variation of the length of the subducting slab, thus of the slab pull force.

1. Introduction

Active marginal basins are associated with subduction zones. In many cases, the link is obvious between the opening of a marginal basin and a major lithospheric process, like a collision. This suggests that opening of marginal basins may be controled by forces acting within the lithosphere itself and not only by convection in the asthenosphere. The couple formed by the opening of the Okinawa basin and the collision in Taiwan is one of the most typical examples.

Using an analog model, Peltzer [1] and Tapponnier et al. [2] have shown that the indentation of a block of plasticine free to move on one side and indented by a rigid body results in the lateral extrusion of blocks and formation of vacuums in between. In the case of the India-Eurasia collision, they point out the analogy between these vacuums and the opening of the Andaman sea and of the South China Sea basins. Using a numerical model with similar conditions, Vilotte et al. [3] and Vilotte [4] have also shown that limited extensional areas may appear. Letouzey and Kimura [5] proposed a similar analogy to explain the opening of the Okinawa basin as a consequence of the collision in Taiwan.

In this paper, we show, using a finite element model with an elasto-plastic behavior, that the lateral extrusion due to the collision is not able to produce any significant extension in the Okinawa basin. Another mechanism should be invoked. We suggest that it is the suction force applied to the edge of the overriding plate. This model of trench retreat associated with lateral collision allows us to explain the shape of the Okinawa basin. Note that we do not take into account the effect of asthenospheric convection.

2. Geodynamical and geological background

2.1. Geodynamical context

The Okinawa basin is a young back-arc basin formed by extension of the Eurasian continental lithosphere behind the Ryukyu trench (Fig. 1), where the Philippine Sea plate is subducted to-

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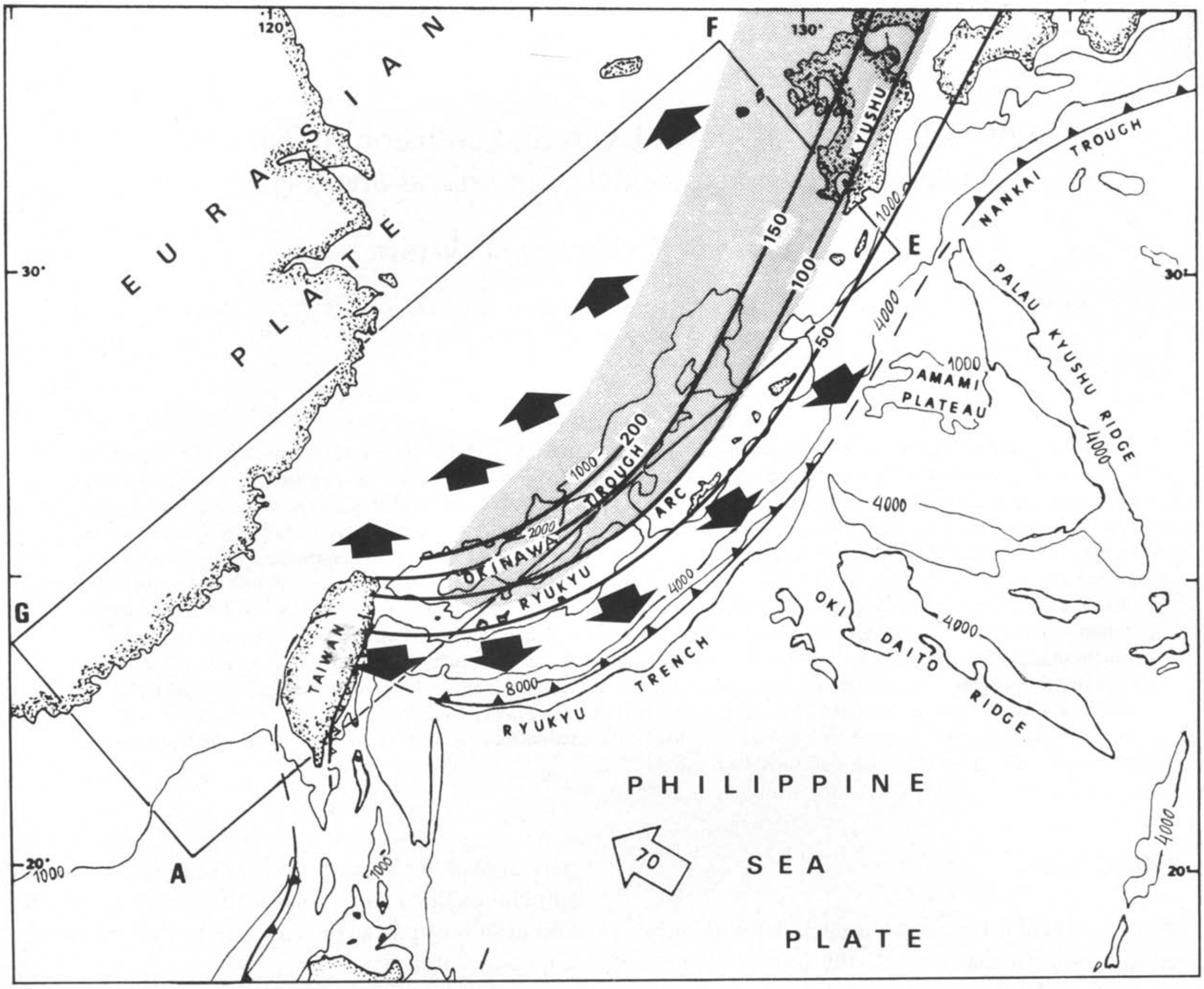

Fig. 1. Geodynamical context of the Taiwan-Okinawa region. Open arrow: direction of motion of the Philippine Sea plate relative to Eurasia (numeral: velocity in km/Ma). Black arrows: directions of extension in the Okinawa basin, from [11]. Thick lines: isodepths of the Wadati-Benioff zone (in km) from [5]. Shaded: Miocene volcanic arc. Location of the model (before deformation) is shown by the rectangle *AEFG*.

ward the northwest at a velocity of 5–7 cm/yr [6]. In the northwestern corner of the Philippine Sea plate, this motion results in the collision in Taiwan of the western border of the plate with the Chinese continental margin (Fig. 1).

The western part of the Philippine Sea plate (West Philippine Basin) was formed between 60 and 45 Ma [7]. The northern part of the basin, along the Ryukyu trench, is characterized by several aseismic ridges: the Palau-Kyushu ridge (a Miocene volcanic arc), the Oki Daito ridge and the Amami plateau. The Ryukyu trench system is active at least since the early Miocene [5]. Its depth varies from 6000 m near Taiwan to 4500 m in front of the Palau-Kyushu ridge subducting beneath the southwestern Japan margin. The subduction of this ridge does not affect intensively the inner wall of the trench [8].

The Okinawa basin is formed of several en-échelon depressions. In the southern part, oceanic accretion started about 1.9 Ma ago [9]. The main grabens trend N70°E in the northern and central parts and N90°E in the southern part [10]. On the basis of focal mechanisms studies, Eguchi and

Uyeda [11] have shown that most of the earthquakes occur in a north-south trending extensional stress field. This implies that the direction of extension in the basin is not radial to the arc. In the southern part of the basin, the extension rates computed by Barbier [12] from seismic profiles range from 2 to 4. The early extensional movements are probably of Miocene age, when subsidence is well documented in the basin, accompanied by uplift on both sides. The opening has split the Miocene volcanic arc whose remains exist on both sides of the basin [5]. The substratum of the Ryukyu outer arc (forearc basin and forearc terrace) is pre-Late Miocene in age in the central and northern Ryukyus. In southern Ryukyus, the metamorphic basement is similar to that of the central Range of Taiwan. The active volcanic arc lies along the inner side of the outer arc, about 200 km away from the trench. It is located above the 100 km isodepth line of the subducting Philippine Sea plate.

The active orogenic zone of Taiwan results from the collision of the western edge of the Philippine Sea plate with the Chinese continental margin [13]. The mountain chains consist of the deformed part of the Chinese continental margin (the Central Range) and of the Philippine Sea plate (the Coastal Range). The main structures trend NNE-SSW. They are mainly controled by the direction of relative plate motion [14]. In the collision zone, the rate of thickening and shortening are very high [15].

Southwest of Taiwan, the passive continental margin borders the South China Sea basin, accreted between 32 and 17 Ma ago [16]. This oceanic basin now subducts beneath the Philippine Sea plate in the Manila trench (Fig. 1).

To summarize, we observe, from northeast to southwest along the Chinese continental margin: (1) a subduction zone (the Ryukyu trench) associated to an active marginal basin (the Okinawa basin), (2) a collision zone (Taiwan), and (3) a passive margin.

2.2. Relationship between the opening of the Okinawa basin and the collision in Taiwan

These two events are linked both in space and in time:

(1) In space, the Okinawa basin extends southwestwards inside the Taiwan collision zone, in the Ilan plain. This extensional zone is installed on a recently inactive part of the collision zone [17].

(2) In time, the collision in Taiwan and the beginning of rifting in the Okinawa basin are synchronous. Both started in the Latest Miocene, about 6 Ma ago [5,13,18].

We suggest that the collision in Taiwan and the subduction of the Palau-Kyushu ridge are responsible for compressive horizontal stress concentration. Consequently, the horizontal deviatoric stress is a tensile stress in other places along the plate boundary. This tensile stress corresponds to a suction force (Figs. 2 and 3), which induces a trench retreat [19].

We have used a finite element model in order to estimate the relative importance, for the opening of the Okinawa basin, of the collision in Taiwan compared with the effect of the suction force.

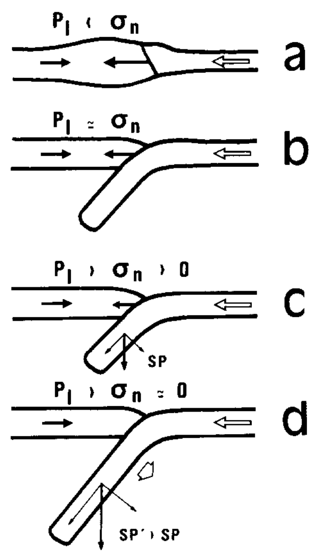

Fig. 2. Cartoons illustrating the relative importance of the lithostatic pressure p_l in the overriding plate and the normal stress σ_n transmitted from the subducting plate, for several geodynamic situations: (a) collision, (b) ridge subduction, (c) short slab subduction, (d) long slab subduction). *SP*: weight of the slab (slab pull). The positive difference between p_l and σ_n is a tensile corresponding to a suction force (see text).

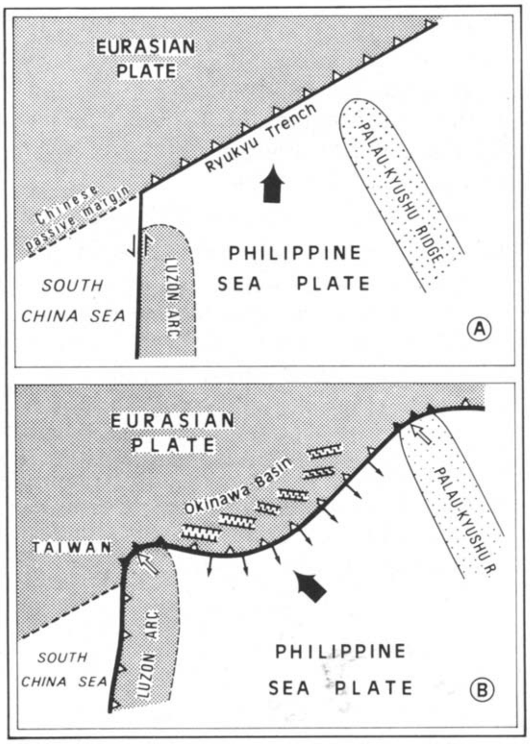

Fig. 3. Evolution of the Taiwan-Okinawa region [17], illustrating the proposed mechanism of retreating trench with lateral anchoring (see text) A. Before collision in Taiwan (note that the Philippine Sea plate was moving northward). B. Present situation.

3. Description of the finite element model

The model used here is two dimensional and concerns the overriding plate only (the Chinese continental margin). The interaction of the subducting plate with the overriding plate is represented by the condition imposed on the boundary. Only the mechanical aspect of the problem will be treated here. No thermal effect is accounted for. The calculations have been made using the finite element program "Geftec" written by D. Aubry at the Laboratory of Soil Mechanics of the Ecole Central (Chatenay-Malabry, France). This program was run on the CRAY computer which was made available to us by the TOTAL-CFP oil company. We have used quadratic elements with 8 nodes and 4 Gauss integration points. Calculations involved 24 steps of time. The boundary conditions increase linearly with steps of time.

3.1 Geometry of the model

The geometry of the overriding plate before deformation is represented by a rectangle 2000 km × 600 km wide (Figs. 1 and 4). It corresponds to a hypothetical initial stage before the collision and before the opening of the Okinawa basin. This rectangle has been divided in 60 elements (Fig. 4). The southeastern border runs from southwest of Taiwan to south of Kyushu in a N60°E direction (Fig. 1). For practical reasons, we thus assume that the paleo-Chinese continental margin was rectilinear before deformation.

As the actual geodynamical processes are tri-dimensional, the two-dimensional approximation means that the model represents an average level of the mechanical lithosphere, which is typically 60 km thick. Below the mechanical lithosphere, the stresses which are transmitted are negligible in comparison with those transmitted by the mechanical lithosphere. The deformations computed in the two-dimensional model are not the surficial ones, accessible to geologists, but average deformations affecting the whole mechanical lithosphere.

3.2. Boundary conditions

We have chosen to use plane stress conditions, which correspond for a two-dimensional model to an infinitely thin plate, where thinning or thickening is possible. By contrast, plane strain conditions would represent that of an infinitely thick

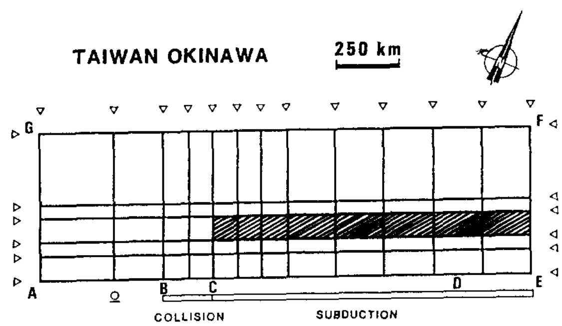

Fig. 4. Geometry and boundary conditions of the finite element model (location in Fig. 1). Boundaries *AG*, *EF* and *FG* are fixed. *AB*, Chinese continental margin (stable); *BC*, Taiwan (collision); *CD*, Ryukyu trench (subduction); *DE*, Palau-Kyushu ridge. Hatchured zone: zone with a lower yield stress for models 15, 17 and 19.

plate where horizontal motions only are allowed. From a geological point of view, the obtained strain field is of strike-slip type. The absence of any major strike slip motions in the Okinawa-Taiwan region, and the occurrence of large thinning and thickening, justify the use of plane stress conditions.

The boundary conditions used are either displacements or stresses. The northeastern (*EF*), northwestern (*FG*) and southwestern (*AG*) boundaries of the model are fixed (Fig. 4) because displacements on it are negligible with respect to those on the southeastern boundary (*AE*, Taiwan and Ryukyu trench). This boundary is divided in three segments as described below (Fig. 4):

—Along the passive margin, southwest of Taiwan (segment *AB*), we have either fixed the boundary *AB* or allowed it to move in the *x*-direction (NE-SW) only. The results are not significantly different for both cases.

—As the kinematics of the collision in Taiwan (segment *BC*) is well known [13,17], we have used displacements as boundary conditions. The indenter is 200 km wide and its total penetration in the model is 120 km. It has a wedge shape and moves in a N300°E direction. The direction of relative motion thus makes an angle of 60° with the plate boundary. Due to its wedge shape, the width of the indenter increases during the collision process.

—Along the Ryukyu trench (segment *CE*), the boundary conditions used in all cases are stresses. If the normal stress transmitted from the subducting plate to the edge of the overriding plate is lower than the mean lithostatic pressure ($\sigma_n < p_l$), the difference is a tensile stress, corresponding to a suction force (Fig. 2c). If, on the contrary, the normal stress is equal to the mean lithostatic pressure, the difference is zero. In other words, no suction force is exerted (Fig. 2b). In the extreme case, the normal stress is zero, so that no stress is transmitted from the subducting plate to the overriding plate and the suction force is equal to the mean lithostatic pressure in the overriding plate (Fig. 2d).

In order to test the effect of subduction of the Philippine Sea plate, we have used three different conditions in the Ryukyu trench: (1) no suction force, (2) constant suction force, and (3) variable suction force and fixed boundary in front of the Palau-Kyushu ridge. From a geological point of view, the two first cases correspond to the absence or to the occurrence of a trench retreat, respectively. In the third case, we wish to take into account the partial collision of the Palau-Kyushu ridge (segment *DE*). We simulate this effect by considering the normal stress equal to the mean lithostatic pressure (no suction force). In addition, it is known from seismological studies that the length of the Philippine Sea slab beneath the Ryukyus increases from Kyushu to Taiwan [20]. It is thus expected that the trench retreat will be greater near Taiwan than near Kyushu (Fig. 2c and d). We consequently let vary the normal pressure from $\sigma_n = p_l$ in front of the Palau-Kyushu ridge to $\sigma_n = 0$ near Taiwan. The value of the mean pressure p_l used in the computations is 9.22×10^8 Pa. The method for computing p_l is given in Appendix 1. In all cases, we take a zero shear stress along *CE*.

3.3 Material behavior

Like the boundary conditions, the behavior of the material should represent the average behavior of the mechanical lithosphere. We have used the elasto-plastic law with the Von Mises criterion. This law takes in account the elastic deformation of the lithosphere submitted to low stresses and its plastic deformation under larger stresses.

Let us note σ the stress tensor, and σ_{ij} its components: σ^D the deviatoric stress tensor, and σ_{ij}^D its components; $\tau = (\frac{1}{3}\sigma_{ij}^D\sigma_{ij}^D)^{1/2}$; ϵ the deformation tensor; ϵ^e the elastic deformation tensor; and ϵ^p the plastic deformation tensor. The elasto-plastic law is described by (1) a yield condition:

$$F(\sigma, k) = 3/\sqrt{2}\,\tau - k$$

where k a constant depending on the material (the yield stress), and (2) a flow rule:

Let us call dF, $d\sigma$, $d\epsilon$, $d\epsilon^e$ and $d\epsilon^p$ the variations of F, σ, ϵ^e and ϵ^p during the time interval dt.

—If $F < 0$ or $F = 0$ and $dF < 0$, only elastic deformation occurs and the tensor of deformation is $d\epsilon^e = d\epsilon = D\, d\sigma$, where D is the linear elasticity matrix.

—If $F = 0$ and $dF = 0$, elastic and plastic deformations occur simultaneously: $d\epsilon = d\epsilon^e + d\epsilon^p$ where $d\epsilon^p = \lambda\, \sigma_{ij}^D$ with $\lambda > 0$ [21].

Three parameters describe the material: the Young's modulus E (10^{11} Pa), the Poisson's ratio

ν (0.49, which means that the material is incompressible; 0.49 is used instead of 0.5 for numerical reasons) and the yield stress k.

In the case of the Okinawa basin, one considers that the opening occurs when the yield condition is reached. The value of the yield stress is taken as $k = 7 \times 10^8$ Pa, except for the Miocene volcanic zone ($k = 5 \times 10^8$ Pa) whose presence induces an increase in temperature of the lithosphere and a decrease of its mechanical strength. These values of the yield stress may appear to be quite large. However, they are somewhat arbitrary and have been chosen in order to be compatible with the mean pressure we have computed for a 60 km thick mechanical lithosphere.

4. Results

In order to obtain a physically reasonable model, we have tested the influence of various parameters and boundary conditions. We present here the main results in a succession that corresponds to the choices we have made to obtain a strain and stress field compatible with the available data. We describe the results using geographic and geological terms in order to make the reading easier. The correspondence between the model and the actual situation is described in Figs. 1 and 4. The parameters used for the different models are given in Table 1.

4.1. Role of the suction force

The first two models presented below (models 16 and 15) were run with an homogeneous medium. We have first computed the effect of the collision in Taiwan only, in order to test the lateral extrusion model. In this model (*model 16*), no suction force is applied along the Ryukyu trench. As a result, one observes that the area corresponding to the Okinawa basin is not deformed and that the subduction zone (southeastern boundary) does not move (Fig. 5). The deformation is limited to a narrow zone around the indenter, where the computed vertical deformation (thickening) is very large. Northeast of this area, there is a limited area where extension occurs (Fig. 6).

With plane stress conditions, large vertical deformation occurs in the collision zone and no lateral extrusion of blocks is possible. Vilotte et al. [3] have obtained results similar to ours. A very limited area with tensile stress exists and no motion of the free boundaries is observed. It demonstrates that, with conditions corresponding to the geological context (occurrence of large thickening and thinning of the lithosphere, but little horizontal displacements), the indentation of a plastic medium by a rigid indenter cannot produce large extensional areas.

Adding the effect of the suction force along the southwestern boundary (Ryukyu trench), as described above, results in a drastic change in the results (*model 15*). A large extensional area develops in front of the subduction zone, which moves southeastwards (Figs. 5 and 6). The maximum tensile stress axis is nearly perpendicular to the boundary (Fig. 7) because of the boundary condition (no shear stress). It rapidly decreases away from the boundary.

The comparison of the results of models 15 and 16 clearly demonstrates that, with plane stress conditions, the collision in Taiwan alone is not sufficient to produce any significant extension in the Okinawa basin. To obtain this extension, it is necessary to apply a suction force along the subduction zone (trench retreat model). Letouzey and Kimura [5] argued that mechanisms such as trench

TABLE 1

Parameters used for the different models

Parameter		No suction force	Uniform suction force	Variable suction force
Yield stress				
all el.:	$k = 7 \times 10^8$ Pa	model 16	model 15	
weak zone:	$k = 5 \times 10^8$ Pa	model 18	model 19	model 17
Other el.:	$k = 7 \times 10^8$ Pa			
Young's modulus, $E = 10^{11}$ Pa				
Poisson's ratio, $\nu = 0.49$				

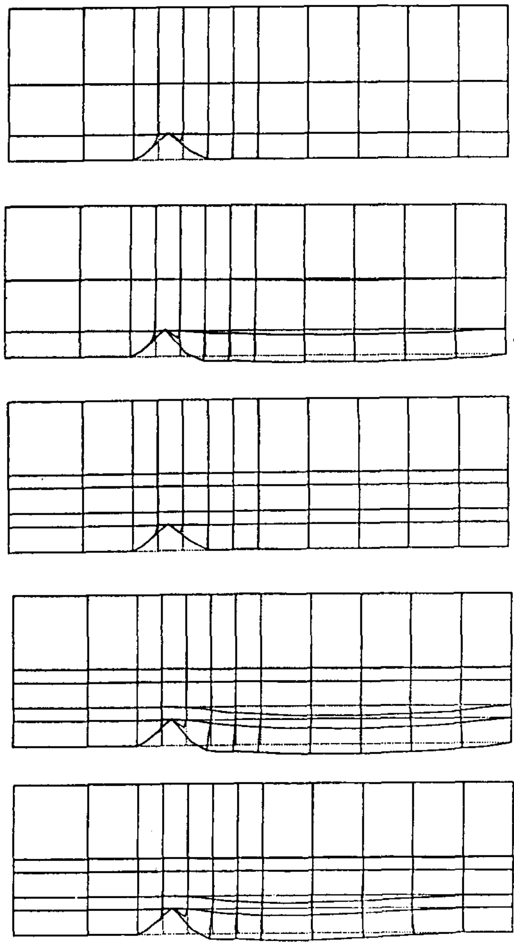

Fig. 5. Deformed models. *15* and *16*: with and without suction force. *18* and *19*: with the weak zone shown in Fig. 4 (18: without, 19: with suction force). *17*: with weak zone and variable suction force (see text).

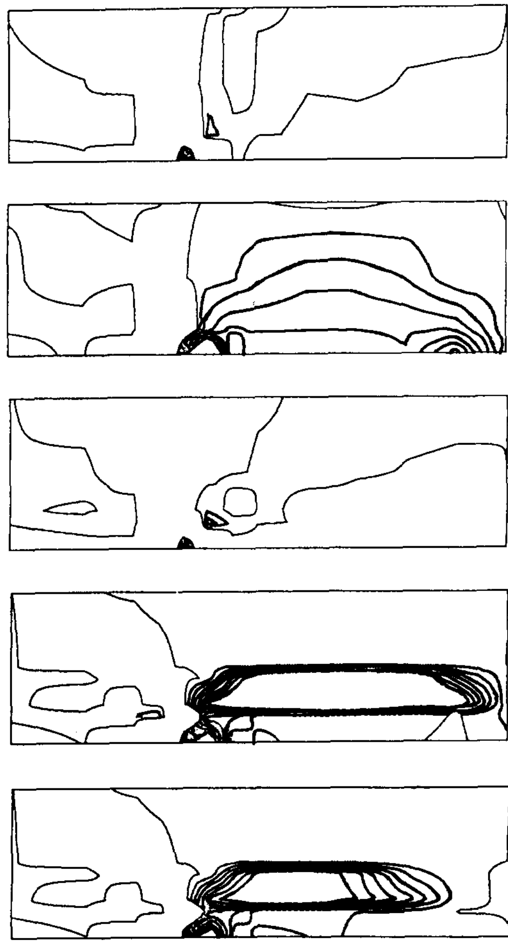

Fig. 6. Negative horizontal strain ϵ_{yy} (in the NW-SE direction) for the five models. Thin line: shortening; thick line: extension.

retreat may only maintain extension but do not produce it. In their model, the extension in the Okinawa basin is initiated by the collision in Taiwan and subsequent lateral extrusion. Our model shows that such an effect is not sufficient to explain the opening of the Okinawa basin. We rather think that the collision in Taiwan simply acts as an "anchor point" for the Philippine Sea plate. Together with the retreat of the Ryukyu trench, this anchoring results in the present arcuate shape of the Ryukyu arc.

The previous models explain the occurrence of extension in the Okinawa basin, but clearly not the observed amount of extension nor the dissymmetry of the basin. In the following, we shall try to explain these two characteristics.

4.2 Role of the Miocene volcanic arc

In order to explain the observed amount of extension, we suggest, following Molnar and Atwater [22], that the Miocene volcanism may favor the opening of the Okinawa basin by weakening the continental lithosphere. To simulate this effect, we have introduced in our model a strip of elements (Fig. 4), where the yield stress is lower (5×10^8 Pa) than in the other elements (7×10^8 Pa). In order to test the effect of this weak zone independently from the effect of the

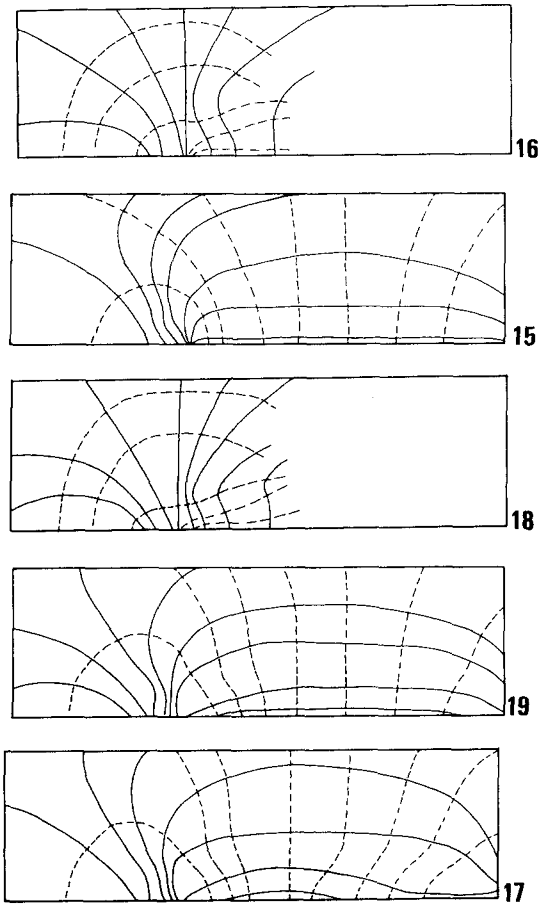

Fig. 7. Trajectories of the maximum compressive stress (solid line) and minimum compressive stress (dashed line) for the five models. Areas with very small deviatoric stresses are left blank.

suction force, we have run a model without suction force (*model 18*). The deformed grid as well as the computed strain and stress field show almost no difference with model 16 (Figs. 5, 6 and 7). The effect of the lower yield stress in the Okinawa area has consequently little effect and does not change our previous conclusion.

In *model 19*, we have introduced both the suction force along the southeastern boundary, as in model 15, and the area of lower yield stress, as in model 18. The strain and stress fields are then deeply modified (Figs. 6 and 7). The extension is almost restricted to the weak zone. The area located between the boundary of the model and the weak zone rotates clockwise near Taiwan (near point C) and counterclockwise near Kyushu (near points D and E) (Fig. 5). The deformation behind the weak zone is very low. The stress field is also modified. The value of the maximum tensile stress is reduced in the Okinawa basin, because, once the yield stress reached, the deformation continues without any increase of the stress.

Models 18 and 19 demonstrate that to obtain a significant extension behind the subduction zone, it is necessary (1) to apply a suction force along the edge of the overriding plate, and (2) to introduce a weak zone corresponding to the Miocene volcanic arc.

However, the computed strain and stress fields are symmetric with respect to the middle part of the Okinawa basin, contrary to the actual pattern. In order to account for this dissymmetry, we now discuss the effect of the buoyant subduction of the Palau-Kyushu ridge and of possible lateral variations in the intensity of the suction force.

4.3 Effect of the subduction of the Palau-Kyushu ridge and of the length of the subducting Philippine Sea plate

Up to here, a uniform suction force was applied along the Ryukyu trench. However, the subduction of ridges like the Palau-Kyushu ridge would inevitably produce a local modification of this suction force. Intuitively, this case is intermediate between the collision and the normal subduction (Fig. 2). To simulate this effect, we choose to apply a normal stress which just balances the lithostatic pressure in the overriding plate. In other words, no suction force is applied in front of the Palau-Kyushu ridge. Another characteristic of the subduction of the Philippine Sea plate we wish to take into account is a possible variation of the suction force along the Ryukyu trench. This is based on the following observation: the maximum depth of earthquakes beneath the Ryukyu arc is greater in the southwestern part (300 km) than in the northern part (200 km) [20] (Fig. 1). Considering that the slab pull force is proportional to the length of the slab [23], one should intuitively expect that the normal stress transmitted to the overriding plate would decrease when the length of the slab increases (Fig. 2). Consequently, the suction force would be greater to the southwest than to the northeast. To model this effect, we have applied a suction force that linearly increases from zero in front of the Palau-Kyushu ridge to its maximum value (the lithospheric pressure) east of Taiwan (*model 17*).

As in model 19, the extension is almost restricted to the weak zone but is less intense in the northeastern part, near line *EF* (Fig. 5). This result was expected because the suction force is smaller there. The general pattern of the stress field is nearly the same as in model 19 (Fig. 6). However, the trajectories of the maximum extension are slightly modified. They trend roughly north-south in the central part of the Okinawa basin, thus are not radial to the arc (Fig. 7).

The dissymmetry of the Okinawa basin can thus easily be accounted for by a reasonable lateral variation in the applied boundary conditions. We suggest that this variation is mainly controled first by the length of the subducting Philippine Sea plate, and second by the buoyant subduction of the Palau-Kyushu ridge.

5. Discussion

The models in which no suction force is applied (models 16 and 18) clearly show that the indentation of the Eurasian margin by the Philippine Sea plate in Taiwan does not result laterally in the formation of an extensional basin. By contrast, the models which take into account the existence of a suction force applied to the edge of the overriding plate (models 15, 17 and 19) show the existence of a developed extensional zone. Model 17 includes a pre-existing weak zone corresponding to the Miocene volcanic arc and a suction force varying along the Ryukyu trench according to the conditions of subduction (presence of a subducting ridge, variation of the length of the slab). It reasonably accounts for:

—The compression restricted to the collision zone of Taiwan, associated with a large thickening, and the fan-shaped pattern of the stress and strain fields.

—The extension, essentially localized along the pre-existing weak zone (Miocene volcanic arc), but greater to the southwest than to the northeast, in good agreement with geological data. This is the direct consequence of the lateral variation of the suction force.

—The very small deformation northwest of the Okinawa basin.

—The arcuate shape of the Ryukyu arc, which is subjected to little extension.

In greater detail, one can observe that the maximum tensional stress is nearly perpendicular to the boundary *CE* in its vicinity (because no shear stress is applied) but rapidely diverges when one moves away from the boundary. The pattern of the computed strain and stress fields is reasonably similar to the one obtained from geological and geophysical data. In the northern and central parts of the Okinawa basin, the direction of the computed tensile stress (N160°E) is perpendicular to the direction of the graben (N70°E). But, in the southern part, the computed tensile stress is highly oblique to the direction of the graben (N90°E). East of Taiwan, one can observe a very sharp gradient of pressure which may correspond to the rapid transition from the general compressive stress field in Taiwan to the extension in the Okinawa basin.

6. Conclusions

In this paper, we have analyzed the relations between lateral collisions and the formation of marginal basins, in the case of Taiwan and Okinawa. In collision zones, the overriding plate obviously cannot move toward the colliding body. If a suction force is applied to a subduction zone located between two collision zones, it would produce an arcuate shape of the arc and marginal basin (Fig. 3). Almost every marginal basin displays this arcuate shape, such as the Mariana trough, bounded to the north by the Ogasawara plateau and to the south by the Caroline ridge. In the case of older marginal basins, we suggest that, among other mechanisms, lateral collisions may have played an important role by anchoring the subduction zone [23]. Such a model of "trench retreat with lateral anchoring" should be considered, especially if the collision and the opening are contemporaneous.

One should notice that our two-dimensional model probably over-simplifies the problem. It does not take into account the vertical structure of the overriding plate. Froidevaux et al. [24] have shown that the vertical stress σ_{zz}, and thus the tectonic stress $\sigma_{xx} - \sigma_{zz}$, depends on the topography of the arc: for a given horizontal stress σ_{xx} transmitted to the arc lithosphere through the subduction boundary, higher is the topography, the more extensional is the tectonic stress. Consequently, any variation in topography of the overriding plate will induce changes in the stress field, in addition to the force imposed at the plate boundary. This mechanism may provide a key to the understanding of episodic back-arc spreading: after some time of back-arc rifting, the volcanic arc will change its location and the back-arc spreading may jump to the site of the new arc, as has happened in the case of the Mariana arc [25]. An alternative is to consider that the suction force may vary episodically, maybe because of the occurrence of slab detachment or the coming into the trench of older or younger oceanic lithosphere which make the slab pull force vary.

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Appendix 1—Method of computation of the mean lithospheric pressure in the mechanical lithosphere

The mean pressure in a mechanical lithosphere of thickness L_M is:

$$P_M = \frac{1}{L_M}\int_0^{L_M} p(z)\mathrm{d}z \tag{1}$$

where $p(z)$ is the pressure at depth z, which is defined by:

$$p(z) = g\int_0^z \rho(z)\mathrm{d}z \tag{2}$$

where $\rho(z)$ is the density at depth z and g the gravity. We consider the lithosphere as formed of two homogeneous parts, the crust and the upper mantle. The density is related to the temperature T by:

$$\rho = \rho_0(1 - \alpha T) \tag{3}$$

where ρ_0 is the density at 0°C and α the coefficient of thermal expansion. The temperature is computed from the equation of heat in steady-state:

$$\frac{\delta K}{\delta z}\frac{\delta T}{\delta z} = R \tag{4}$$

where K is the thermal conductivity and R the radiogenic heat production. Combining equations (2), (3) and (4) and with parameters listed in Table A-1, one obtains the pressure in the crust p_c and in the upper mantle p_m:

$$p_c(z) = \rho_0^c g\left[z - \alpha\left(R_c z^3/6K + \phi_0 z^2/2K\right)\right] \tag{5}$$

$$p_m(z) = p_c(L_c) + \rho_0^m g\left[\{1 - \alpha[T(L_c) - L_c G]\}(z - L_c) - \alpha G\left(z^2/2 - L_c^2/2\right)\right] \tag{6}$$

where $G = [T(L_c) - T_a]/L_m$ and ϕ_0 the surface heat flow. With the numerical values of Table A-1, the mean pressure of a 60 km thick mechanical lithosphere is $P_M = 9.22 \times 10^8$ Pa.

TABLE A-1

Parameters used to compute the mean pressure in the mechanical lithosphere

g acceleration of gravity	9.81 m s^{-1}
ρ_0^c density of crust at 0°C	2700 kg m^{-3}
ρ_0^m density of upper mantle at 0°C	3350 kg m^{-3}
α_c coefficient of thermal expansion (crust)	3.28×10^{-5} °C^{-1}
α_m coefficient of thermal expansion (upper mantle)	3.28×10^{-5} °C^{-1}
R_c radiogenic heat production in the crust	1.25×10^{-6} W m^{-3}
R_m radiogenic heat production in the upper mantle	0
K_c thermal conductivity of the crust	2.51 J m^{-3} s^{-1} °C^{-1}
K_m thermal conductivity of the upper mantle	2.51 J m^{-3} s^{-1} °C^{-1}
T_0 temperature at the surface of the lithosphere	0°C
T_a temperature at the bottom of the lithosphere	1333°C
L_c thickness of the crust	30 km
L_m thickness of the lithospheric upper mantle	95 km
L_M thickness of the mechanical lithosphere	60 km
ϕ_0 surface heat flow	6.27×10^{-2} J m^{-2} s^{-1}

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