Subduction and Oil Migration

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ABSTRACT

Petroleum and natural gas pools are abundant within the thick prisms of sediment deposited along many rifted continental margins. Where crustal collisions that assemble composite continents occur, the rifted-margin sediment prisms are drawn down against and beneath the suture belts thus formed. During such partial subduction, fluid hydrocarbons may be driven updip away from the subduction zones to accumulate in reservoirs along adjacent platform margins and within growing foreland fold-thrust belts. The immense petroleum accumulations of the Persian Gulf province southwest of the Zagros suture belt may owe their origin to this process. Similar oil migration in response to partial subduction may have influenced the distribution of petroleum in foreland basins generally; if so, strategies for exploration can perhaps be improved by taking this factor into account.

INTRODUCTION

> Large total pore volume is not an exclusive property of the Persian Gulf synclinorium, an area which excels only because the reservoir pore space is filled with oil.
>
> Kamen-Kaye, 1970, p. 2391.

Although at least half the world's known reserves of crude oil are located along the Persian Gulf within a triangular area about the size of Texas, the ultimate reasons for their location there remain uncertain. Special conditions are suggested by the fact that a high proportion of the reservoirs are full to the spill point. I present here a speculative conclusion on the nature of the governing geologic control based on the nearly unique plate tectonic setting of the Persian Gulf. My analysis assumes possible direct relations between plate movements accompanying subduction and the opening of migration paths for petroleum (see also Ellison, 1974).

RIFTED-MARGIN SEDIMENT PRISMS

In plate tectonic theory, ocean basins are initiated by continental separations that begin with intracontinental rifting. When full separation of continental fragments is thus achieved, the raw edges of continental blocks along rifted continental margins are in preferred positions to receive thick prisms of sediment composed both of debris washed off the adjacent continental blocks and of biogenic calcareous materials deposited in shoal areas at the flanks of the adjacent oceans. These rifted-margin sediment prisms are deposited initially both on fault-segmented quasicontinental crust, formed by extensional attenuation of continental basement drawn out thin during continental separation, and also on oceanic crust offshore where the continental rise is constructed.

The growing rifted-margin sediment prism (Fig. 1) imposes sufficient load on the lithosphere near the interface between old continental and new oceanic crust to induce downbowing of the lithosphere by flexure (Walcott, 1972). This flexure tilts the surface of the continental block seaward to allow landward parts of the rifted-margin sediment prism to encroach as much as 100 to 250 km beyond the initial continental edge, which may be depressed as much as 2.5 to 5 km. In time, continued growth of the rifted-margin sediment prism may also allow its oceanward edge to advance well into the adjacent oceanic basin until the continental shelf, and perhaps even part of an accretionary coastal plain, come to stand above fully oceanic basement. This type of rifted-margin sediment prism, developed by wholesale sedimentary progradation of the continental edge, was aptly termed a continental embankment by Dietz (1963). The term serves to distinguish such a progradational feature from the continental terrace-slope-rise configuration, which is characteristic where actual sedimentary progradation of the continental slope is slight, although depositional covering and masking of the initially raw continental edge may be extensive.

Accumulations of petroleum in rifted-margin sediment prisms are well known. The natural association of offshore source beds and nearshore reservoir beds of various kinds is inherent. In addition, two effects combine to exert a pumping action that drives fluid hydrocarbons updip from offshore source beds into favorable reservoir beds: (1) the progressive loading of offshore source beds due to depositional growth of the rifted-margin prism, and (2) the progressive seaward tilting of the continental edge and the successive layers of the rifted-margin prism due to flexural bending of the lithosphere under the growing sedimentary load offshore. These effects are probably most influential within fully developed continental embankments where potential conduit beds, intercalated with sealing beds, connect offshore source beds with inshore facies suitable as reservoir beds without interruption by thin-slope facies. Dietz (1963) initially applied the concept of continental embankment to the sedimentary prism of the Texas-Louisiana Gulf Coast, a region that contains at least half the known reserves of crude oil in the conterminous states.

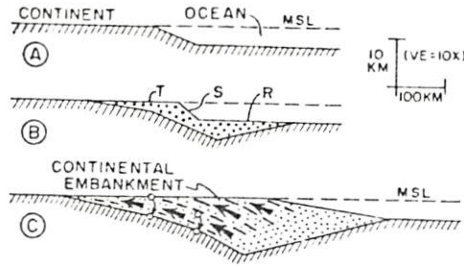

Figure 1. Growth (schematic) of rifted-margin sediment prism (stippled). A, rifted continental margin without sedimentation; B, continental terrace (T)–slope (S)–rise (R configuration; C, progradational continental embankment; small arrows show rotational tilt of basement along continental margin downward toward ocean basin; heavy arrows show updip migration of hydrocarbons parallel to bedding (dashes).

CONTINENTAL COLLISIONS

In plate tectonic theory, composite continents are assembled by crustal collisions that occur when the consumption of oceanic lithosphere beneath arc-trench systems results in closure of an oceanic basin. Crustal collision is an apt term because continental blocks of thick crust offer gravimetric resistance to plate consumption (McKenzie, 1969). The arrival of a continental block at a subduction zone where the intervening oceanic lithosphere was consumed will thus throttle subduction, and the position of the previous subduction zone will be taken by a crustal suture belt marking the line of tectonic juxtaposition of the two continental blocks involved in the crustal collision. Figure 2 illustrates cases of continental collision in which one of the continental margins has a marginal arc-trench system and the other has a rifted-margin sediment prism.

The surface of oceanic lithosphere is depressed from 2.5 to 5 km below the ordinary level of the ocean floor where it enters a trench to descend beneath the associated subduction zone. Presumably, at least the seaward part of a rifted-margin prism is initially depressed by a similar amount when a rifted continental margin first begins to encounter a subduction zone in the early stages of continental collision. As collision proceeds, partial subduction of some tilted offshore part of the rifted-margin prism may be expected to occur. As collision moves toward completion, with the two continental blocks locked together across a suture belt, progressive deformation of the rifted-margin prism may be expected to develop sequentially from distal to proximal parts of the prism. Deformation is coeval initially with partial subduction and later with uplift along and near the suture belt after plate consumption is wholly arrested. While partial subduction is underway prior to final suturing, a foreland basin may be expected to develop above the pre-existing rifted-margin prism, and the foreland fold-thrust belt will display tectonic transport away from the closing suture belt.

Under the circumstances outlined, fluid hydrocarbons contained within the rifted-margin prism prior to continental collision may be driven updip away from the subduction zone. During early stages of collision, they may enter reservoir horizons beneath the foreland basin, and during later stages they may enter reservoirs within the folded flank of the foreland basin.

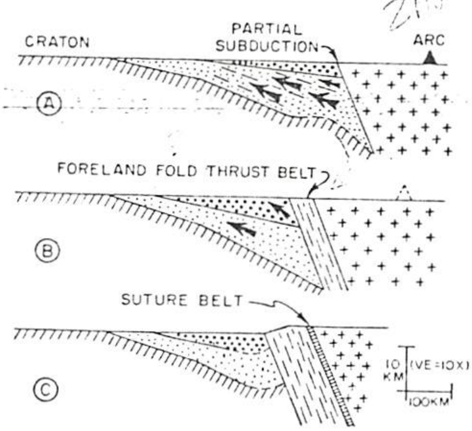

Figure 2. Development (schematic) of foreland basin (heavy stipples) and suture belt from continental collision between arc-trench system (crosses) and rifted-margin sediment prism (light stipples). A, early stage of encounter; B, full collision; C, postcollision uplift of foreland fold-thrust belt. Heavy arrows show induced migration of hydrocarbons.

PERSIAN GULF

The geologic history of the Persian Gulf province (Fig. 3), including the Zagros belt, was marked by (1) late Paleozoic and (or) early Mesozoic continental separation followed by growth of Mesozoic ocean floor, (2) late Mesozoic and early Tertiary plate consumption resulting ultimately in oceanic closure, and (3) late Tertiary continental collision and suturing (Dewey and others, 1973). I suggest that oil migration related to partial subduction along the Zagros suture belt may be the crucial factor that accounts for the extraordinary productivity of the Persian Gulf province.

Similar stratigraphic sections that appear laterally continuous (Stöcklin, 1968, Fig. 2) suggest that Arabia and Iran were connected parts of a single African continental block lying south of Tethys from "Infracambrian" through mid-Triassic times. The tectonic unity of Iran then and later is suspect, but the important point is the lack of clear evidence for stratal or structural discontinuity across the Zagros belt much prior to early Mesozoic time. Partition of the pre-existing platform occurred along the Zagros trend by Late Triassic time (Stöcklin, 1968, p. 1240) and may have been a mid-Permian event, if widespread transgression in Arabia is a valid indicator (Kamen-Kaye, 1970, p. 2373). Jurassic and Cretaceous rocks display marked stratal discontinuity across the Zagros Crush Zone, which developed after mid-Miocene time (Wells, 1969). From the presence of ophiolitic assemblages (Crawford, 1972, p. 108) among the deformed Jurassic to Pliocene rocks (Wells, 1969, p. 390) of the Zagros Crush Zone, the partition of the platform is inferred to have been a full continental separation to form a belt of Mesozoic oceanic crust that lay between central Iran on the northeast and Arabia plus the Persian Gulf region to the southwest. The Zagros Crush Zone is thus seen as a crustal suture belt formed by late Tertiary continental collision. The vergence of late Cenozoic folds in the Zagros Range on the Arabian side of the suture and the presence of arc-type intrusions and volcanic rocks of late Mesozoic and early Tertiary age on the Iranian side of the suture indicate the polarity of subduction during oceanic closure and continental collision (Vialon and others, 1972). An Arabian Gulf plate passed beneath a central Iranian plate (Crawford, 1972, p. 108).

Late Cretaceous obduction of ophiolites along the Oman flank of the Arabian block (Allemann and Peters, 1972) has uncertain significance in the plate tectonic evolution of the region. Two points of view appear conceivable: (1) Any major effects of this event were confined to the region along and east of the Oman Line, which separates the Zagros orogenic belt from the Makran region (Ahmed, 1969) on tectonic strike to the southeast; and (2) the event marks the initiation of crustal collision between the Arabian Gulf block and central Iran (see Takin, 1972). The latter view (Haynes and McQuillan, 1974) is apparently favored especially by the presence of eastern-derived chert clasts in the uppermost Cretaceous and Paleocene section of the Zagros Range (James and Wynd, 1965, p. 2197, 2220).

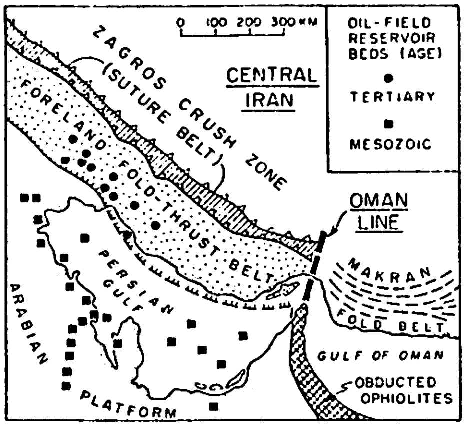

Figure 3. Sketch map showing tectonic position of Persian Gulf oil fields. (For rough analogy with model of Fig. 2, Mesozoic sequence is rifted-margin prism and Tertiary sequence is foreland basin fill.)

Kamen-Kaye (1970) showed that the sediment prism beneath the Persian Gulf province has the gross form of an asymmetric synclinorium. The gentle southwestern flank is draped across the edge of the Arabian platform, and the steep northeastern flank is tucked against and beneath the Zagros fold-thrust belt. Isopachs of sediment thickness reflect the overall form of the synclinorium well only for the Tertiary, during which time a foreland basin was present. Isopachs for Mesozoic strata suggest accumulation as a rifted-margin prism upon an extensively fragmented continental margin open toward the northeast, where Cretaceous radiolarites and flysch are present along and near the Zagros Crush Zone.

Major oil fields occur in two main settings: (1) in Mesozoic strata of broad arches and structural terraces near the flank of the Arabian platform on the southwest flank of the synclinorium, and (2) in Tertiary strata of tight folds in the Zagros foothills above the axial region of the synclinorium. During partial subduction prior to final uplift of the Zagros Range, oil could have been driven updip into tilted strata of the combined rifted-margin prism–foreland basin sequence of the Persian Gulf synclinorium during late Cenozoic time, and at times as early as the late Mesozoic as well if the Zagros collision was multistage. Presumed sources were thus strata that were depressed and loaded both depositionally beneath the subduction-related foreland basin and tectonically beneath the sequentially developed fold-thrust belt and within the associated subduction zone of the suture belt.

Kent and Warman (1972) reached several conclusions that together tend to support this interpretation: (1) the dominantly platform sedimentary successions in the drilled oil-field sections are remarkably deficient in conventional source rocks; (2) there is widespread evidence for synorogenic and postorogenic migration of oil into structures that were not effective traps at earlier stages in structural development; and (3) although the oil is distributed in reservoirs ranging from Jurassic to Miocene in age, a generic similarity in the fundamental chemical composition of oils throughout the province implies some commonality of origin. The most likely reported sources for the oils are basinal limestone and marine shale of offshore facies laterally equivalent to shelf strata in the oil fields but lying to the northeast (Dunnington, 1958), or toward the Zagros subduction zone. The oil fields thus lie on the southwest flank of the restored basin in which the probable source beds occur (Falcon, 1958).

Alternative explanations for the unmatched productivity of the Persian Gulf province invoke other special conditions whose efficacy can be challenged. Prolific carbonate reservoirs with unusually effective evaporite caprocks are widespread, but large estuarine sand reservoirs with modest shale caprocks are also important in the province. The intriguing suggestion that source beds and reservoir beds are intercalated in almost unique fashion encounters the difficulty that such presumed source beds commonly are not now demonstrably petroliferous (Kamen-Kaye, 1970, p. 2391–2392) and may never have been. A recent argument by Irving and others (1974) rests on the paleogeographic setting they infer for the Persian Gulf province, but other sites shown to have similar settings are not so rich in petroleum; indeed, most striking to me is their demonstration that world oil reserves as a whole, *exclusive* of the Persian Gulf province (whose existence imposes a dominating bias), are uniformly distributed with regard to paleolatitude. I conclude that the history of subduction adjacent to the Persian Gulf province has enhanced greatly the effectiveness of all other conditions favorable for petroleum accumulation and is the crucial factor that has made the concentration of reserves there apparently unique in the world.

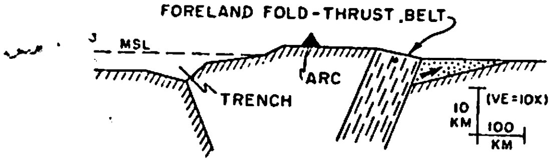

Figure 4. Tectonic position (schematic) of foreland basin (stippled) behind magmatic arc instead of adjacent to suture belt. (Arrow shows oil migration in response to partial subduction during limited underthrusting of foreland beneath rear flank of continental margin arc.)

FORELAND BASINS

As noted by Coney (1973), back-arc thrusting is associated with the development of foreland fold-thrust belts and foreland basins that occur in continental interiors behind continental margin arc-trench systems (Fig. 4). Partial subduction, in this case related to strictly limited underthrusting of the cratonic foreland beneath the *rear* flank of the arc, may thus influence oil migration along the orogenic flanks of *all* pericratonic foreland basins, regardless of whether the adjacent orogen is a collision orogen or an arc orogen.

In discussing oil migration in Wyoming, Sheldon (1967) argued that the oil now in late Paleozoic reservoir beds in central Wyoming was driven updip from organogenic source beds in the Phosphoria Formation now exposed in the Idaho-Wyoming thrust belt some 100 to 250 km west of the producing fields. He attributed the "driving force for the eastward fluid migration" to "the differential loading of the sedimentary rocks during development of the Cordilleran miogeosyncline, . . . as well as tectonism in the miogeosyncline" (Sheldon, 1967, p. 53). In brief, the oil migration was in response initially to sedimentary loading and flexure during Paleozoic time along the Cordilleran continental margin formed by Precambrian rifting, and later to Mesozoic tectonic loading and flexure beneath a foreland fold-thrust belt along the flank of a foreland basin lying east of the batholith belt that marks the position of a magmatic arc initiated in Mesozoic time along the continental margin (see, for example, Coney, 1974). By drawing reconstructed paleostructure contours on late Paleozoic horizons as they lay beneath the Cretaceous foreland basin prior to full development of the encroaching fold-thrust belt, Sheldon (1967, p. 61–62) showed that regional dips of the order of 20 m/km existed across the region.

As the basement beneath foreland basins can be drawn down 5 km or more, with structural depths increasing toward the orogenic belts, Sheldon's method of drawing paleostructure contours is essential to gain a correct view of regional dips during times of potential oil migration driven by partial subduction. The configuration of a foreland basin floor after post-thrusting uplift has raised the flanking fold-thrust belt is not an accurate guide to its configuration when underthrusting was underway. A correct reconstruction of paleostructure contours for such a possibly critical period in basin evolution could influence strategies for petroleum exploration.

SUMMARY

The largest reserves of petroleum are inferred here to accumulate where conditions are most favorable for long-distance updip migration of oil from offshore source beds into attractive reservoirs in nearshore deposits along or near platform margins. The requisite regional dips and overburden loads are attained within the sediment prisms deposited along rifted continental margins and also beneath foreland basins associated with foreland fold-thrust belts adjacent to major orogens. Apparently optimum relations for oil concentration thus occur in the Middle East where a rifted-margin sediment prism was drawn partly into a subduction zone, now a suture belt marking the site of continental collision, and was partly buried beneath a foreland basin sequence.

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