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Role of Fault Rejuvenation in Hydrocarbon Accumulation and Structural Evolution of Reconcavo Basin, Northeastern Brazil[1]

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ABSTRACT

From a geometric analysis of the fault pattern in the Reconcavo basin, Brazil, supported by a reinterpretation of the early opening history of the South Atlantic Ocean, it is inferred that the basin formed as a result of Valanginian (Early Cretaceous) motion on a major N40°E-striking left-lateral transform fault located offshore between Salvador and Recife. This left-lateral motion was due to the location of the Valanginian pole of South American–African plate rotation within northern Brazil, at 2.5°S, 45.0°W, rather than farther north as interpreted previously.

Left-lateral movement along the inferred transform created three fault sets: (1) a predominant set striking N30°E ± 20° (1σ); and two lesser developed sets striking (2) N13°W ± 6° and (3) N37°W ± 12° (1σ). Sets (1) and (3) are interpreted, respectively, as Riedel and conjugate Riedel shears (with an extensional component) to the N40°E-trending left-lateral transform fault. Set (2) formed as an extensional fault system. Intersections of these three sets subdivide the basin into triangular and diamond-shaped blocks.

The Reconcavo basin continues northward in northeastern Brazil into the Tucano and Jatoba basins. These basins collectively form a north-south-trending, mega half-graben within continental crust.

Geohistory curves for Early Cretaceous units in the Reconcavo basin indicate that the syn-tectonic Valanginian shales of the lacustrine Candeias Formation began to generate hydrocarbons during the earliest subsequent deposition of the Ilhas Formation (?Hauterivian). Because diamond-shaped structural traps had formed earlier during the Valanginian, hydrocarbons generated in the Candeias Formation are believed to have then migrated into the Sergi Formation (?Upper Jurassic) reservoir units in structurally juxtaposed fault blocks. During Barremian to Aptian time, deposition of fluvial, lacustrine, and alluvial sediments of the Ilhas and Sao Sebastiao Formations occurred.

Rejuvenation as normal faults of earlier formed strike-slip and normal faults occurred in the latest Aptian (106 Ma) when the pole of South American–African plate rotations jumped to 41.3°N, 43.8°W. This pole jump caused extension along the previously formed transform margin between Salvador and Recife and the abandonment of rifting in the Reconcavo basin.

Rejuvenated faults tapped earlier filled Sergi Formation reservoirs, which then leaked earlier reservoired hydrocarbons up these fault planes into higher reservoirs in the Ilhas and Sao Sebastiao Formations. This structural history thus explains the frequency distribution and orientation of faults in the basin, Sergi Formation production from corners of diamond-shaped fault blocks, and production from stratigraphically and structurally higher reservoirs (Ilhas and Sao Sebastiao Formations) in rollover folds and stratigraphic traps charged by second-phase faulting.

INTRODUCTION

The Reconcavo basin lies on Brazil's Atlantic Coast near the town of Salvador (Figure 1). The principal petroleum province of Brazil, the approximately 10,000 km^2 (3,900 mi^2) area has produced over 1 billion bbl of 35-40° API gravity oil since 1939. The Bahia Supergroup (Figure 2), an uppermost Jurassic to Lower Cretaceous nonmarine sequence up to 6,500 m (10,000 ft) thick, is the main objective for petroleum exploration there.

The basin is an intracratonic half-graben which, as deduced from borehole studies, underwent two phases of Cretaceous faulting (Ghignone and Andrade, 1970). These include: (1) an earlier, post-Berriasian phase during deposition of the Candeias Formation (Figure 2), and (2) a later, post-Barremian phase following deposition of the Sao Sebastiao Formation.

Hydrocarbon migration and accumulation into reservoirs in the Sergi and Candeias Formations were controlled by the initial phase of faulting, whereas hydrocarbons in reservoirs in the Ilhas and Sao Sebastiao Formations were controlled by the later phase. However, earlier formed reservoirs undoubtedly were affected by the later faulting phase, which rejuvenated earlier formed faults (Ghignone and Andrade, 1970). The modes of formation and reactivation of earlier formed faults are the subjects of this paper.

Although the phenomenon of reactivated faults is becoming more widely recognized (Donath, 1962; Helwig, 1976; Jackson, 1980, Cohen, 1982, 1983), the details of the plate tectonic framework within which reactivation occurs are commonly not well known. Presented here is a tectonothermal analysis of the Reconcavo basin. The analysis allows an interpretation of the basin's geometry and history of faulting, explains the apparent variation

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between hydrocarbon trap and age of reservoir units, and offers kinematic and dynamic implications that are consistent with a reinterpretation of the evolution of the South Atlantic Ocean (Rabinowitz and LaBrecque, 1979).

FAULT ANALYSIS

A structural analysis of the fault distribution in the Reconcavo basin utilized those faults mappable at 1:100,000 scale at the surface. The faults' cumulative lengths and attitudes are presented in a rose diagram in Figure 3. The diagram was constructed by measuring the azimuth of faults at 1 cm intervals at 1:100,000 map scale (1 km fault segments) and summing them at 5° increments.

It is clear that the data have a trimodal distribution: (1) a dominant fault set striking N30°E ± 20°; and two subdominant sets striking (2) N13°W ± 6° and (3) N37°W ± 12° (1σ). The trends of fault sets (1) and (3) thus encompass an acute angle of 67°; fault sets (1) and (2), and (2) and (3) form angles of 43° and 24°, respectively. In addition, all fault sets mutually offset one another. This was determined by comparing the relative frequencies of one fault set terminating against another. Of 638 measured fault intersections, 304 involved faults terminating against northeast-trending faults; 334 terminated against northwest-trending faults.

The Candeias Formation (Figure 2) demonstrates thickness variations in the subsurface that are clearly related to fault movement, whereas the thicknesses of stratigraphically lower units are relatively constant. The age of the initial faulting episode is therefore coeval with this formation. From regional constraints detailed below, both the timing of faulting and Candeias Formation deposition are taken as Valanginian.

The Coulomb shear criterion deduced for these faults is 23° (Figure 4). This value is consistent with the nature of Upper Jurassic–Lower Cretaceous sedimentary units in the basin (an alluvial/fluvial/lacustrine assemblage with many overpressured shale sequences and shale diapirs) and with experimental data (Handin, 1966).

Because of the angular relations among the fault sets, their mutually cross-cutting relations, their age, and their orientation vis-à-vis a left-lateral transform fault (discussed later), the faults are interpreted to have formed as a result of an inferred Valanginian, left-lateral shear couple oriented along a N40°E trend. Sets (1) and (3) originally formed, respectively, as left- and right-lateral strike-slip faults (Riedel shears) with a large dip-slip component, whereas set (2) formed as an extensional fault between them. The angular relations presented in Figure 4 support such an interpretation, based on theoretical considerations and by comparison with experimental data (Friedman, 1964; Price, 1968).

The predominance of fault set (1) over others may perhaps be interpreted using the following experimental results. Figure 5 shows synthetic and antithetic shear faults developed in clay models. The magnitude of shear strains in the progressive deformation of the material is similar in both examples yet either fault set has an equal chance to occur (Freund, 1974). It is clear, however, that whichever set forms first continues to develop at the expense of the others (Figure 5). Thus, the predominance of set (1) by itself neither requires nor implies a unique explanation. However, if fault sets are later rejuvenated, those most favorably oriented to the subsequent stress directions will be preferentially re-utilized. As discussed below, due to latest Aptian plate tectonic reorganization, it is postulated that the predominance of fault set (1) reflects its more favorable original orientation (Figure 6).

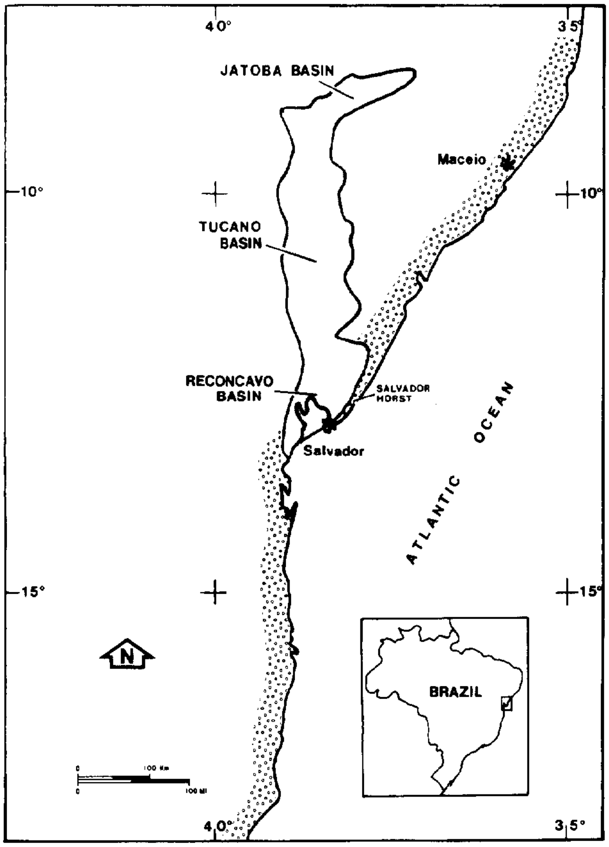

Figure 1—Location map of Reconcavo basin in northeastern Brazil. Note northward continuation of Reconcavo basin into Tucano and Jatoba basins. Also note sigmoidal, "S" shaped form of three basins.

TECTONIC SIGNIFICANCE OF FAULT PATTERN

Rabinowitz and LaBrecque (1979) presented a reinterpretation of South Atlantic gravity and magnetic data and their implications for the Mesozoic evolution of adjacent continental margins. During the earliest opening of the South Atlantic (~130-107 Ma), the pole of rotation for South America and Africa was located at 2.5°S, 45.0°W, near Sao Luis in northern Brazil (Rabinowitz and Labrecque, 1979). In previous tectonic interpretations (Le Pichon and Hayes, 1971), the pole was located much farther north. The significance of the pole's relative proximity derives from the expected nature of movement along breakup-related faults. In the cases of a distant pole, all faults along the developing continental margins of South America and Africa would be normal or right-lateral types (Figure 7A). With a nearby pole (and one within the Gondwana continent itself), zones of local extension, shear, and

AGE				GROUP	FORMATION	LITHOLOGY	THICKN (m)
TERTIARY	PLIOCENE				BARREIRAS	SANDSTONE	50
TERTIARY	MIOCENE				PREGUICA	GREEN SHALE, THIN LMS	20
LOWER CRETACEOUS	APTIAN				MARIZAL	SANDSTONE CONGLOMERATE	70
LOWER CRETACEOUS	BARREMIAN		BAHIA SUPERGROUP	MASSACARA	SAO SEBASTIAO	SANDSTONE RED SHALE GREEN & BLACK SHALE SANDSTONE	MAX 2,800
LOWER CRETACEOUS	NEOCOMIAN	HAUTERIVIAN	BAHIA SUPERGROUP	MASSACARA	ILHAS	SHALE, SILTSTONE SANDSTONE LIMESTONE	MAX 1,700
LOWER CRETACEOUS	NEOCOMIAN	VALANGINIAN	BAHIA SUPERGROUP	SANTO AMARO	CANDEIAS	GRAY & GREEN SHALE LENTICULAR SANDSTONE FRACTURED SHALE THIN LIMESTONE SANDSTONE	300 to 2,100
LOWER CRETACEOUS	NEOCOMIAN	BERRIASIAN	BAHIA SUPERGROUP	SANTO AMARO	ITAPARICA	GREEN & MAROON SHALE	MAX 180
JURASSIC	UPPER PURBECKIAN ?		BAHIA SUPERGROUP	BROTAS	SERGI	SANDSTONE	MAX 461
JURASSIC	UPPER PURBECKIAN ?		BAHIA SUPERGROUP	BROTAS	ALIANCA	RED SHALE SANDSTONE RED SHALE, EVAPORITE	MAX. 695
P-Є						GRANITE	

Figure 2—Generalized stratigraphic column of units in Reconcavo basin. Ages are poorly defined; from regional correlations, however, Candeias Formation is believed to be Valanginian in age. (Modified from Ghignone and Andrade, 1970.)

compression could develop depending on the plate configuration (Figure 7B). Whereas the Brazilian continental margin from Salvador to Recife (which trends N40°E; see Figure 4) would be interpreted as undergoing extension if rotating about a far pole (Figure 7A), if related to a near pole it would be interpreted as experiencing left-lateral shear (Figure 7B).

Rabinowitz and LaBrecque (1979) presented compelling geophysical arguments supporting the near-pole hypothesis for the early rotation of Africa and South America. They postulated that following this initial breakup pattern, the pole jumped farther north to 41.3°N, 43.8°W, during the latest Aptian (Figure 8). This pole was maintained at least until the Campanian. The latest Aptian pole jump resulted in extension along the Salvador-Recife portion of the Brazilian continental margin where left-lateral shear occurred earlier (cf. Figures 7, 8).

The conclusions reached in the present study of fault patterns in the Reconcavo basin concur extremely well with these inferred tectonic developments. The trimodal distribution of faults in the basin (Figure 3) is interpreted to represent two Riedel shears, with trends of N30°E ± 20° (R) and N37°W ± 12° (R′), and a set of extension faults, trending N13°W ± 6° (Figure 4). These fault trends were established contemporaneously during the Valanginian. Moreover, their geometries may be related kinematically to left-lateral shear along the N40°E-trending continental margin between Salvador and Recife (cf. Figures 4, 8), which was operative during this time (Rabinowitz and LeBrecque, 1979). Following a jump of the pole of South American-African plate rotation in the latest Aptian, these earlier established fault planes would have been used as dip-slip faults during post-Aptian extension and opening of the South Atlantic Ocean. This explains the frequency distribution of Reconcavo basin faults (Figure 3).

The entire series of interconnected, marginal basins in northeastern Brazil (Figure 1) (Reconcavo-Tucano-Jatoba) formed as a megascopic, sigmoidal "tension gash" (cf. Figures 1, 4). This is based on (1) the north-south trend of the western, basin-bounding granitic horst block (Figure 1); (2) the sigmoidal shape of the aligned Reconcavo-Tucano-Jatoba sedimentary basins (noting

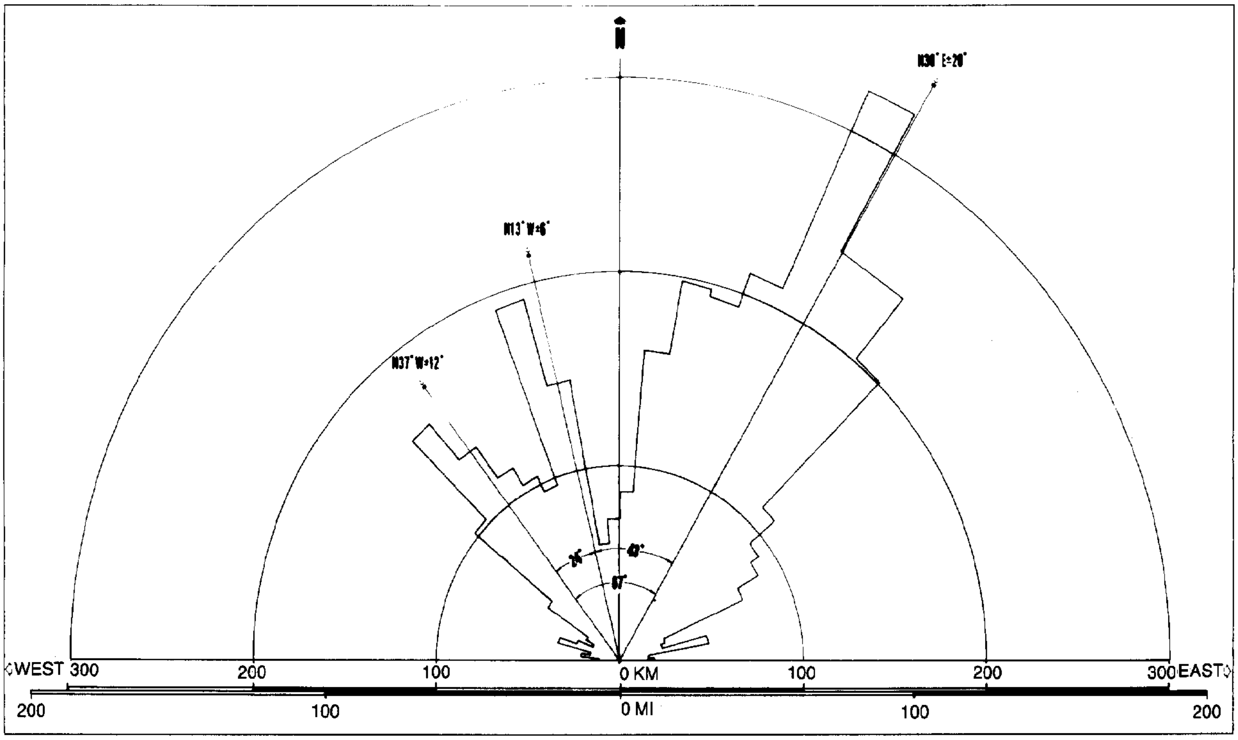

Figure 3—Rose diagram of faults from 1:100,000 scale geologic map of Reconcavo basin. Faults have trimodal distribution with peaks at N30°E ± 20°, N13°W ± 6°, and N37°W ± 12°. n = 3,558.

that the Tucano-Jatoba arm is far better developed); and (3) the deduced orientation for Reconcavo basin extension faults that formed during Valanginian shearing (Figure 4).

The exact location in the offshore of the former trace of the original shear zone may be difficult to determine. Fainstein and Milliman (1979) noted that "the paucity of deep seismic data ... make it difficult to speculate on the stratigraphy or history of the plateaus or how they relate to landward sedimentary basins. ...the ridges or seamounts underlying the plateau" area offshore of the Jatoba-Tucano-Reconcavo basins "may have formed after initial separation of South America from Africa." Therefore, the trace of the original strike-slip fault system parallel with the coast is overprinted and veiled by a younger structural geometry.

THERMAL EVOLUTION OF RECONCAVO BASIN

Royden et al (1980) determined heat-flow curves as a function of age for basement compositions and thicknesses ranging between purely oceanic (γ = 1.0) and purely continental (γ = 0.0) end members (γ is the oceanic fraction of the crust) (Figure 9). They presented two models for heat-flow variation: (1) instantaneous necking and (2) dike injection (Royden et al, 1980). From Figure 9 it is clear that for equal values of γ these two models are similar after ~20 m.y. For γ less than 0.6 however, there are significant heat-flow differences for ages under 20 m.y.

The value of γ for the Reconcavo basin was estimated using regional gravity models. These models indicate that the mantle beneath the basin shallows eastward to ~7 km (23,000 ft) beneath the sedimentary column, just west of the N40°E-trending Salvador horst. East and west of this zone, the crust-mantle interface deepens to depths of more than 25 km (15.5 mi).

Carvalho and Vacquier (1977) measured heat flow and conductivity and calculated geothermal gradients in oil fields in the basin. Present-day heat-flow data ranged from 0.87 ± 0.18 to 1.25 ± 0.15 HFU and conductivities ranged from 5.71 ± 0.06 to 5.94 ± 0.06 ($\times 10^{-3}$) cal cm^{-1} sec^{-1} $°C^{-1}$. Calculated geothermal gradients ranged from 15.0 ± 3.1 to 21.4 ± 2.7°C km^{-1} (0.82 - 1.77°F/100 ft). These cool gradients are believed to be due to either the local presence of shale diapirs, oil field depth, or poor distribution of bottom-hole temperature measurements (Carvalho and Vacquier, 1977).

Speculation on Age of Hydrocarbon Generation

Using the present-day sedimentary crustal thickness determined from gravity models and assuming an original crustal thickness of 35 km (22 mi) (Falvey, 1974; Royden et al, 1980), a γ of 0.8 is calculated for the central Reconcavo basin. Using heat-flow curves for γ = 0.8 (Figure 10), the paleoheat-flow history for the basin may be estimated using either instantaneous-necking or dike-injection models. The only significant difference between these two models occurs for $\gamma \leq 0.6$ and ages $\leq$ 20 m.y.; instantaneous-necking models were used for the following calculations.

Table 1 lists calculated geothermal gradients for the basin in 5-m.y. increments using as an average observed thermal conductivity 6×10^{-3} cal cm^{-1} sec^{-1} $°C^{-1}$ (Carvalho

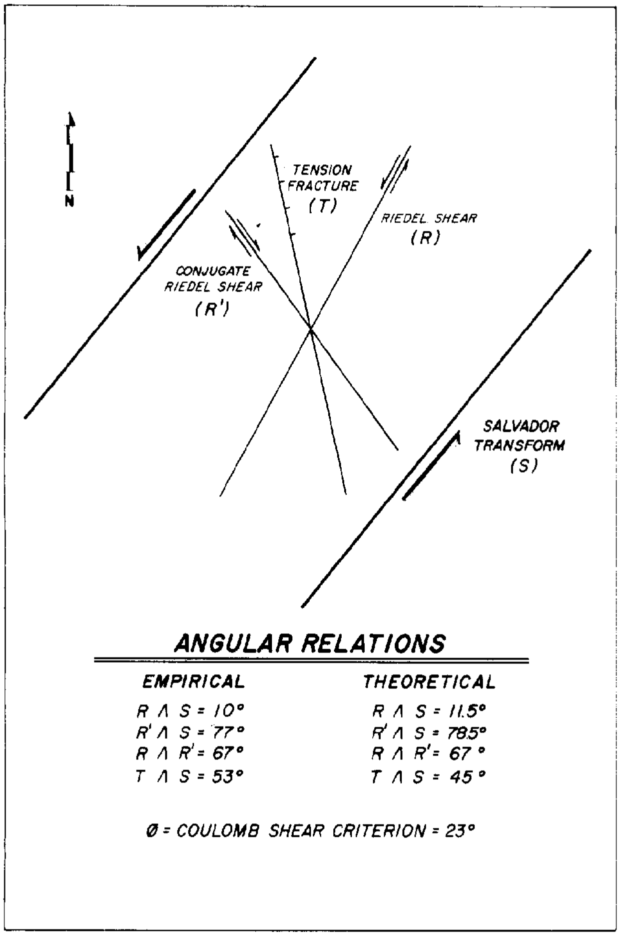

Figure 4—Angular relations of faults within Reconcavo basin and theoretical faults formed by left-lateral shear couple trending N40°E and with $\phi = 23°$. Riedel shear faults form at angles of $\phi/2$ (R) and $90 - \phi/2$ (R′) to shear couple. Tension faults (T) form at 45° to applied shear couple.

and Vacquier, 1977). These thermal gradients were superimposed on a composite burial history curve using data from boreholes 6-MGP-1 and AR-1 after the method discussed by Waples (1980) and modified by Cohen (1981). Table 2 lists time-temperature intervals (TTI) (Waples, 1980; Cohen, 1981) for the Reconcavo basin.

The ages of the lithostratigraphic units are only poorly indicated by their ostracod fauna. Thus, the only time constraints for the basin derive from (1) the syntectonic (Valanginian) development of the Candeias Formation (Santo Amaro Group) (Figure 2), and (2) the pre-Aptian age of the Sao Sebastiao Formation (Massacara Group) (Figure 2). From these and regional tectonic constraints, the following approximate ages of lithostratigraphic horizons are used: (1) top of basement, 140 m.y.; (2) top of the Brotas Group, 135 m.y.; (3) top of the Santo Amaro Group, 126 m.y.; (4) top of the Massacara Group, 115 m.y.

The time-stratigraphic control is not very precise, especially in the lower part of the stratigraphic column, and in all probability, the rock-stratigraphic units discussed in this paper are time-transgressive.

From Figure 10, it is clear that the apparent decrease in the sediment accumulation rate during 140-135 m.y. is consistent with regional uplift preceding rifting (Falvey, 1974). This would be even more pronounced were an older age assigned to the top of basement. Moreover, the increase in the apparent sediment accumulation rate during the Valanginian is consistent with the inception of South American and Africa plate separation (Figure 8) (Rabinowitz and LeBrecque, 1979).

It is apparent that at the time the uppermost Candeias Formation units were being deposited, basal Candeias units became thermally mature for oil generation (Figure 10). Hence, as the lowermost units of the overlying Ilhas Formation were deposited, basal units of the Candeias Formation began to generate oil. Oil was thus generated following the major Valanginian faulting phase. This faulting was responsible both for (1) juxtaposing source units in the Candeias Formation with reservoir units in the Sergi Formation, and (2) forming diamond-shaped structural traps to hydrocarbon migration.

DISCUSSION

Implications of Fault Pattern and Rejuvenation for Hydrocarbon Migration and Accumulation

Figure 11 shows the location of major oil fields in the Reconcavo basin. Within three of these fields—Aqua Grande, Dom Joao, and Buracica—the structural trap for hydrocarbon accumulation is an updip corner formed by the intersection of two faults (Ghignone and Andrade, 1970, their Figures 7, 8, 11). Although some production in the Reconcavo basin is from traps formed by rollover anticlines on the downdropped limbs of second-phase faults (e.g., Miranga field, see Ghignone and Andrade, 1970, their Figure 9), stratigraphic pinch-outs (e.g., Taquipe field, see Ghignone and Andrade, 1970, their Figure 12), or diapirs, these are predominantly within super-Candeias reservoirs. Corners of diamond-shaped fault blocks seem to represent the dominant trap type for reservoirs in the sub-Candeias section. This association between style of trap and age of reservoir is thus believed to be genetic.

Figure 12 offers a general model for the structural and stratigraphic evolution of the Reconcavo basin. In pre-Valanginian time (Berriasian, Figure 12), deposition of the Alianca, Sergi, and Itaparica Formations occurred atop eroded Precambrian crystalline rocks. During the Valanginian, coeval with Candeias Formation deposition, strike-slip (with an extensional component) and normal faults subdivided the basin into diamond-shaped blocks and juxtaposed possible source rocks of the Candeias Formation with reservoir units in the Sergi Formation (Valanginian, Figure 12). As deposition of units of the Ilhas Formation ensued and faulting waned, lowest Candeias units began to generate oil. This oil migrated into reservoirs in the adjacent Sergi Formation (Hauterivian-Barremian, Figure 12). Continued deposition of the Ilhas Formation occurred and, finally, the Sao Sebastiao formation was deposited (Hauterivian-Barremian, Figure 12).

During the latest Aptian, renewed faulting reactivated preexisting Valanginian strike-slip and normal faults as normal faults. This allowed communication via fault

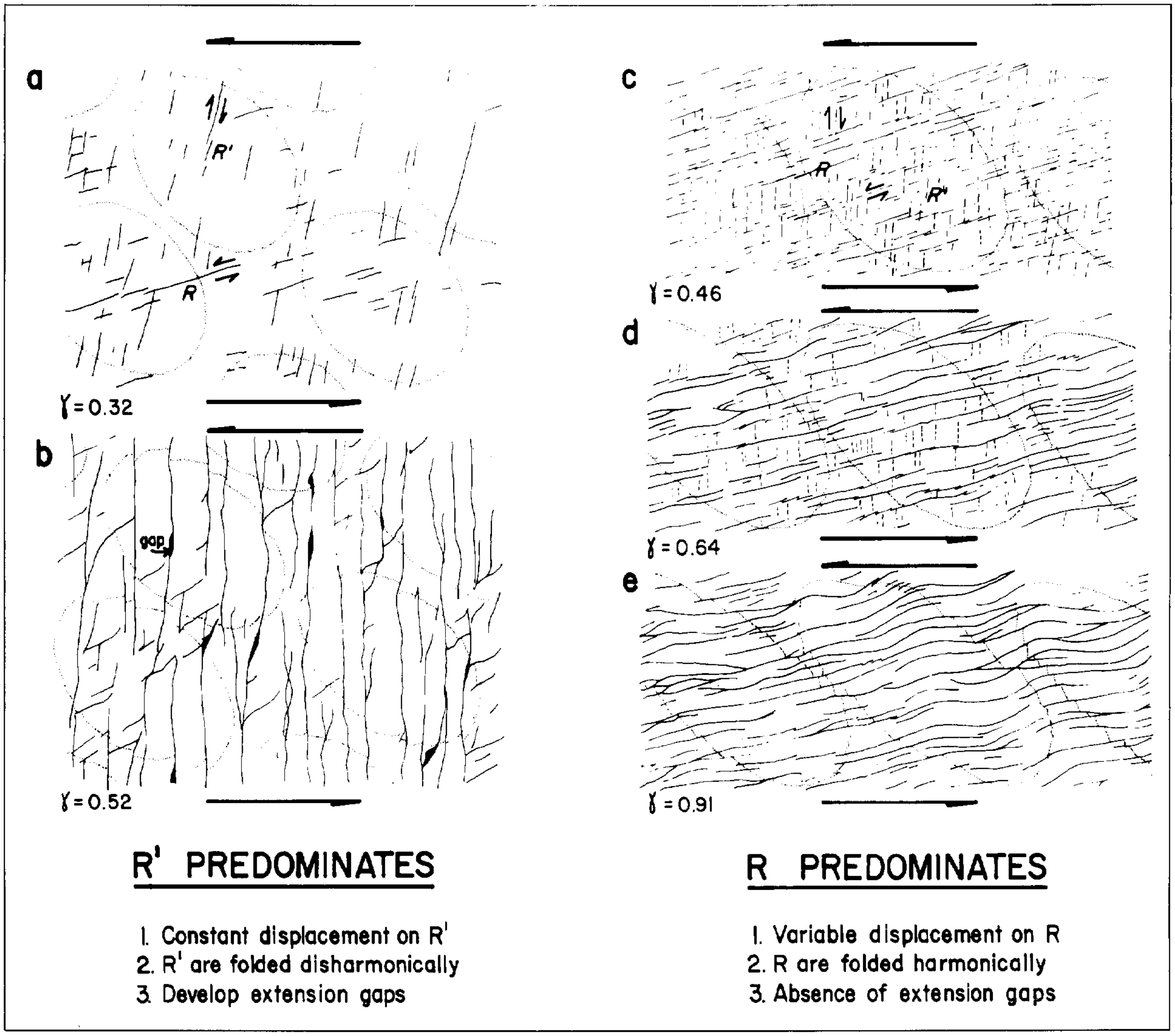

Figure 5—Experimental models in which either Riedel (R) or conjugate Riedel (R′) shear faults predominate. For equal magnitudes of same shear strain (γ), either fault type may develop, each type having distinctive physical characteristics (after Freund, 1974).

planes between oil-filled reservoirs in the Sergi Formation and unfilled reservoirs in the Ilhas and Sao Sebastiao Formations (Aptian, Figure 12). The potential stratigraphic traps developed during deposition of the Ilhas and Sao Sebastiao Formations as well as the structural traps formed during fault rejuvenation could thereby have been filled by secondary migration of oil originally in Sergi reservoirs. This then explains the observation that sub-Candeias reservoirs are associated with corners of diamond-shaped fault blocks whereas younger, super-Candeias reservoirs are associated with other trap types (e.g., rollover folds to second-phase faults, stratigraphic pinch-outs, or diapirs). This speculation could be further tested geochemically.

Double Rifts, Heat Flow, and Source Maturity

It was demonstrated that a high heat-flow history early in the basin's evolution explains the thermal maturity of source materials in the Reconcavo basin. Because the crust-mantle interface thins beneath the basin and thickens again both eastward and westward, the crustal geometry of northeastern Brazil mirrors very closely that of the modern-day southwestern Red Sea, where a double rift zone is developed (Lowell et al, 1975) (Figure 13). There, the double rifting caused extension of the continental crust over a broader area than would be achieved by single rifting (Figure 13). Moreover, double rifting leads to higher heat-flow regimes beneath each of the two Red Sea rift zones separated by cooler and thicker intervening zones (Lowell et al, 1975). The early thermal maturity of the Lower Cretaceous oil source units in the Santa Amaro Group may be related to a higher heat-flow regime developed during the process of continental extension coeval with the breakup of the South American and African plates (Rabinowitz and LaBrecque, 1979). Therefore, the Reconcavo basin is a failed, mega half-graben that predates continental separation along the Brazilian margin between Salvador and Recife.

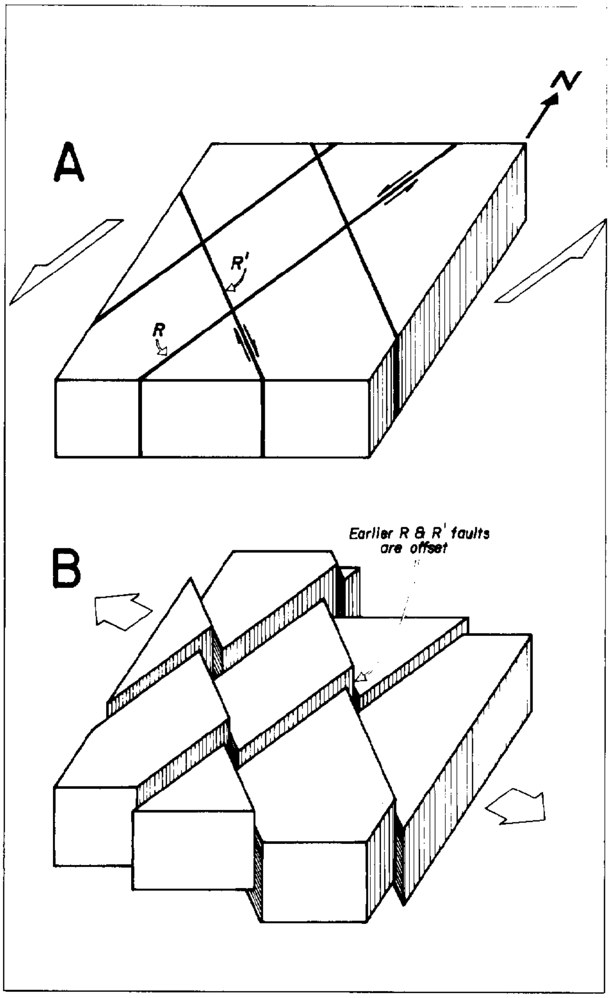

Figure 6—Block diagram illustrating inferred two-phase fault history for Reconcavo basin. A. Latest Jurassic-Early Cretaceous shear oriented N40°E (parallel with modern-day Salvador-Recife continental margin) forms Riedel shears trending N30°E ± 20° and N37°W ± 12° (shown) and tension faults trending N13°W ± 6° (not shown). B. Mid-Cretaceous, northwest-southeast extension causes dip-slip on preexisting faults. This pattern of shear then extension is related to Aptian pole jump during breakup of South America and Africa (see text for discussion).

SUMMARY

From a structural analysis, it is deduced that the Reconcavo basin formed during the Early Cretaceous in a position at the southern end of a north-south-trending, mega half-graben. This tensional feature extends northward from the Reconcavo basin, through the Tucano and Jatoba basins. The Reconcavo basin formed during the Valanginian when the South American and African plates began to separate. Because the pole for this phase of plate rotation was within northern Brazil, the nature of motion along northeastern Brazil's continental margin from Salvador to Recife was dominated by left-lateral shear oriented N40°E. This could have caused the three observed fault sets in the Reconcavo basin: (1) a predominant set striking N30°E ± 20° (1 γ), and two lesser developed sets striking (2) N13°W ± 6° and (3) N37°W ± 12° (1 γ).

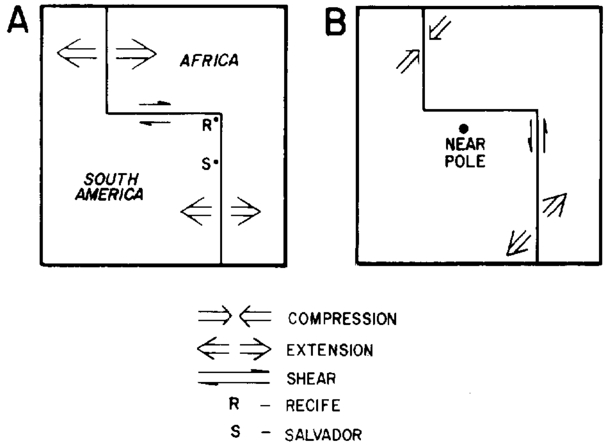

Figure 7—Effect of nearby versus distant poles of rotation on nature of deformation on same continental configuration. A. With distant pole, all margins undergo either extension or shear. B. With nearby pole, shear, extension, and compression may develop. Moreover, shear occurs in near-pole case where extension would occur in distant-pole case.

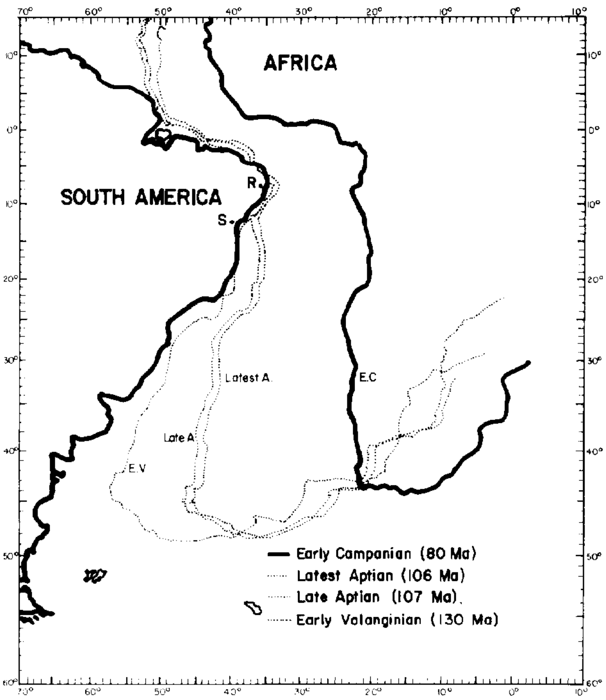

Figure 8—Plate tectonic interpretation of South America-Africa breakup pattern based on magnetic and gravity data (after Rabinowitz and LaBrecque, 1979). South America is in its present-day position. During Valanginian to late Aptian, South American continental margin between Salvador (S) and Recife (R) acted as conservative plate margin (transform fault), whereas after the Aptian it acted as extensional margin. This change was due to pole jump from near 2.5°S, 45.0°W, to 41.3°N, 43.8°W, in latest Aptian (see text for discussion).

Sets (1) and (3) are interpreted, respectively, as Riedel and conjugate Riedel shears (with an extensional compo-

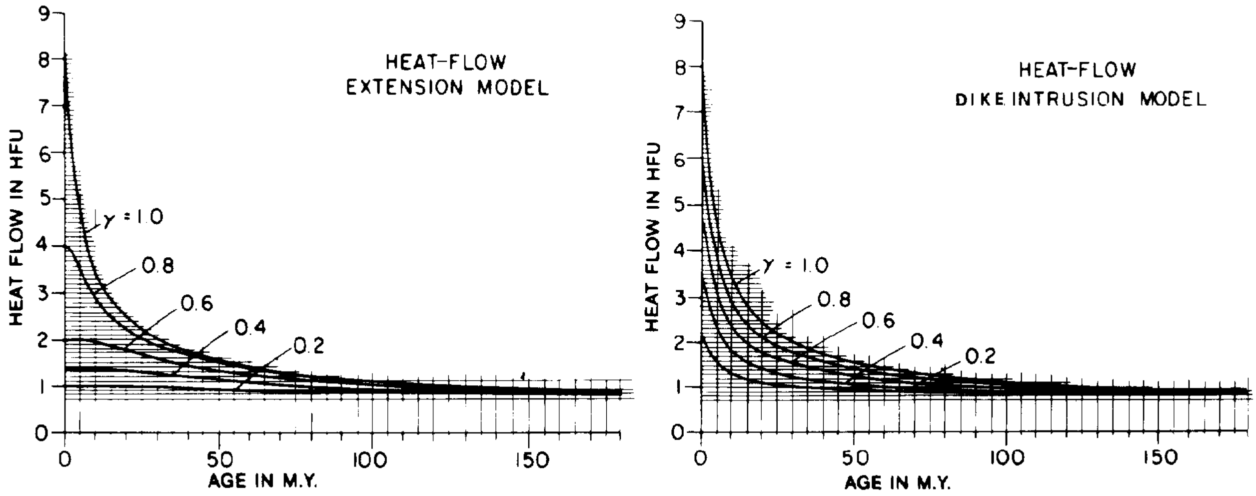

Figure 9—Heat-flow diagrams. Two models of heat-flow evolution of continental margins, dike injection, and instantaneous extension, provide quantitative estimates of geothermal gradients and source maturities in given basin (after Royden et al, 1980).

nent) to the inferred N40°E-trending left-lateral shear couple. Set (2) formed as an extensional fault and, indeed, it parallels the Reconcavo basin.

According to thermal studies of the Reconcavo basin, syntectonic Valanginian shales of the Candeias Formation (Santo Amaro Group) could have begun to generate liquid hydrocarbons during the ?Hauterivian when deposition of the overlying Ilhas Formation (Massa Cara Group) began.

Diamond-shaped fault traps formed during Valanginian deformation are interpreted to have received hydrocarbons generated in the Candeias Formation during the ?Hauterivian. These hydrocarbons migrated into sandstone reservoirs of the Sergi Formation (?Upper Jurassic).

In the latest Aptian, the pole of South American-

Table 1. Heat-Flow (Q) and Geothermal-Gradient (GG) History for Reconcavo Basin

Time (Ma)	Q (HFU)	GG (K)*
130	4.0	70
125	3.6	60
120	2.9	50
115	2.5	40
110	2.2	40
105	2.0	30
100	1.9	30
95	1.8	30
90	1.7	30
85	1.6	30
80	1.5	30
75	1.5	30
70	1.4	20
65	1.3	20
60	1.3	20
55	1.2	20
50	1.2	20
45	1.2	20
40	1.1	20
35	1.1	20
30	1.1	20
25	1.0	20
20	1.0	20
15	1.0	20
10	1.0	20
5	1.0	20
0	0.9	20

*K = 6×10^{-3} cal cm^{-1} sec^{-1} $°C^{-1}$.

Table 2. TTI Calculation for Reconcavo Basin

Temperature Interval °C	r^n	Δ Time (m.y.)	Interval TTI	Total TTI
	Top of Brotas Group			
20-30	2^{-8}	0.715	0.003	0.003
30-40	2^{-7}	0.715	0.006	0.009
40-50	2^{-6}	0.715	0.011	0.020
50-60	2^{-5}	0.715	0.022	0.042
60-70	2^{-4}	0.715	0.045	0.087
70-80	2^{-3}	0.715	0.089	0.176
80-90	2^{-2}	0.715	0.179	0.355
90-100	2^{-1}	0.715	0.358	0.713
100-110	2^{0}	0.715	0.715	1.428
110-120	2^{1}	0.715	1.430	2.858
120-130	2^{2}	0.715	2.860	5.718
130-140	2^{3}	0.715	5.720	11
140-150	2^{4}	0.715	11	23
150-160	2^{5}	0.715	23	46
160-170	2^{6}	0.8	51	97
170-180	2^{7}	0.8	102	199
180-190	2^{8}	0.8	205	404
190-200	2^{9}	0.8	410	813
200-210	2^{10}	0.8	819	1633
210-220	2^{11}	4.0	8192	9825
210-200	2^{10}	3.7	3789	13614
200-190	2^{9}	2.9	1485	15098
190-180	2^{8}	3.1	794	15892
180-170	2^{7}	4.3	550	16443
170-160	2^{6}	4.0	256	16699
160-150	2^{5}	5.5	176	16875
150-140	2^{4}	7.0	112	16987
140-130	2^{3}	11.0	88	17075
130-120	2^{2}	17.5	70	17145
120-110	2^{1}	27.0	54	17199
110-100	2^{0}	31.0	31	17230

continued.

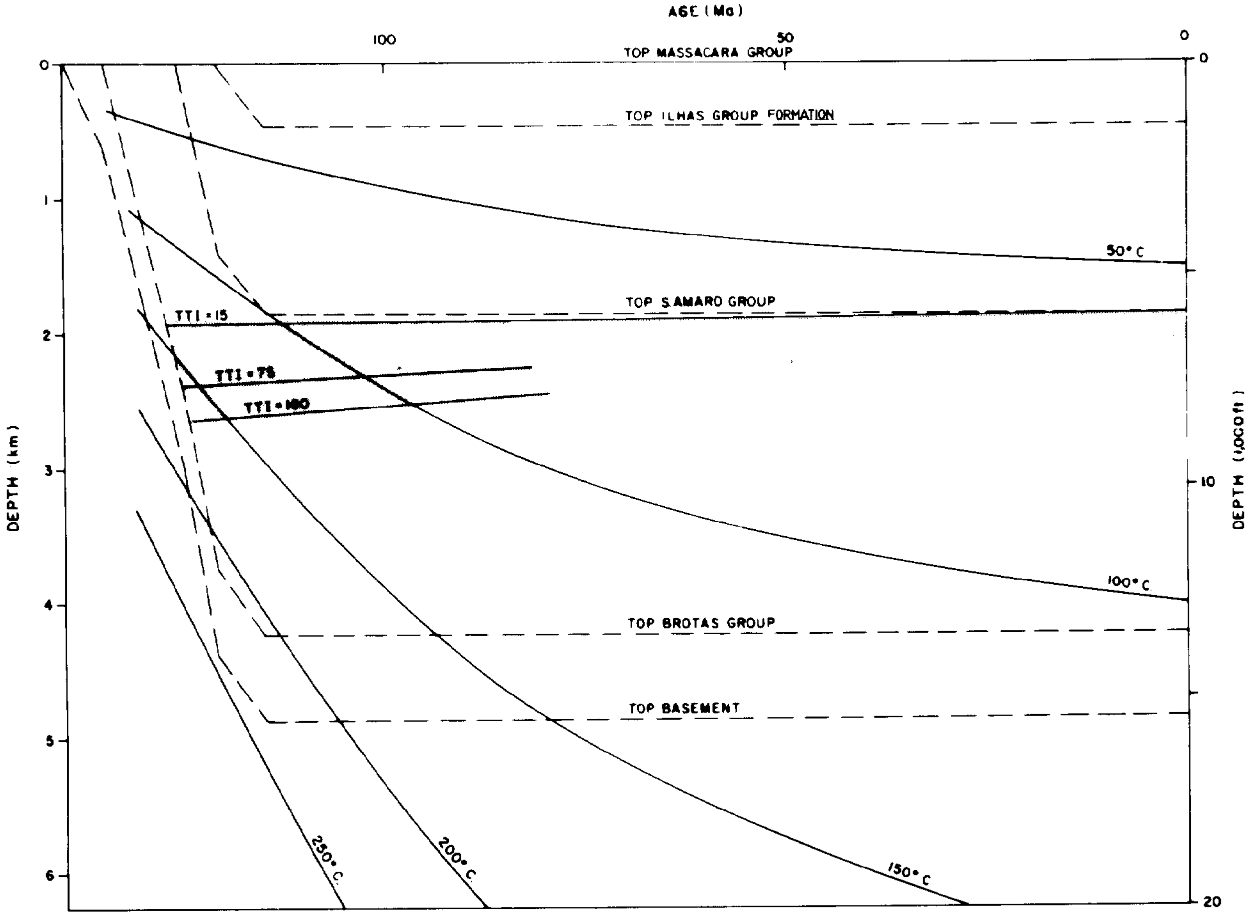

Figure 10—Thermal-burial history curve for units in Reconcavo basin. Included are basement, Brotas Group, Santo Amaro Group, and Massacara Group. Thermal gradient evolution with time as calculated from Figure 9 and Table 1. Also shown are time-temperature interval (TTI) values for initiation (15), zenith (75), and termination (160) of oil generation.

Table 2. Continued

Temperature Interval °C	r^n	Δ Time (m.y.)	Interval TTI	Total TTI
Top of Santo Amaro Group				
20-30	2^{-8}	0.57	0.002	0.002
30-40	2^{-7}	0.57	0.004	0.006
40-50	2^{-6}	0.57	0.009	0.015
50-60	2^{-5}	0.57	0.018	0.033
60-70	2^{-4}	0.57	0.036	0.069
70-80	2^{-3}	0.57	0.071	0.140
80-90	2^{-2}	0.57	0.142	0.282
90-100	2^{-1}	13.50	6.75	7.032
90-80	2^{-2}	9.50	2.375	9.407
80-70	2^{-3}	18.0	2.25	11.657
70-60	2^{-4}	50.0	3.125	14.782
60-50	2^{-5}	30.0	0.936	15.718

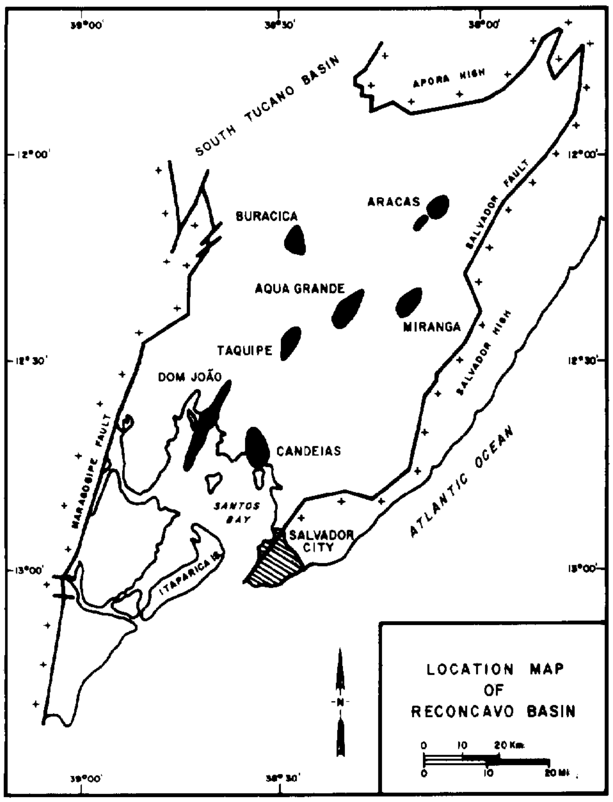

Figure 11—Major oil field location map, Reconcavo basin.

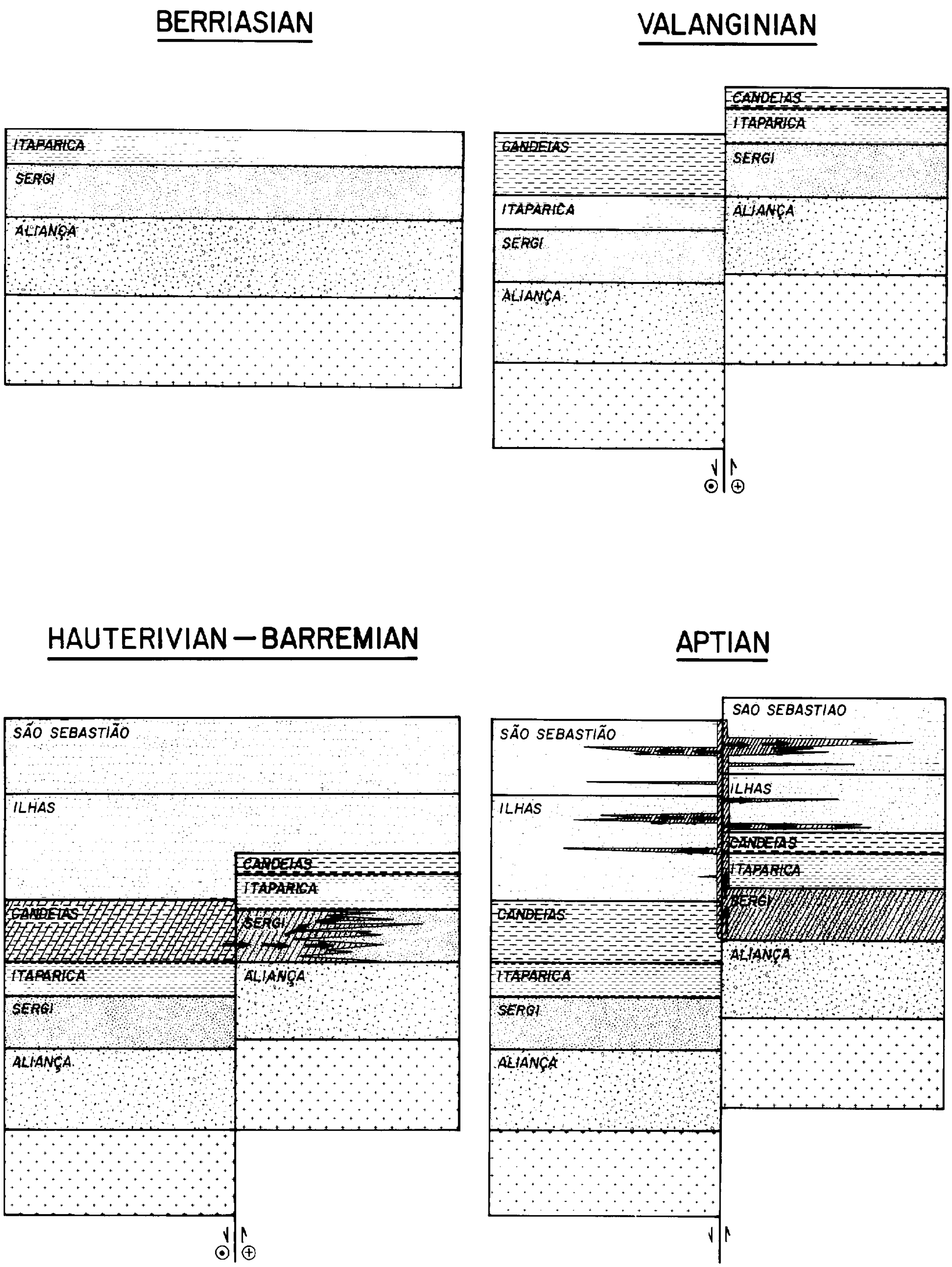

Figure 12—Hypothetical evolution of hydrocarbon generation from Berriasian through Aptian. Diagonal pattern represents oil generation; arrows indicate migration pathway.

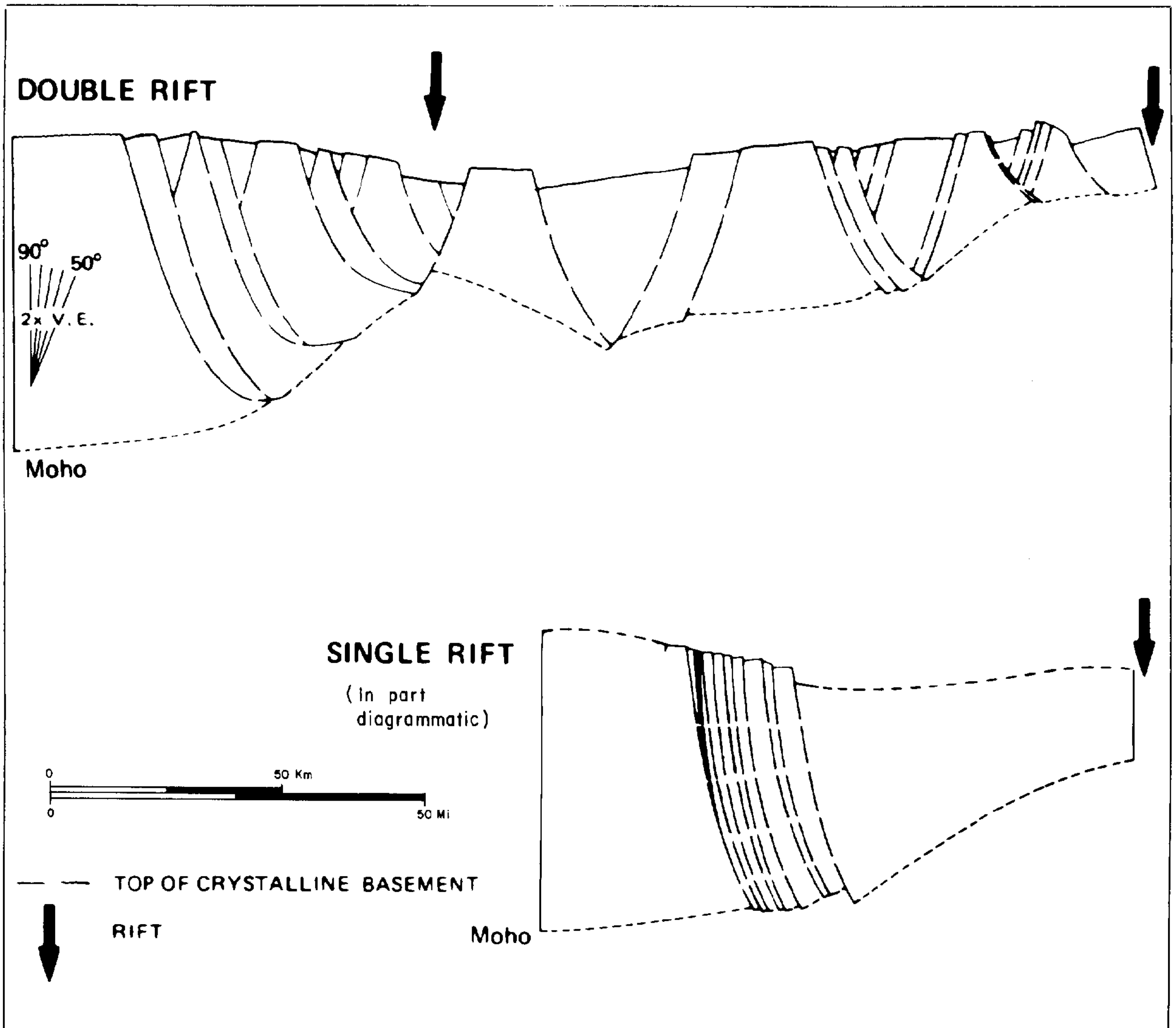

Figure 13—Structural profiles (2 × vertical exaggeration) of single and double rifts (after Lowell et al, 1975).

African plate rotations jumped to 41.3°N, 43.8°W. This jump resulted in extension along the previously formed conservative plate margin between Salvador and Recife and in rejuvenation as normal faults of preexisting faults in the Reconcavo basin. This fault rejuvenation allowed a tapping of earlier filled Sergi Formation reservoirs, causing leakage along fault planes into stratigraphically higher reservoirs in the overlying Ilhas and Sao Sebastiao Formations.

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