



Subduction zones and their hydrocarbon systems

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ABSTRACT

Subduction zones are common tectonic features central to large-scale crustal and elemental cycling, and they are accompanied by basins often with thick sedimentary fill and structures suitable for hydrocarbon preservation. However, significant hydrocarbon production occurs in only a handful of subduction zone locations. Here we explore our current understanding of the controls on hydrocarbon systems associated with subduction zones, in terms of the strongly variable conditions inherent to this tectonic setting that either favor or limit petroleum production, and in the context of three case studies (Cook Inlet and Sacramento basins, USA; Talara basin, Peru). This review concentrates on continental rather than intra-oceanic subduction settings due to limited basin preservation and hydrocarbon prospectivity in the latter. Overall, the primary limitations on hydrocarbon potential in forearc and/or trench-slope basins are time-to-maturation (low geothermal gradients), reservoir quality, source-rock presence and quality, structural complexity, and depth to reservoir. The latter two conditions may explain why offshore exploration has been limited near subduction zones, even where onshore production is robust and/or hydrocarbon seeps are common. Prospectivity may increase with enhanced seismic imaging and offshore infrastructure in some locations, and with the economic development of unconventional resources such as gas hydrates in accretionary prisms or deep shale gas in forearc basins. In any case, the presence of hydrocarbon systems in subduction zones, whether prospective or not, is an important part of the cycling of carbon and other elements at active convergent margins.

INTRODUCTION

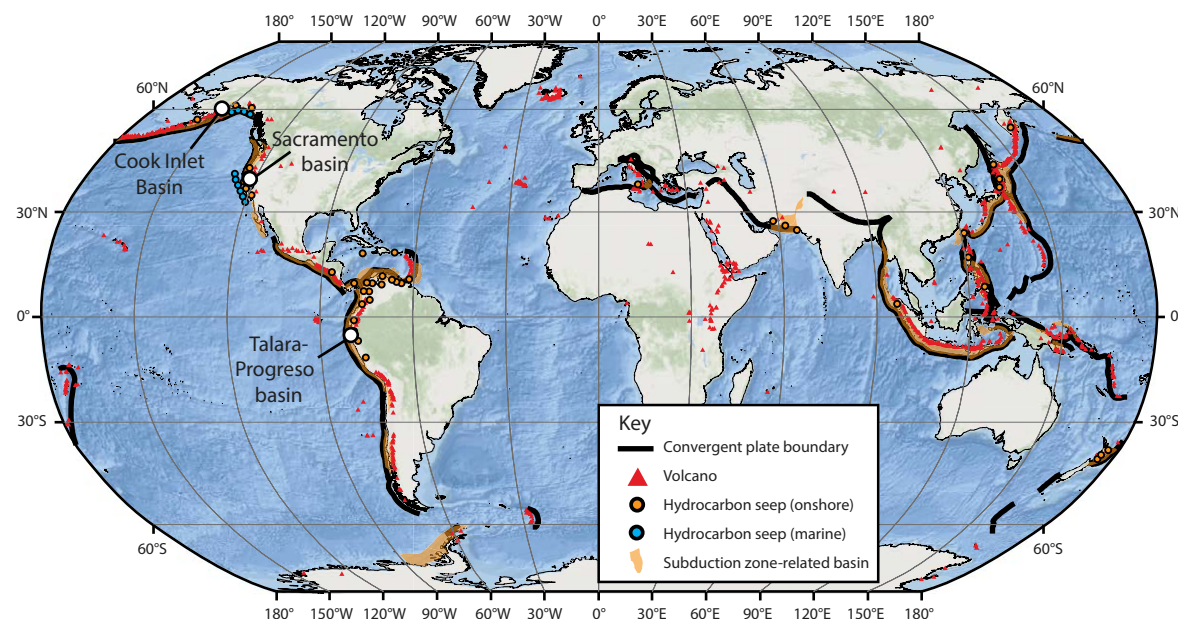
Subduction zones are prominent tectonic features that form along most of Earth's convergent plate boundaries, and they are responsible for large-scale cycling of crust and fluids into the mantle. Their ancient counterparts have been observed within collisional terranes such as the Alpine-Himalayan (e.g., Garzanti and van Haver, 1988; Kazmer et al., 2003) and Appalachian-Caledonide (e.g., Dewey, 1971; Leggett et al., 1982) belts or along transitional strike-slip margins as in southern California (USA) (e.g., Dickinson, 1970). Approximately 45,000 linear km of subduction zones exist on Earth's surface (Fig. 1), with accompanying thick marine to nonmarine sedimentary accumu-

lations, structural complexity, and opportunities for organic output and burial. Despite these seemingly favorable conditions for active petroleum systems, subduction zones are generally considered one of the least prospective basin types for commercial petroleum production (Dickinson and Seely, 1979; Dickinson, 1995). Of the ~1700 billion barrels of oil (BBO) total world commercial oil reserves (BP Energy Outlook, 2017), only ~4 BBO have been produced from forearc and trench-slope basins (Table 1), as opposed to the prolific hydrocarbon production from other convergent-margin settings such as foreland basins (Howell, 1993).

However, evidence for petroleum generation is widespread in subduction-related basins: oil and gas seeps, hydrocarbon shows in petroleum exploration wells, and geographically limited but locally significant petroleum production (Fig. 1). In addition to the implications for the carbon cycle, which is globally significant at convergent margins (e.g., Kelemen and Manning, 2015), this suggests that conditions for organic-rich source-rock maturation, the foundation of any working petroleum system (Tissot and Welte, 1978), are widespread within subduction zones. Geologic theory suggests that the number of oil and gas fields of a given size, as well as the total per-field resource, should follow a log-normal distribution, with numerous small accumulations and few large ones (Kaufman, 1964; Thomas et al., 2004). Subduction-related basins, on the other hand, display a skewed distribution of proven petroleum reserves (Fig. 2), with a disproportionately high percentage having significant (≥ 1500 million barrels of oil equivalent [MMBOE]) cumulative production and the majority of remaining basins having very minor (< 15 MMBOE) historical production (Table 1). Subduction zones, particularly the offshore portions of forearc basins, may be poorly explored relative to other tectonic settings, and their low prospectivity may to some degree represent a missed opportunity.

This manuscript provides a thorough examination of the controls specific to hydrocarbon occurrence and production in subduction zones, in particular within forearc basins along continental margins, where there is high preservation potential compared with intraoceanic basins. Our review is aimed at understanding the reasons behind the highly skewed distribution of petroleum production in this tectonic setting, where production appears to be divided between basins with very significant or very minor hydrocarbon production. We consider the geologic factors that promote and/or suppress the development of commercial petroleum systems in subduction zones and where there might be potential for future exploration. In general, it is clear that highly variable conditions near subduction zones create many encouraging possibilities for

Figure 1. Map of the locations of modern subduction zone basins (modified from Robertson Tellus Sedimentary Basins of the World Map, accessed December 2016 from American Association of Petroleum Geologists Databases' GIS Open Files), including the distribution of subduction zone hydrocarbon seeps (from Etiope, 2009). Convergent plate boundaries and volcanoes are from The University of Texas at Austin Institute for Geophysics PLATES Project. Marked are the locations of the productive basins used as case studies.



hydrocarbon generation and preservation, but that these wide-ranging conditions can cloud predictions, especially for high-risk offshore development. Continued prospectivity in forearc and trench-slope basins, however, is reasonable due to their generally limited offshore exploration to date as well as the evolving interest in unconventional and ultra-deep resources. Finally, we recognize that improving our knowledge of hydrocarbon presence in subduction zones—in terms of volume, distribution, and migration pathways—can be used toward stronger modeling of Earth's very active carbon (and other elements) cycling at convergent margins.

THE SUBDUCTION ZONE

Architecture

We define “the subduction zone” as extending from the trench axis to the magmatic front (Fig. 3), where petroleum systems may develop within forearc and/or trench-slope basins and are directly influenced by subduction-related heat flow, deformation, and magmatism. Trench-slope basins occur in and immediately seaward of an accretionary prism, the imbricate-thrusted wedge of off-scraped oceanic and terrigenous material that develops with adequate sediment supply to the trench (Fig. 3A). Forearc basins may be isolated from the trench by a “trench-slope break” (Dickinson, 1995), the bathymetric or topo-

graphic high associated with the landward limit of subduction accretion. In a non-accreting (often extensional) subduction zone lacking an up-thrust prism (Fig. 3B), forearc sedimentation may occur nearly unimpeded into the trench, filling and/or draping horst-graben structures in an overall subsiding basin.

Large-scale subduction-zone architecture depends in part on the composition of overriding lithosphere. Continental arcs (Fig. 3A) typically contribute more sediment to the forearc and trench than oceanic island arcs, and this translates to the tendency for thicker forearc basin fill and a thicker accretionary prism associated with ocean-continent convergence (Dickinson, 1995). However, subduction zone morphology mostly varies with convergence rate and orientation, as well as descending slab age and angle (e.g., Molnar and Atwater, 1978).

The geometry of trench-slope basins depends on the supply of sediment to the trench and whether the subduction zone is accretionary or erosional (Karig and Sharman, 1975; Schweller and Kulm, 1978; Underwood and Moore, 1995). Erosional trenches, usually in association with intraoceanic convergence, are not connected to significant sources of terrigenous sediment except along continental margins with an active or exhumed arc (e.g., Talara, Peru; Fildani et al., 2008) and tend to be deep (>9000 m) and narrow (<5 km) (e.g., Mariana, Tonga; Underwood and Moore, 1995). On the other end of the spectrum are accretionary trenches where high sediment input from a continental arc (e.g., eastern Aleutian) or proximal continental drainage (e.g., southern Barbados) contributes to a shallow (3000–5000 m) and wide (>10 km) wedge.

TABLE 1. PRODUCTIVE BASINS RELATED TO SUBDUCTION ZONES (FOREARC TO TRENCH)

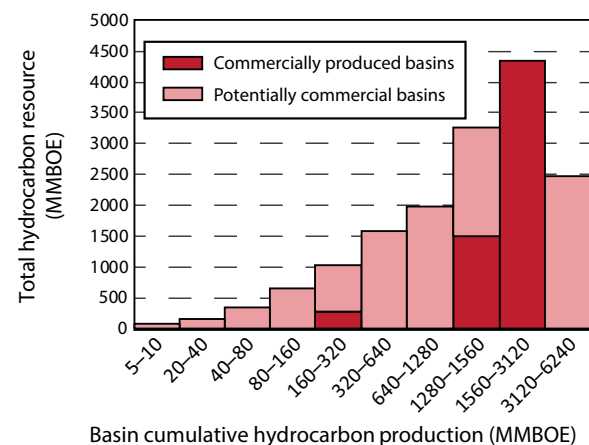
Basin	Location	Arc-trench system	Arc type ¹	Geotectonic feature	Oil production (MMBO)	Gas production (BCFG)	Total production (MMBOE)	Maximum fill thickness (m)	Reservoirs	Source rock	Traps	Reference
Cook Inlet	United States	Alaska-Aleutian	Continental (I)	Forearc	1300	7800	2600	17,000	Eocene–Pliocene fluvial and/or turbidite ss	Middle Jurassic and late Cenozoic marine shale	Anticlines; stratigraphic	Stanley et al. (2011)
Talara	Peru	Peru-Chile	Continental (I)	Forearc and trench slope	1680	340	1737	18,000	Cretaceous–Paleogene nonmarine and/or marine ss	Cretaceous–Paleogene marine shale	Block faults; stratigraphic	Higley (2004)
Sacramento	United States	Farallon-Sierra (ancient)	Continental (I)	Forearc (ancient)	12	9000	1512	20,000	Late Cretaceous–Miocene nonmarine and/or marine ss	Late Cretaceous marine shale	Anticlines; stratigraphic	Scheirer et al. (2006b); Jenden and Kaplan (1989)
Progreso	Peru-Ecuador	Peru-Chile	Continental (I)	Forearc	220	255	263	9000	Oligocene–Miocene nonmarine and/or marine ss	Oligocene–Miocene marine shale	Structural variety	Higley (2004)
Cascadia accretionary complex	United States	Pacific-Cascades	Continental (I)	Trench slope	0.0125	—	0.01	n.d.	Turbidite ss	Marine shale	Thrust anticlines	www.dnr.wa.gov website
Franciscan accretionary complex	United States	Farallon-Sierra (ancient)	Continental (I)	Trench slope	Minor	87	14.5	>3350	Pliocene turbidite ss	Marine shale	Faulted anticlines; stratigraphic	McLean (1988)
Tobago Trough	Barbados	Lesser Antilles	Intraoceanic (VI)	Accretionary prism	9	—	9	10,000	Miocene–Pliocene turbidite ss	Cretaceous–Miocene marine shale	Thrust anticlines	Schenk et al. (2012)
Joban	Japan	Northeast Japan	Intraoceanic (V)	Forearc	—	<2.25	0.4	5000	Oligocene–Miocene shallow marine ss	Cretaceous–Paleogene coal	Faulted anticlines	BP Energy Outlook (2016)
Sagara	Japan	Northeast Japan	Intraoceanic (V)	Forearc	Minor	—	Minor	n.d.	Miocene turbidite sandstone	Miocene fluvial-deltaic shale	Anticlines	Kato (1992); Yessalina et al. (2006)
Seram Island	Indonesia	Banda	Intraoceanic (VI)	Accretionary prism	9	—	9	n.d.	Triassic–Jurassic shoreline ss, reef	Triassic–Jurassic marine shale	Stratigraphic	Gribi (1973); Charlton (2002)
East Coast Basin	New Zealand	Hikurangi	Continental (I)	Forearc	Minor	Minor	—	4000	Cretaceous and/or Neogene nearshore and turbiditic sandstone	Cretaceous–Paleocene marine shales	Fault-bound anticlines; stratigraphic pinchouts	New Zealand Petroleum and Minerals, Ministry of Business, Innovation, and Employment (2014)

Abbreviations: BCFG—billion cubic feet of gas; MMBO—million barrels of oil; MMBOE—million barrels of oil equivalent; n.d.—not determined; ss—sandstone.

¹Based on categories in Dickinson (1995). I—contains mainland volcanoes within continental landmass; V—migratory system with continental basement beneath arc; VI—migratory system without continental basement in arc.

Up-thrusted blocks within the accretionary wedge create bathymetric barriers and flat-floored basins conducive to the ponding of gravity-flow sediments (Moore and Karig, 1976), especially proximal to submarine canyons serving as conduits between the forearc and the trench. These trench-slope basins tend to increase in sedimentary thickness landward toward the trench-slope break. For example, Pliocene–Pleistocene slope deposits within the Nankai accretionary prism reach thicknesses of 1200 m and pinch out seaward over a distance of <10 km against buried thrust antiforms (Ramirez et al., 2015). Siliciclastic sediment in trench-slope basins is delivered via transport transverse to the magmatic front or axial transport parallel to strike of the accretionary wedge

Figure 2. Distribution of cumulative hydrocarbon production from subduction zones based on the total basin resource size (after Thomas et al., 2004). Probability theory that assumes a log-normal basin resource distribution (Kaufman, 1964) suggests the possibility of future discoveries of commercial quantities of hydrocarbons in subduction zones. MMBOE—million barrels of oil equivalent.



A Compressional forearc (e.g., with ocean-continent convergence)

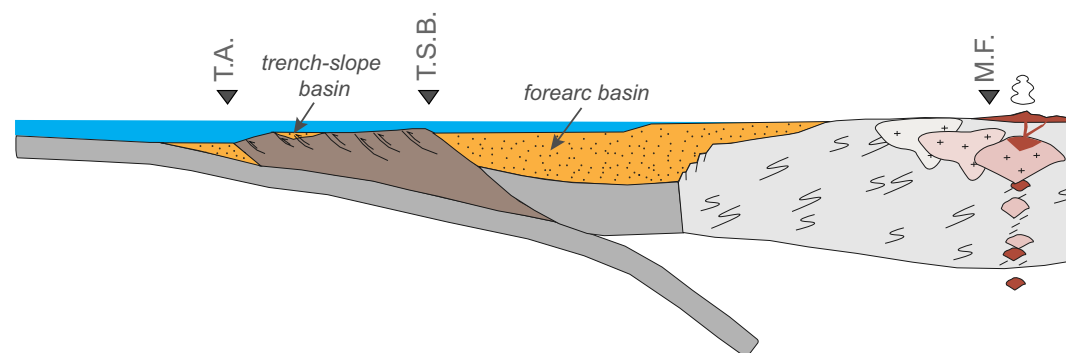
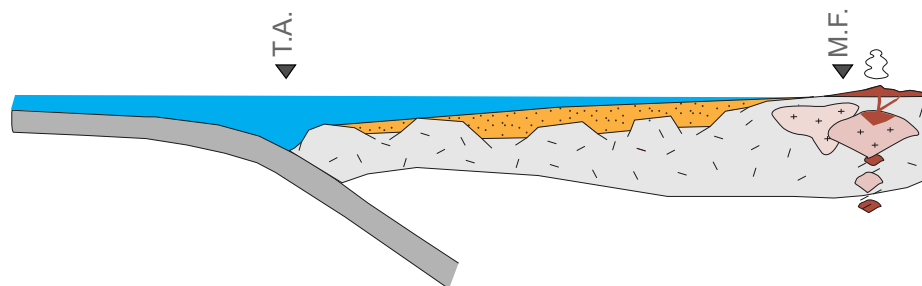


Figure 3. (A) Conceptual cross section through an accretionary subduction zone. Modified from Dickinson (1995). (B) Conceptual cross section through a non-accreting (erosive) subduction zone. T.A.—trench axis; M.F.—magmatic front; T.S.B.—trench slope break.

B Extensional forearc (e.g., with ocean-ocean convergence)



(Thornburg and Kulm, 1987); mass wasting into the trench is common upon the filling of trench-slope basins (e.g., Nankai trench; Ramirez et al., 2015). Migration of the trench-slope break can lead to stratigraphic transitions where early-phase slope deposits are overlain by later-phase forearc deposits, as is the case in the Kumano forearc basin (Ramirez et al., 2015), where the active deformation front within the Nankai accretionary prism moved oceanward during the Pliocene.

Forearc basins tend to be relatively narrow (25–125 km wide) with thick sedimentary wedges (1000–15,000 m) that fill elongate (50–500 km) troughs just seaward of their magmatic arcs (Dickinson and Seely, 1979; Dewey, 1980; Dickinson, 1995). Forearc basin fill is consistently thicker along continental margins (typically ~3000–6000 m) than along intraoceanic margins (typically ~1000–3000 m) due to the larger supply of siliciclastic sediment from continental arcs (Dickinson, 1995). Individual forearc basins are bound along strike by basement highs and/or fault offsets that mostly isolate their fill from that of neighboring forearc troughs and can be strung together along strike for thousands of kilometers (Fig. 1).

Subsidence of forearc basins, a key parameter in the deposition of source and reservoir units as well as hydrocarbon maturation, depends on the interplay between the age of subducted oceanic crust, the plate convergence rate, the thickness of trench fill, the tectonic loading by an accretionary wedge, the isostatic loading by forearc sediments, and the thermotectonic subsidence of the massif related to arc migration (von Huene and Scholl, 1991; Dickinson, 1995; Clift and Vannucchi, 2004). This diversity of subsidence mechanisms also means that parts of the same forearc basin may undergo significantly different subsidence, as occurred in the Great Valley of California (USA) where the eastern (arc-ward) margin experienced gradual thermo-tectonic subsidence due to basin filling, while the western (trench-ward) margin underwent highly variable tectonic subsidence and uplift due to the descent angle and age of the downgoing slab (Moxon and Graham, 1987). In general, forearc basins demonstrate the greatest range of subsidence curves of any tectonic setting (Xie and Heller, 2009), likely due to a combination of their tectonic and thermal variability as well as a paucity of observational constraints.

Interactions between the rate of convergence and the volume of trench fill—and even regional climate shifts that affect sediment supply into the trench—can cause dramatic and basin-wide subsidence that can have significant implications for organic preservation and/or the deposition of thick, turbiditic reservoirs. In the south-central Chile forearc, a region known for its coal reserves and coalbed methane, Miocene cooling may have inhibited the sediment supply to the trench, thereby causing subduction erosion and forearc extension and basin-wide subsidence that allowed the deposition of deepwater deposits onto the coal beds (Encinas et al., 2012). Multi-phase structural overprinting is particularly common where oblique subduction causes wrench faulting and large-scale, strike-slip blocks such as in the South China Sea (Yang et al., 2012) and the northern Andean forearc (Fildani et al., 2008).

Evolution and Preservation Potential

Subduction zone features are seldom neatly preserved in the geologic record. In modern systems, for example, up to 75% of modern oceanic arcs are tectonically erosive (von Huene and Scholl, 1991; Stern, 2010), that is they experience a net loss of crust from the forearc front and/or base into the trench over $\sim 10^6$ – 10^7 years (Draut and Clift, 2013). Many non-accreting subduction zones and their trench-slope and forearc basins are progressively diminished by subduction erosion (von Huene and Scholl, 1991), in particular around the Pacific Rim, where rates of trench retreat range from ~ 1 – 5 km/m.y. along various convergent margins (von Huene and Lallemand, 1990; Vannucchi et al., 2001; Lارسن et al., 2002; Clift et al., 2003). But where accretion outpaces tectonic erosion over long ($\sim 10^7$) time scales, forearc basins can be well preserved under certain circumstances. For an accretionary forearc to develop, sediment thickness in the trench must exceed ~ 1 km, an occurrence that depends both on the supply of sediment into the trench and a rate of convergence that allows sediment accumulation rather than erosion (von Huene and Scholl, 1991; Clift and Vannucchi, 2004). With an effective accretionary backstop, then, a forearc basin has the opportunity to deepen and fill, increasing its chances at preservation through sheer volume. In fact, mature forearcs—where the available accommodation space has been completely filled—may be more likely to survive postsubduction tectonism. This is based on the observation that more than half of ancient forearc basins are filled with sedimentary successions up to 7500–12,500 m thick, whereas the vast majority of modern forearcs include <6000 m of basin fill (Dickinson, 1995).

The preservation of intraoceanic arc systems is generally less likely than compared with continental arc systems, because they lack the proximity to continental massifs and the resulting supply of siliciclastic sediment to their trenches in order to promote accretionary buildup. However, the chance of preservation of forearc and/or trench basins within intraoceanic arc systems increases just prior to a collision event, due to the increased supply of sediment from the incoming continent or island arc (Draut and Clift, 2013).

Forearc survival and/or resilience may also be promoted by a postsubduction transition to a new tectonic regime. For instance, the transition from a convergent to strike-slip margin along the southwestern U.S. margin (Atwater, 1970) allowed for a near-complete preservation of the Farallon–North America forearc in the Great Valley sequence; similarly, the Hokonui basin in New Zealand (Dickinson, 1971) and the Vizcaino basin in Baja California (Busby-Spera and Boles, 1986) are now preserved along a transform margin. Several ancient forearc basins exist along inactive volcanic arcs where subduction has ceased, such as the Tamworth Trough in Australia (Leitch, 1975; Korsch, 1977), as well as the Sarawak basin in Borneo and the southeast Palawan and Iloilo basins in the Philippines (Hamilton, 1979). Seaward migration of subduction and associated uplift of the forearc region has helped preserve ancient basins such as Central Kalimantan in Indonesia (Hamilton, 1979), Nemuro in Hokkaido (Japan) (Okada, 1974; Kimura and Tamaki, 1985); the Coast Range in Oregon (USA) (Heller and Ryberg, 1983), Ochoco in Oregon (USA) (Dickinson, 1979); and Hornbrook in California and Oregon (USA) (Nilsen, 1984). Subduction polarity reversal can also help preserve a forearc basin by moving it into the backarc regime, as happened with the New Ireland basin in Papua New Guinea (Marlow et al., 1988). In addition, flat-slab subduction often forces inversion of the overlying forearc (e.g., Matanuska Valley basin above the Yukatat microplate, southern Alaska), and can enhance forearc preservation by supplying sediment to adjacent low-lying basins (e.g., Cook Inlet; Finzel et al., 2011; Ridgway et al., 2012).

Collision of an arc or continent can preserve a sutural forearc basin within the suture belt, with varying degrees of associated deformation. Such sutural basins have been documented in the Coastal Range of Taiwan (Lundberg and Dorsey, 1988); the Yezo basin in Hokkaido, Japan (Okada, 1983); the Magog basin in Quebec, Canada (St. Julien and Hubert, 1975); the Midland Valley in Great Britain (Dewey, 1971); the Sanandaj basin in Iran (Cherven, 1986); the Indus Trans-Himalayan belt of India (Garzanti and van Haver, 1988); and the Burmese Lowland of Burma (Mukhopadhyay and Dasgupta, 1988).

■ HYDROCARBON OCCURRENCE IN WORLD'S SUBDUCTION ZONES

Seeps

Not all petroleum basins are associated with hydrocarbon seeps, just as not all seeps are associated with petroleum basins. However, the occurrence of hydrocarbon at the surface can be an indication of a working petroleum system in terms of the presence of source-rock and migration pathways. Subduction zones certainly do not lack hydrocarbon seeps (Fig. 1), and in fact, active convergent margins more frequently host cold seeps than do passive margins (Levin, 2005; Suess, 2014) due to pore pressure differentials achieved during overthrusting and sediment burial within accretionary prisms and forearcs, respectively (Saffer and Tobin, 2011; Freundt et al., 2014), as well as the presence

of ample faults along which fluids can migrate. Some of the best studied seeps associated with petroleum basins within modern or fossil subduction zones include: offshore Paita, northwestern Peru (Olu et al., 1996); Palawan Trough, South China Sea (Zielinski et al., 2007); Cascadia margin, USA (Ryu, 1995; Collier and Lilley, 2005); East Coast Basin, New Zealand (Campbell et al., 2008); and Barbados (Kiel and Hansen, 2015). Seeps have also been studied along non-producing subduction zones that have hydrocarbon potential including offshore Pakistan (Fischer et al., 2012), Costa Rica (Füri et al., 2010), and Japan (Juniper and Sibuet, 1987).

Hydrocarbon seeps have been used toward understanding the role of diffuse outgassing on the total carbon flux in subduction zones (see Kelemen and Manning, 2015 and references therein). Widespread observations of hydrocarbon seeps and carbonate chimneys in forearc basins suggest a significant output of CO₂ (e.g., Haggerty, 1987; Campbell et al., 2002; Fryer, 2012), although it is often unknown if this CO₂ comes from subducted oceanic sediments or from continental or accretionary prism sediments. Kelemen and Manning (2015) suspect that current diffuse outgassing rates are underestimated, and that forearc flux may be a large part of the total subduction cycling of carbon.

Shows and Production

In subduction zone basins, the distribution of proven reserves follows a trend that is distinguished from total global distribution (e.g., log-normal) in its strong skew toward a few very productive basins and only a handful of small basins (Table 1; Fig. 2). The few productive basins (>200 MMBOE) have several features in common. The Cook Inlet, Talara, Sacramento, and Progreso basins are all in a forearc position backed by a continental rather than island arc (Table 1; Fig. 1). As discussed in the prior section, the proximity to a continental arc is associated with thicker basin fill and greater chance for preservation of an older forearc (Dickinson, 1995). The top three producers (Cook Inlet, Talara, Piura [Peru], and Sacramento, California [USA]) contain up to ~17,000 m sedimentary thicknesses, including marine and nonmarine reservoir facies, and marine and nonmarine (gas-prone) shale as their source rocks. There are notable differences between the top-producing basins. The Cook Inlet and Sacramento basins developed landward of a prominent accretionary wedge and include mostly anticlinal structural traps, whereas the Talara basin is a strongly eroding margin that lacks an accretionary high and includes mostly extensional and transtensional, block-fault traps. Also, the Sacramento basin is considered an ancient forearc, because the tectonic regime transitioned from a convergent to strike-slip margin as the Mendocino triple junction migrated north in the middle Miocene; its production is based on subduction-related reservoirs and source rocks, but certainly its geothermal gradient and some of its structural features have been influenced by passage of the triple junction. The Cook Inlet straddles a west-east transition from active volcanism to flat-slab quiescence, whereas the Talara basin sits along a section of the Andean volcanic arc that has been inactive since the Pliocene. Production in the

Sacramento and Talara basins is entirely onshore, whereas in the Cook Inlet production is from both onshore and offshore fields. The Talara and Progreso basins currently produce almost entirely oil, the Sacramento basin produces entirely gas, and the Cook Inlet produces an even mix of oil and gas (Table 1).

The remaining economic subduction zone basins have very small (<20 MMBOE) production, comprise a mix of forearc, accretionary wedge, and trench-slope settings, and are positioned in front of both oceanic and continental arcs (Table 1).

CASE STUDIES

The following case studies describe the geology and production from forearc basins with the largest reserves of any subduction zone region: Cook Inlet, Alaska (USA), Talara (Peru), and Sacramento (USA) (Fig. 1). These examples demonstrate the commonalities among forearc basins that support hydrocarbon production (e.g., thick basin fill, source-rock presence) and those that limit economic potential (e.g., low geothermal gradient and structural complexity), as well as the diversity of geologic features (e.g., accretionary versus erosional margins) that make generalizations difficult. We explore subduction zone hydrocarbon more generally, with these and other forearc and/or trench-slope basins in mind, in a follow-up section titled “The Petroleum System in Subduction Zones.”

Cook Inlet, Alaska (USA)

The Cook Inlet Basin of southern Alaska (USA) has the greatest total petroleum production from a subduction zone, with ~1300 million barrels (MMB) oil and 8 trillion cubic feet (TCF) gas produced since 1958 (Table 1; LePain et al., 2013), with mean undiscovered recoverable resources estimated to be ~600 MMB oil, 19 TCF gas, and 46 MMB natural gas liquids (Stanley et al., 2011). The historic oil-to-gas production ratio of the Cook Inlet Basin is ~50% (1 barrel of oil = 6 thousand cubic feet of gas), which is only surpassed in oil-richness next to the Talara and Progreso basins of Peru and Ecuador (Table 1). The Cook Inlet Basin formed in response to subduction and associated arc magmatism over a period of 200 m.y. (Coney and Jones, 1985; Fisher et al., 1987). The basin may have initiated as an oceanic-oceanic subduction zone associated with an oceanic island arc, and it was translated northward along dextral faults (Stamatikos et al., 2001; Trop and Ridgway, 2007) before accreting to the North American plate during the Cretaceous (LePain et al., 2013). Southern Alaska has experienced significant growth of the accretionary prism since the late Mesozoic or early Cenozoic, with the trench presently located ~350 km outboard of the Alaska-Aleutian Range batholith and the modern arc (Fig. 4). Portions of the accretionary prism are today emergent (e.g., Kodiak Island; Fig. 4).

The Cook Inlet Basin preserves an aggregate thickness of more than 18 km of Jurassic to Cenozoic fill (Fig. 5; Kirschner and Lyon, 1973; LePain et al., 2013).

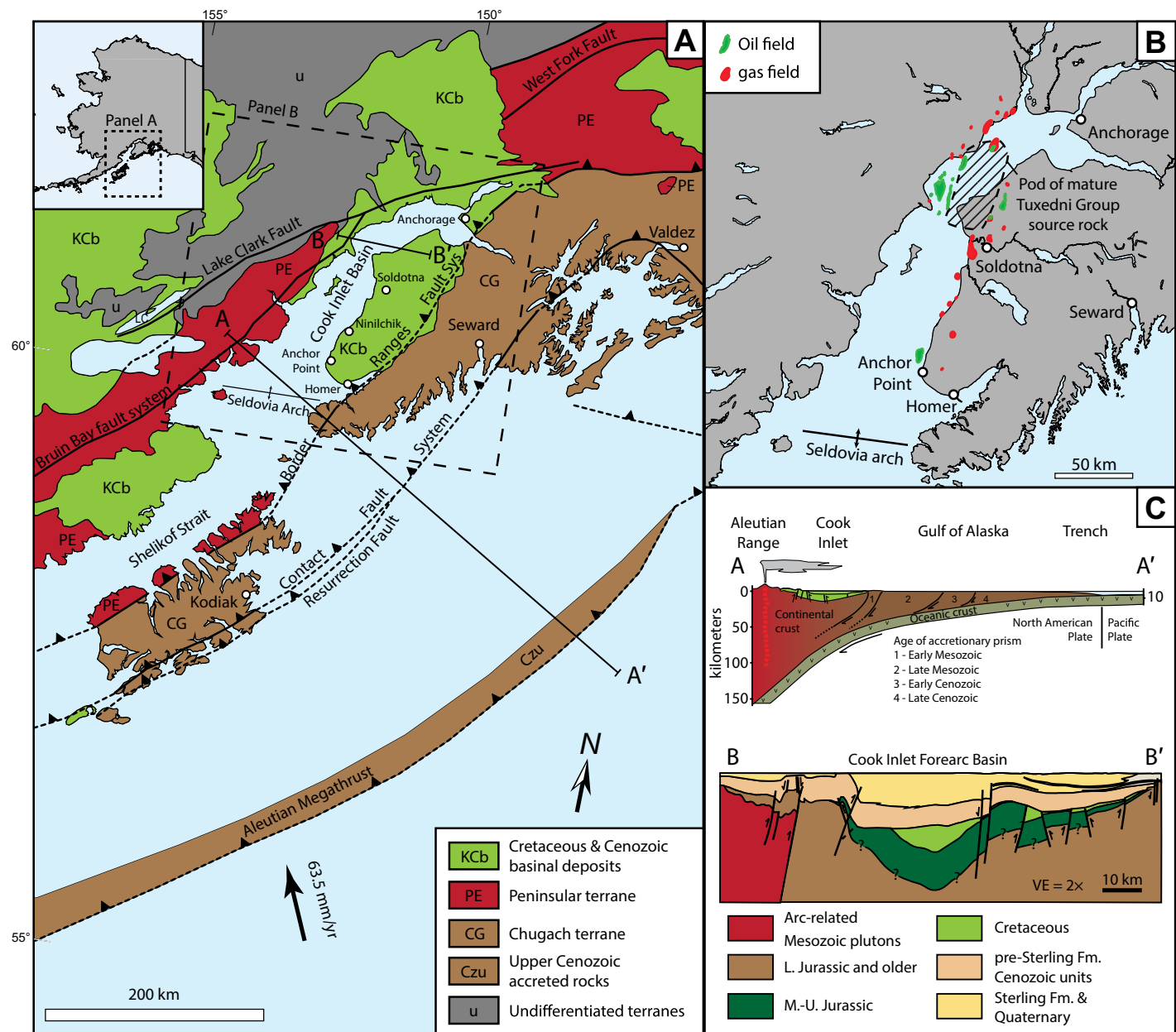


Figure 4. (A) Major tectonic features of southeastern Alaska and the Cook Inlet Basin. (B) Oil and gas fields of the northeastern Cook Inlet Basin. Pod of mature Tuxedni Group source rock from Magoon (1994a, 1994b). (C) Cross sections across the Cook Inlet segment of the Cook Inlet Basin (locations shown in Panel A). Modified from LePain et al. (2013). L.—Lower; M.—Middle; U.—Upper; Fm.—Formation.

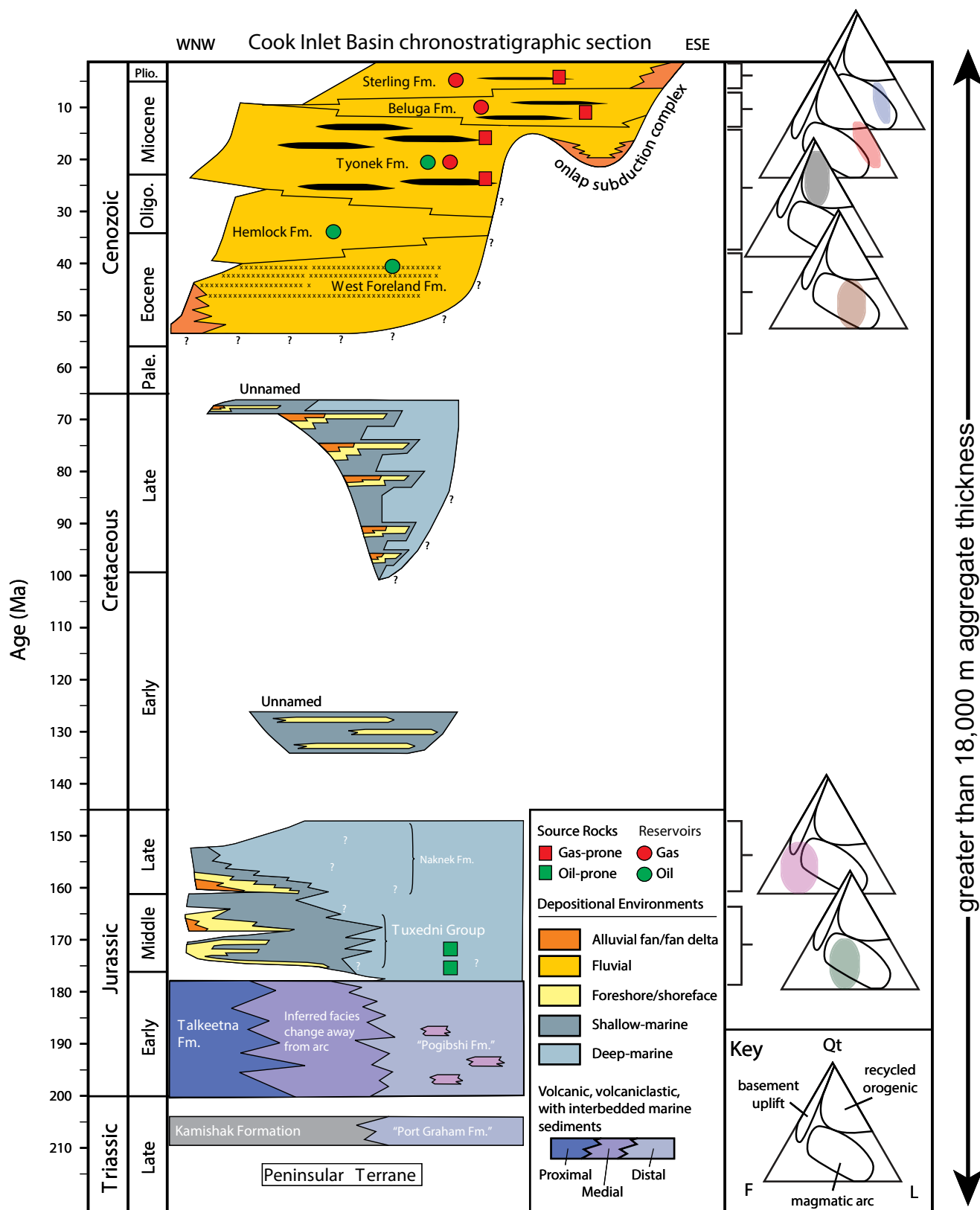


Figure 5. Stratigraphic column of the Cook Inlet forearc basin. Modified from LePain et al. (2013). Oligo.—Oligocene; Pale.—Paleocene; Plio.—Pliocene; Fm.—Formation; WNW—west-northwest; ESE—east-southeast; Qt—total quartz; F—feldspar; L—lithics.

In general, the Mesozoic fill of the basin (at least 10.7 km) is dominantly marine, with some alluvial fan, fan delta, and foreshore faces along the basin margin (Fig. 5; LePain et al., 2013). The Cenozoic fill of the basin (7.6 km aggregate thickness) is dominantly nonmarine and is separated from the underlying Mesozoic units by a pronounced, regional unconformity that may be related to subduction of a spreading center during latest Cretaceous–Paleocene time (Nokleberg et al., 1994; Kortyna et al., 2013; LePain et al., 2013; Finzel and Enkelmann, 2017).

Petroleum source rocks include (1) oil-prone, organic mudstone of the lower Tuxedni Group (middle Jurassic) (Fisher and Magoon, 1978; Magoon, 1994a) and (2) gas-prone coal in Eocene–Miocene units (Claypool et al., 1980; Magoon, 1994b; LePain et al., 2013). Available data from the Tuxedni Group suggest modest source-rock quality, with an average total organic carbon (TOC) of 1.7 wt% (maximum of 2.1 wt%) and an average hydrogen index (HI) of 296 reported for thermally immature subsurface samples (Magoon and Anders, 1992). Magoon (1994a) estimated that ~4% of the total quantity of hydrocarbons generated within the Tuxedni Group have been preserved in known petroleum accumulations.

The Cook Inlet Basin is characterized by generally low heat flow (23–40 mW/m²) and relatively cool geothermal gradients (19–27 °C/km; Magoon, 1994a; Lillis and Stanley, 2011) relative to average continental crust (~30 °C/km), typical of many forearc basins (Allen and Allen, 2013) and likely exacerbated by flat-slab subduction in the Cenozoic (Finzel et al., 2015). The top of the oil window (0.6% vitrinite reflectance) within the center of the Cook Inlet Basin is inferred to be located at greater than 5 km depth (Johnsson et al., 1993) or 6.5 km depth (Magoon, 1994a). The timing of source-rock maturation is uncertain, but initial oil generation is variably thought to have occurred during the Paleocene to Miocene (Magoon, 1994a, 1994b; Lillis and Stanley, 2011).

Major petroleum reservoirs in the Cook Inlet Basin are within nonmarine units of Eocene to Pliocene in age (Fig. 5). Oil is predominantly produced from the Oligocene–Miocene Hemlock and Tyonek formations, with lesser quantities recovered from the Eocene West Foreland Formation. The majority of gas produced from the Cook Inlet Basin is contained within sandstone and conglomerate reservoirs of the Neogene Tyonek and younger formations that are thought to be sourced from coals within these same units (Fig. 5; LePain et al., 2013). Isotopic data suggest a biogenic, microbial origin of this gas and minor associated liquids (Claypool et al., 1980; Magoon and Anders, 1992; Magoon, 1994b).

Despite potential for stratigraphic traps, the large majority of exploration and consequent petroleum production from the Cook Inlet Basin is from structural traps within four-way, faulted anticlinal closures (LePain et al., 2013). The provenance and composition of sandstone within the Cook Inlet Basin vary throughout the stratigraphic section, with some units composed of volcanic lithic-rich detritus (e.g., the Tuxedni Group) and others composed of arkosic detritus sourced from denuded arc-root, or batholithic, rocks (e.g., the Naknek Formation) (LePain et al., 2013; Fig. 5), but not following a predictable “unroofing” sequence (i.e., Dickinson, 1995) because volcanism continued spo-

radically through the Cenozoic (Kortyna et al., 2013; Finzel and Enkelmann, 2017). Sand with higher abundances of unstable, lithic grains is more prone to diagenetic alteration and porosity destruction with burial (Bloch, 1994), although some shallow reservoirs maintain good reservoir properties despite a high proportion of volcanic rock fragments (e.g., the Sterling Formation; LePain et al., 2013; Fig. 5). Changing tectonic styles has lent a complexity to the provenance and, therefore, sediment composition in the forearc region of southern Alaska (Finzel et al., 2015). Specifically, spreading-ridge subduction and flat-slab subduction of the Yukatat microplate (Kortyna et al., 2013; Finzel et al., 2015; Finzel and Enkelmann, 2017) forced uplift and erosion of distant inboard terranes and the eastern forearc region and intermittent magmatism, supplying the Cook Inlet with largely recycled and basement-derived sediment in the Cenozoic.

Talara Basin, Piura (Peru)

The Cretaceous–Tertiary Talara basin in coastal northwest Peru is one of the oldest producing basins in South America; its first well was drilled in 1874 (Travis, 1953). Cumulative production through 1996 in the Talara basin was ~1700 MMB oil and ~2 TCF gas, mostly from onshore fields in the northern third of the basin (Higley, 2004). Despite its lengthy production history, the Talara basin has considerable potential, with estimates of mean undiscovered resources at ~1700 MMB oil and ~4800 billion cubic feet (BCF) gas as well as 255 MMB of natural gas liquids (Table 1; Higley, 2004). In particular, offshore gas in this region is considered a promising but untapped resource due to market and infrastructure limits.

The Talara basin sits within the Andean forearc associated with subduction of the Nazca plate beneath South America (Fig. 6). The arc eastward of Talara is currently quiescent due to flat-slab subduction (Bernal et al., 2002; Lamb and Davis, 2003) but was active during major basin subsidence and filling in the Paleogene (Hessler and Fildani, 2015). The basin is bounded on its seaward side by the Peru–Chile trench and to the east by the Amotape Mountains, a sliver of Paleozoic–Mesozoic Andean basement emplaced in the latest Cretaceous to earliest Paleocene (Mourier et al., 1988; Aspden and Litherland, 1992; Spikings et al., 2005). The Talara basin is one of ten Tertiary basins along Peru's coastal forearc region, each isolated by faulting and basement uplifts related to Mesozoic–Cenozoic convergence tectonics (Higley, 2004). The Talara basin is separated from its northern neighbors (e.g., Tumbes and Progreso basins) by the Dolores–Guayaquil megashear and the Pillars de Zorritos basement high (Kraemer et al., 1999), and from its southern neighbors (Sechura and Trujillo basins) by the Amazonas megashear, the Paita–Tamarindo–Illescas basement highs, and subsurface faults (Zúñiga-Rivero et al., 2001; Fildani et al., 2008). These topographic barriers varied with time and were not always impediments to sediment transfer across depocenters. For instance, the late Eocene stratigraphy of the Talara basin appears to extend across the Lancones (east of the Amotape Mountains; Figs. 6 and 7) and Sechura basins, with complete

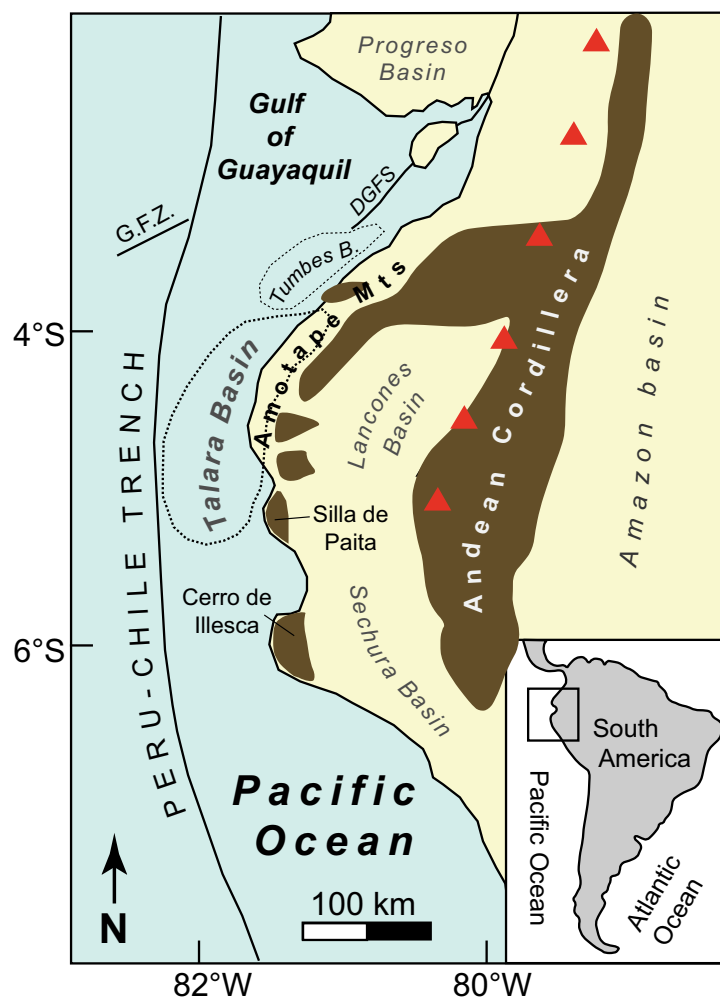


Figure 6. Map showing the location of the Talara basin in northwestern Peru. Modified from Hessler and Fildani (2015). DGFS—Dolores-Guayaquil fault system; G.F.Z.—Guayaquil fracture zone.

geographic separation by the late Oligocene (Caldas et al., 1980; Valencia and Uyen, 2002).

Subduction of the Farallon-Nazca plate system beneath the westward-moving South America plate began in response to opening of the South Atlantic Ocean in the Albian (Nürnberg and Muller, 1991). In northern Peru, calc-alkaline arc magmatism and contractional deformation had commenced by the early Senonian, although changing convergence rates and geometries

influenced basin subsidence as well as faulting and sedimentation patterns through the late Cretaceous and Tertiary. The Talara basin and the region north to the Dolores-Guayaquil megashear is flooded by continental-type crust (Lonsdale, 1978; Shepherd and Moberly, 1991; Witt et al., 2006) similar to Cordilleran basement comprising Paleozoic–Mesozoic metasedimentary and granitoid rocks in the nearby Andes Mountains.

The Paleogene forearc basin fill in Talara is ~10,000 m thick, with accumulation predominantly associated with significant early Eocene subsidence accompanied by roughly east-west extension and at least partly related to tectonic erosion during subduction (Fig. 8; Fildani et al., 2008). The oldest units (lower and lower middle Eocene) were deposited in mostly fluvial and marginal marine to outer shelf environments during a period of rapid plate convergence; a marked deepening of the basin in the middle Eocene and a predominance of bathyal turbidite deposition is associated with extension related to more oblique convergence and/or subduction erosion that may have been exacerbated by trench overfill during the early phase of basin deposition (Fildani et al., 2008), a process similar to that noted by Wells et al. (2003). Sediment delivered to the Talara basin was derived from granitoids and metamorphic basement of the proximal Amotape Mountains and more distal Andean Cordillera, as well as from contemporaneous arc volcanic rocks (Hessler and Fildani, 2015). The composition of sediment entering the Talara basin was generally similar through the Eocene, with some upsection changes in proportions of volcanic to plutonic material and detrital zircon spectra that indicate an overall shift from a more eastern provenance in the lower Eocene to a more northeastern provenance in the middle Eocene (Fildani et al., 2008; Hessler and Fildani, 2015).

Source-rock deposition in the Andean forearc would have required two conditions (Pindell and Tabbutt, 1995): (1) periods of low terrigenous sediment supply, perhaps due to relatively low relief of the Andean Cordillera (Ziegler et al., 1981) and (2) oceanographic upwelling to help concentrate organic matter in forearc sediments. Based on these assumptions, proposed source rocks in the Talara basin have included: the Cretaceous Redondo Shale and Muerto Limestone (Zúñiga-Rivero et al., 1998; Gonzales and Alarcon, 2002), the Paleocene Balcones and Eocene Pale Greda shales (Zúñiga-Rivero et al., 1998), and the Oligocene Heath Formation (Gonzales and Alarcon, 2002) (Fig. 8). Cretaceous–Oligocene shales and limestones in the Talara basin have TOC values of 1.1–1.3 (Gonzales and Alarcon, 2002), i.e., the potential to generate hydrocarbon. The median American Petroleum Institute (API) gravity of Talara oils is 32° (light grade), with lower API gravity values corresponding to higher sulfur content (0.03%–0.26%) and likely increased biodegradation (GeoMark Research Inc., 1998). Median nickel (5.5 ppm) and vanadium (4.0 ppm) distributions in the Talara basin oils indicate sourcing from mostly marine shales, with several samples showing higher nickel contents that suggest a possible nonmarine or mixed marine–nonmarine shale source and likely some degree of biodegradation and secondary hydrocarbon mixing (GeoMark Research Inc., 1998; Higley, 2004).

Molecular biomarker data from Fildani et al. (2005) provided a more detailed insight into the origin of hydrocarbon in the Talara basin. Based on analysis of 30 oils (onshore and offshore) and six potential source rocks from

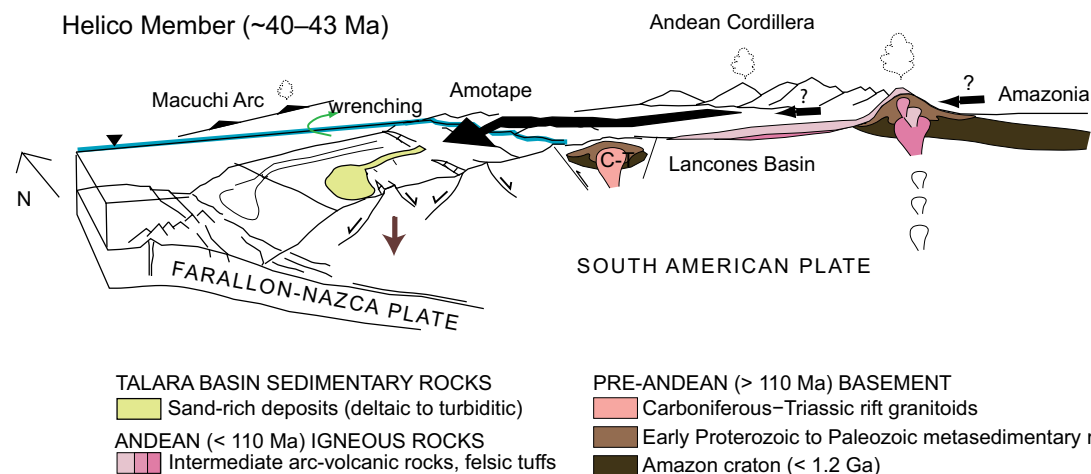


Figure 7. Conceptual west-east cross section of the Talara basin during Eocene time, showing the likely source areas of sediment delivered to submarine fans were the Andean Cordillera and the Amotape terrane. Modified from Hessler and Fildani (2015).

across the basin, the Talara oils appear to fall into one “oil family” (with high oleanane and/or hopane) that originated from an Eocene–Oligocene source rock similar to that observed in the nearby Progreso basin but not observed in the Talara basin. Specifically, relatively high oleanane indicates significant contribution of terrestrial organic matter into a mixed (likely deltaic) marine to nonmarine environment. A high ratio of 24-norcholestanes to 27-norcholestanes, as well as abundant C25 highly branched isoprenoid (HBI) alkanes, confirm the importance of marine upwelling to concentrate organic matter in the depocenter. Earlier proposed Cretaceous source-rock candidates (Zúñiga-Rivero et al., 1998; Gonzales and Alarcon, 2002) do not appear to contribute hydrocarbon to the oils currently being produced in Talara but may contribute to an as yet undiscovered petroleum system in the underexplored southern and/or offshore parts of the basin (Fildani et al., 2005).

Thermal maturation of hydrocarbon in Talara source rocks, especially those deposited during the Eocene–Oligocene, likely occurred when the basin achieved its maximum sedimentary thickness (~8000 m) during the Miocene (Pindell and Tabbutt, 1995), although Kingston (1994) and Gonzales and Alarcon (2002) indicated that Cretaceous source rocks could have reached thermal maturity by the late Eocene. At least two phases of hydrocarbon migration are suggested by gas chromatograms (GeoMark Research Inc., 1998): (1) the first occurring in the Miocene during a compressive phase, where oil became trapped in anticline and/or dome closures; and (2) the second occurring with subsequent extension and normal faulting (Zúñiga-Rivero et al., 1998). The shift from compression to extension may be associated with subduction of the Carnegie Ridge to the north and escape tectonics in the Gulf of Guayaquil (Fig. 6; Witt et al., 2006).

The understanding of oil migration distances and pathways in the Talara basin varies depending on which formation one considers to be the dominant source rock. Sanz (1988) suggested that lateral migration was limited in on-

shore fields, based on well and outcrop stratigraphic relationships showing source-rock shales closely intercalated with reservoir sandstones. Gonzales and Alarcon (2002) pointed to subsurface and geochemical evidence supporting the idea that oil migrated up to 600 m vertically and 50 km laterally out of Cretaceous source rocks. Both scenarios are based on source rocks having existed within the current boundaries of the Talara basin, such that vertical migration was the dominant pathway.

However, the stratigraphic record indicates that the Talara basin was not always isolated from neighboring forearc regions (Caldas et al., 1980; Valencia and Uyen, 2002; Fildani, 2004), raising the possibility that hydrocarbon was generated and migrated from outside the current basin boundary, prior to structural isolation in the Neogene. The most recent geochemistry study, and the only one based on molecular biomarker analysis, found no genetic link between oils and Cretaceous or Eocene shale samples from the Talara basin (Fildani et al., 2005) and suggested that Talara oils were sourced from younger and possibly more distal (i.e., extrabasinal) source rocks than previously thought. They suggest three possible migration scenarios that weigh heavily on the timing of structural segmentation of the forearc. In all scenarios, the candidate source rock is the upper Miocene–lower Oligocene Heath Formation (or as yet unidentified equivalent), the only known formation in the region whose shale extracts match Talara oils (Fildani et al., 2005; Peters et al., 2005). The largely deltaic Heath Formation outcrops north of the Talara basin and has been penetrated in the Progreso basin (Kraemer et al., 1999; Peters et al., 2005), but its upper Miocene–lower Oligocene equivalent in the Talara basin has not been drilled. In the first scenario, oil was generated from the Oligocene Heath Formation in the Progreso basin and migrated southward up to 100 km to charge the thick Eocene reservoirs in the Talara basin; the migration would have occurred prior to structural segmentation of the Talara and

TALARA REGION STRATIGRAPHY

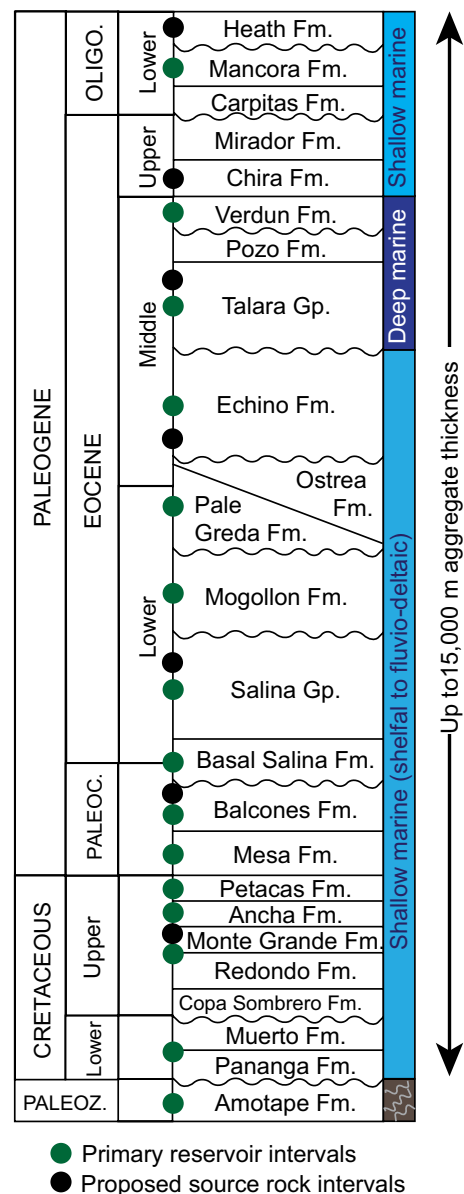


Figure 8. Composite stratigraphic column for the Talara basin region, showing the reservoir intervals and proposed source rocks. Modified from Higley (2004).

Progreso forearcs, which likely coincided with collision of the Carnegie Ridge with the trench in the mid-Miocene (Witt et al., 2006). The second scenario invokes a strongly extensional Paleogene forearc (related to subduction erosion), in which the southern equivalent of the Heath Formation was deposited in the offshore segment of the Talara basin; in this case, thick horst-graben sedimentary fill allowed for oil maturation and lateral migration of tens of kilometers into Eocene reservoirs. In the third scenario, a period of compression and basin inversion in the late Oligocene (Serranne, 1987) could have thrust Eocene reservoirs over Oligocene source rocks. As Fildani et al. (2005) noted, it is possible that a combination of aspects of these scenarios contributed to the petroleum system in the Talara basin, but that in any case, the structural complexity related to subduction dynamics played a significant role in migration.

Current oil production in Talara occurs in onshore reservoirs mostly within Eocene nearshore to marine sandstones (Fig. 8), but also from basement (Paleozoic quartzite) as well as Cretaceous–Paleocene and Oligocene sandstones; up to a dozen formations produce per well (Higley, 2004). Porosity and permeability values in Talara sandstone reservoirs have typical ranges of 10%–20% and 5–100 mD (Bianchi, 2002; Lopez Chavez et al., 2002). Framework grains are mostly quartz and feldspar (plagioclase dominant) but include variable amounts of lithic volcanics (andesitic to basaltic), metaquartzite, and schist. The proportion of lithic volcanic grains varies upsection (Fildani et al., 2008), presumably with activity in the arc as well as the configuration of drainage divides through time (Hessler and Fildani, 2015). This has a strong effect on reservoir quality; the two reservoirs with the highest proportion of lithic volcanic grains also have the lowest permeabilities (<5 mD; Bianchi, 2002; Fildani et al., 2008). Reservoir quality does not have a clear dependence on depositional environment, although those within deepwater channelized systems are more compartmentalized (Higley, 2004).

Sacramento Basin, California (USA)

The Sacramento basin of northern California (Fig. 9A) ranks third among cumulative hydrocarbon production within subduction zone basins, with cumulative production of more than 9 TCF natural gas (Scheirer et al., 2006b) and ~12 MMB oil and condensate (Table 1; Jenden and Kaplan, 1989). The basin is thought to be mature with respect to petroleum exploration, with modest estimates of undiscovered, technically recoverable resources (0.5 TCF natural gas and 0.3 MMB natural gas liquids; Scheirer et al., 2006b).

The Sacramento basin is part of a remnant forearc basin that formed in response to Cretaceous to early Cenozoic subduction of the Farallon plate beneath North America (Fig. 10; Dickinson and Seely, 1979). Subduction ceased in response to the northward migration of the Mendocino Triple Junction during the late Neogene that resulted in a transition to the transform margin of the San Andreas fault system (Atwater, 1970; Atwater, 1989). The Sacramento basin is continuous with the San Joaquin basin to the south and nominally separated by a subsurface basement high near the town of Stockton, California (Fig. 9B).

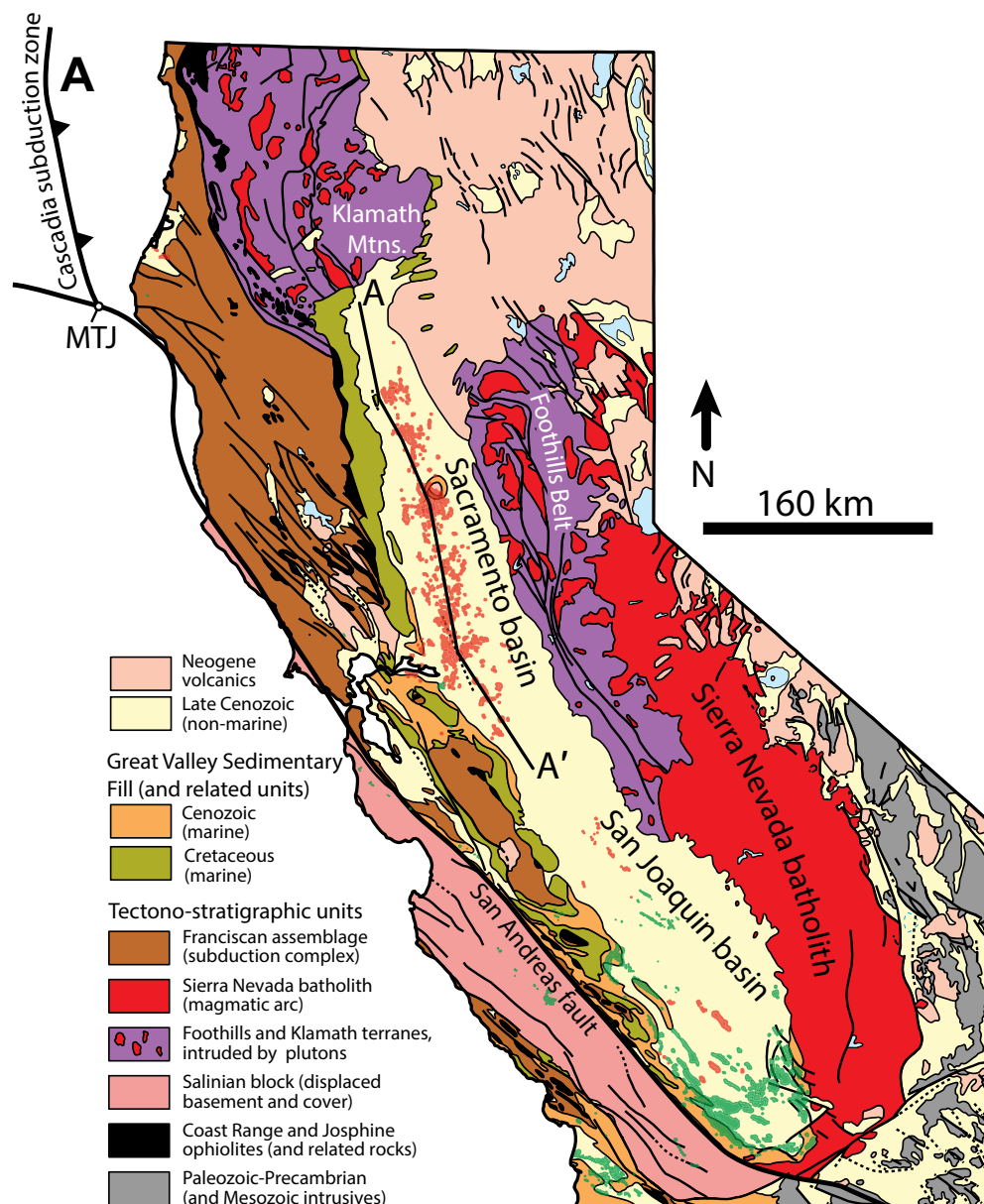
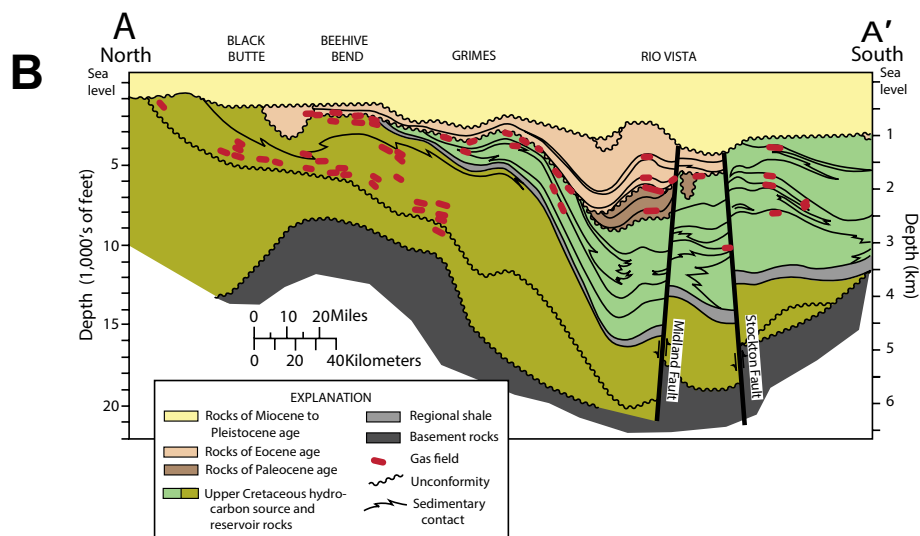


Figure 9. (A) Generalized geologic map of northern and central California. Modified from Dickinson et al. (1996), the California Geological Survey (2006), and Sharman et al. (2015). Oil and gas field outlines from the California Department of Conservation Division of Oil, Gas, and Geothermal Resources (1982). (B) Schematic north-south cross section across the Sacramento Basin (after Scheirer et al., 2006b). Approximate location of cross section in (A). Abbreviations: MTJ—Mendocino Triple Junction; Mtns.—Mountains.



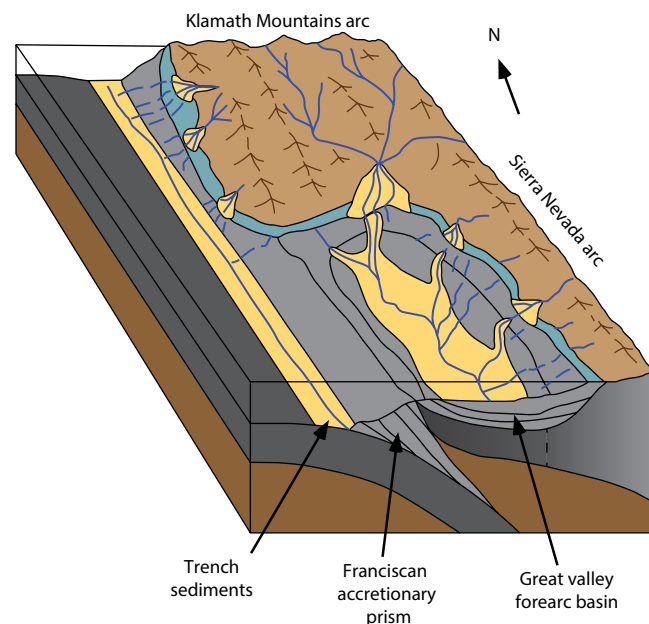


Figure 10. Block diagram illustrating schematic sediment routing patterns in the Sacramento basin during the Cretaceous (after Short and Ingersoll, 1990; Williams and Graham, 2013).

Although the Sacramento and San Joaquin basins are both “fossil” forearc basins, the San Joaquin basin has been more significantly overprinted by Neogene strike-slip successor basins and wrench tectonism than the Sacramento basin (Graham, 1987). These differences play a critical role in influencing the petroleum systems of these basins; the Sacramento basin is gas-dominated and only modestly petroliferous, whereas the San Joaquin basin comprises one of the major oil-producing provinces in the United States with 21 fields with oil reserves in excess of 100 MMB oil and three of the ten largest fields in the United States (Tennyson et al., 2012). Although some of the San Joaquin basin’s resources are contained within or sourced from units deposited within a forearc setting (e.g., the upper Cretaceous Moreno and middle Eocene Kreyenhagen formations; He et al., 2014), many of the source rocks (e.g., Miocene Monterey Formation), reservoirs, and traps that form the largest fields are related to subsequent strike-slip tectonism along the central San Andreas fault (Graham, 1987). Because it is difficult to disentangle which components of the petroleum system are a result of subduction versus strike-slip basin history in the San Joaquin basin, we focus on the Sacramento basin that constitutes a more pristine example of an ancient forearc basin, although its western margin has experienced late Neogene transpressive deformation (Harwood and Helley, 1987; Unruh et al., 1995).

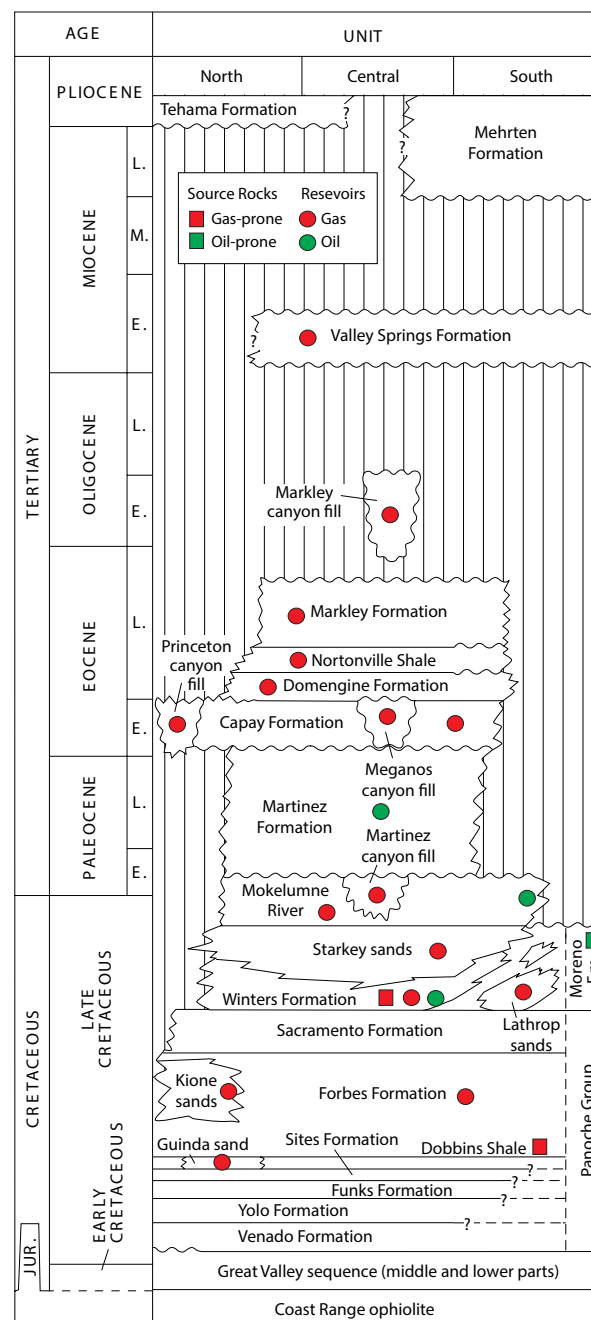
The Sacramento basin is positioned south of the Klamath Mountains and west of the Northern Sierra Foothills Belt, both of which are composed of accreted arc-related terranes that are intruded by Jurassic–earliest Cretaceous plutons (Figs. 9A and 10; Dickinson, 2008). Deposition within the Sacramento basin initiated in the earliest Cretaceous (Surpless et al., 2006) and persisted throughout the Cretaceous as an under-filled, deep-marine basin that evolved into a shelved forearc during the Paleogene (Figs. 10 and 11; Graham, 1987). An Andean-style magmatic arc was active during forearc deposition until ca. 85 Ma when the locus of volcanism migrated inland, thought to be related to a lowering of the angle of plate descent (Saleeby, 2003). Arc magmatism briefly resumed in Oligocene–Miocene time prior to shutting off as the Mendocino Triple Junction migrated north of the Sacramento basin (Dickinson and Snyder, 1978). The basin presently forms a southward-plunging synclinorium characterized by a great thickness (more than 15 km; Ingersoll, 1979) of Cretaceous strata along a steeply dipping, faulted western limb and a thinner eastern limb where upper Cretaceous units onlap the foothills of the Sierra Nevada Mountains (Graham, 1987). The western half of the basin structurally overlies rocks of oceanic floor affinity (Coast Range Ophiolite) and is structurally emplaced against the Franciscan subduction complex to the west (Fig. 9; Hopson et al., 1981; Dickinson, 1995).

Hydrocarbon production from the Sacramento Basin is dominantly dry gas, with minor production of condensate and oil (Table 1; Jenden and Kaplan, 1989). Geochemical analysis of Sacramento basin hydrocarbon has suggested that gas is predominantly derived from a mixture of (1) post-mature, gas-prone source rocks and (2) biogenic, microbial methane (Jenden and Kaplan, 1989). Marine shale in the Forbes Formation (Dobbins Shale) and in the Winters Formation is thought to constitute the major gas-prone source rocks in the basin (Jenden and Kaplan, 1989; Magoon et al., 2007). Organic matter in Sacramento basin source rocks is dominantly Type III (Graham, 1987), with 44% humic (woody) kerogen on average (Jenden and Kaplan, 1989). A number of fields in the vicinity of the Sacramento River delta have higher liquids content, including a small number of oil fields, suggesting hydrocarbons sourced from the oil-condensate window (Jenden and Kaplan, 1989). The presence of oil-prone Eocene shale in the southernmost Sacramento basin may account for some of the minor oil production in the Sacramento Delta vicinity (Fig. 11; Magoon et al., 2007).

As with other forearc regions, the typical geothermal gradient in the Sacramento basin is low (18–25 °C/km) but increases to 25–35 °C/km near the Sacramento River delta (Lico and Kharaka, 1983; Scheirer et al., 2006a). Depth to the top of the oil window ranges from less than 1 km to more than 4 km for the Dobbins Shale (Fig. 11; Jenden and Kaplan, 1989; Scheirer et al., 2006a), with peak oil generation occurring during the Eocene (ca. 45 Ma).

Gas reservoirs are found throughout the stratigraphic column of the Sacramento basin, particularly within Santonian and younger units (Figs. 11 and 12; California Department of Conservation Division of Oil, Gas, and Geothermal Resources, 1982). A variety of trapping mechanisms are present, including combination structural-stratigraphic traps (particularly associated with

Figure 11. Stratigraphic column of the Sacramento basin (modified from Magoon and Valin, 1994). Source rock and reservoir information is from Jenden and Kaplan (1989) and the California Department of Conservation Division of Oil, Gas, and Geothermal Resources (1982). L.—Late; M.—Middle; E.—Early; Jur.—Jurassic; Fm.—Formation.



truncation of reservoir facies against mud-filled submarine canyons), faulted anticlinal closures, and structural traps on the flanks of volcanic intrusions (e.g., Sutter Buttes) (Fig. 12; Beyer, 1988). Sandstone petrofacies record a shift from volcanic (andesitic) to intermediate plutonic/volcanic and finally to felsic plutonic that reflect the progressive unroofing of volcanic arc sources to their batholithic roots (Dickinson and Rich, 1972; Ingersoll, 1981). For this reason, shallower (latest Cretaceous–Paleogene) sandstones are prone to better reservoir quality as a result of lower abundances of unstable, lithic framework grains (Beyer, 1988).

Sandstone reservoirs are commonly overpressured (typically 0.6–0.8 psi/ft), with the top of overpressure occurring as shallow as 1.2 km along the basin margins but more typically as great as 3 km within the basin center (Lico et al., 1983; Magoon, 1994b). Horizontal tectonic compression associated with transpression in the California Coast Ranges is thought to be the dominant cause of overpressure in the Sacramento basin (Lico et al., 1983).

THE PETROLEUM SYSTEM IN SUBDUCTION ZONES

The current scarcity of giant oil and gas fields related to subduction zones (Table 1) leads to the questions: why do subduction zones appear to limit the production of hydrocarbon? And in the subduction zones with significant petroleum reserves, what features are responsible for creating a working petroleum system? In this section, we discuss the basin dynamics endemic to subduction zones that either inhibit or aid in the development of source rock and reservoir as well as the maturation and migration of hydrocarbon into appropriate traps. We will also discuss the possibility that subduction zones are underexplored and/or underexploited in terms of potential petroleum systems.

Source Rock

The presence of source rock in subduction-zone basins depends on the balance of several conditions: (1) primary productivity of organic matter; (2) conservation of organic matter in low-oxygen environments with low rates of bacterial consumption; (3) concentration of >0.5% TOC in sediments due to intermediate settling rates of fine-grained material and low to medium rates of dilution from clastic sedimentation (Tissot and Welte, 1978; Bohacs et al., 2005). Poor achievement of a single condition (e.g., weak primary productivity) can be partially offset by strong achievement of the others (e.g., very low oxygen and optimal sedimentation rate). On the other hand, there can be a positive feedback among these conditions. For instance, areas of high primary productivity can become strongly reducing through an initial decay of organic matter, at the same time limiting bacterial consumption.

Accretionary prisms and trenches tend to have limited source rock, perhaps due to high rates of siliciclastic input related to steady, proximal structural modifications (Underwood and Moore, 1995). Modern trench and trench-slope sediments of Nankai Trough, Cascadia, and the Aleutians, where sediment flux is high, contain <1% TOC (Dow, 1979; Kvenvolden and von Huene, 1985;

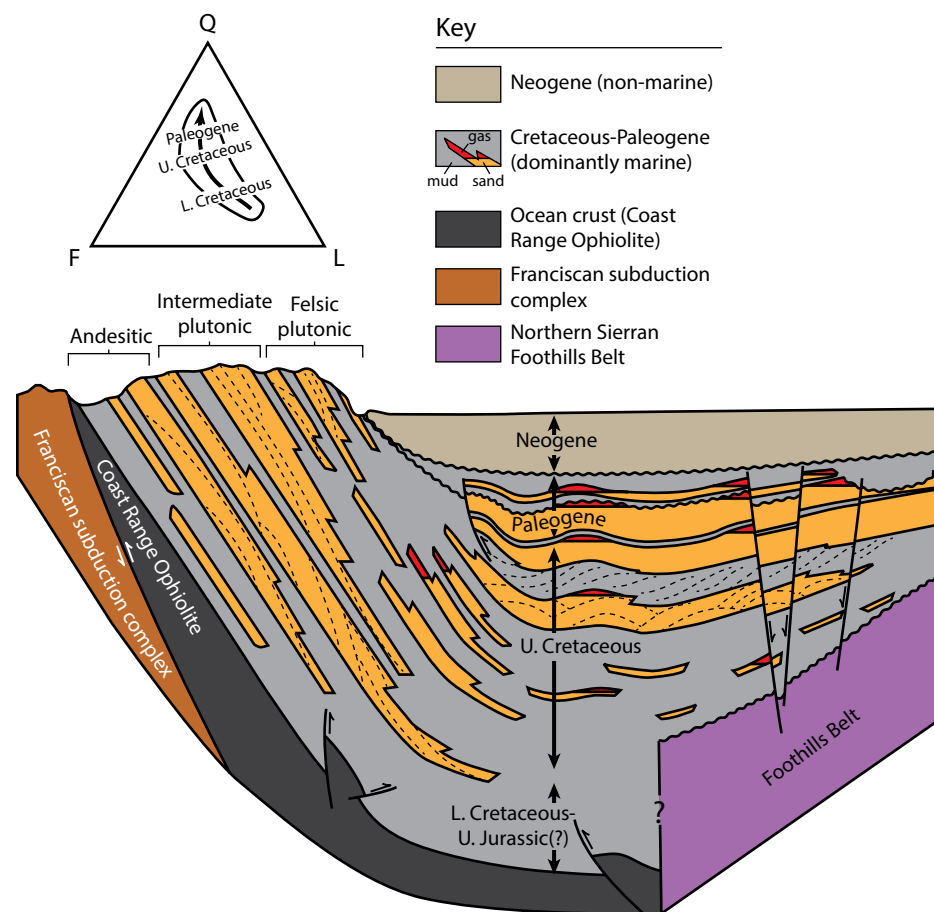


Figure 12. Schematic west-to-east cross section across the Sacramento basin illustrating a variety of hydrocarbon trap types and the evolution of sand composition from andesitic to felsic plutonic (after Beyer, 1988).

Mukhopadhyay et al., 1986). However, the accretionary prism exposed in Barbados contains viable source rock (1%–4% TOC; Larue et al., 1985), as do trench-slope deposits along the Middle America Trench offshore Mexico and Guatemala (Summerhayes and Gilbert, 1982a, 1982b; Gilbert and Cunningham, 1985). Strong coastal upwelling along the coast of Peru is associated with high TOC (1%–8%) in trench-slope deposits (Suess and von Huene, 1988).

Whereas source rock in trench and trench-slope basins may be limited by high sediment influx, barriers to source-rock deposition in forearc basins may be related more to their open marine positioning (Dickinson, 1995). Thus accumulation of high-quality, oil-prone source rock may require special circumstances, such as strong coastal upwelling that corresponds with generally high organic

productivity (Suess et al., 1988). For example, one of the largest forearc petroleum systems, the Talara Basin in northwestern Peru, has oil with a molecular biomarker signature suggestive of influence from coastal upwelling in generating the organic matter that later sourced oil and gas fields (Fildani et al., 2005). On the other hand, hydrocarbons produced from the other two largest subduction-related basins (Cook Inlet, Alaska, and Sacramento, California) are from less organic-rich source rocks (TOC typically <2%; Jenden and Kaplan, 1989; Magoon and Anders, 1992) whose deposition was not influenced by marine upwelling. Oils generated in Cook Inlet fields derived from Jurassic mudstones with modest average TOC of 1.7 wt% (Magoon and Anders, 1992), and those in the Sacramento basin are related to predominantly terrestrially-derived Type III kerogen with an average TOC of ~1.0% (Graham, 1987; Jenden and Kaplan, 1989). It may be that coastal upwelling is generally limited within closed forearc basins behind accretionary convergent margins (e.g., Sacramento Basin) and more prevalent in forearc basins that open seaward along erosive margins (e.g., Peru). However, we also may not fully understand the marine positioning of these basins early in their history, particularly in the case of the Cook Inlet, which was in an intra-oceanic setting and farther south during deposition of its Jurassic source rocks (Stamatakis et al., 2001; Trop and Ridgway, 2007).

Hydrocarbon Generation

Rising temperature, itself a function of burial depth, is the primary driver of the chemical reactions that transform organic matter into oil and gas. The transformation ratio—the percentage of kerogen that has been converted to hydrocarbon—depends on the interplay between temperature, time, pressure, and kerogen type. Time and pressure are subordinate to temperature as a factor; the function of time is linear, while the influence of temperature on hydrocarbon generation grows exponentially (Tissot and Welte, 1978). Modeling has shown that oil generation takes on the order of 5–10 million years at its most rapid, and can require, at its slowest, more than 100 million years (Tissot et al., 1974). Certain basins, such as the Pannonian basin in central Europe, where the subsidence rate (>500 m/m.y.) and geothermal gradient (50 °C/km) are particularly high, experienced rapid oil generation from relatively young (Pliocene) source rocks (Tissot and Welte, 1978). Interestingly, there are several subduction-related basins around the circum-Pacific (e.g., San Joaquin, USA; Indonesia) where Miocene–Pliocene source rocks underwent fairly rapid hydrocarbon generation due to high subsidence rates and geothermal activity (Tissot and Welte, 1978). In the case of the San Joaquin basin, Miocene–Pliocene subsidence and a high geothermal gradient were associated with the approach of the Pacific–Farallon spreading center and the transition from convergent to strike-slip tectonics (e.g., Graham, 1987; Goodman and Malin, 1992).

Subsidence mechanisms can be highly favorable in subduction zone settings. Subsidence of the Great Valley basin in California (USA) can be entirely explained by isostasy related to sediment load (Dickinson et al., 1987; Williams and Graham, 2013), and thermotectonic subsidence can occur at higher rates in forearc basins compared to passive continental margins (Heller, 1983). Due

to their positioning near a promising source of siliciclastic sediment (arc and massif), forearc basins along continental margins offer favorable subsidence, sedimentation, and burial conditions for hydrocarbon generation. Typical sedimentation rates for continental margin forearc basins are on the order of 100–300 m/m.y., with axial thicknesses of ~2000–6000 m (Dickinson, 1995). In contrast, forearc basins associated with intraoceanic arcs have notably slower sedimentation rates (~50–250 m/m.y.) than those along continental margins, although their axial thicknesses are comparable (Dickinson, 1995). This relates to the generally limited supply of terrestrial sediment in intraoceanic forearcs, where the axial fill is instead dominated by volcanoclastic debris and, in tropical zones, carbonates (Exon and Marlow, 1988).

The major limitation for hydrocarbon generation in subduction zones is a typically low geothermal gradient due to the underlying cold oceanic lithosphere. In the Jurassic–Tertiary Great Valley forearc, for instance, gradients were persistently “subnormal,” ranging from 9 to 15 °C/km between 90 and 65 Ma (Dumitru, 1988). However, in the South China Sea, extension in the forearc region caused mantle upwelling that raised geothermal gradients enough to accelerate the maturation of hydrocarbon (Yang et al., 2012). Locally enhanced thermal maturity may also be related to volcanic intrusions (e.g., the Sutter Buttes; Sacramento basin, USA) or proximity to the active magmatic arc (e.g., the eastern Puget Sound forearc and Cascade arc, USA; Blackwell et al., 1990). In the Cook Inlet, a high geothermal gradient in the accretionary prism may have positively impacted hydrocarbon generation during the early Cenozoic, when subduction of a spreading ridge gave rise to “near-trench” plutons (Haeussler et al., 2003; Cole et al., 2006; Trop, 2008; Kortyna et al., 2013; Finzel et al., 2015). The age and cooling history of the subducted lithosphere most certainly influence geothermal gradients and hydrocarbon maturation in forearc and/or trench-slope basins, as mentioned above in reference to the rapid generation of hydrocarbon from Miocene–Pliocene source rocks around the Pacific Rim. The subduction of relatively young oceanic lithosphere along the Cascadia margin and beneath the Nankai Trough raises the geothermal gradient significantly, especially in the accretionary prism (Yamano et al., 1984; Shi et al., 1988). Accretionary wedges are particular in that heat flow can be enhanced at shallow depths (<2 km) due to the clay dehydration reactions and dewatering processes common to overthrust sedimentary packages (Reck, 1987; Davis et al., 1990; Fisher and Hounslow, 1990).

Reservoir

The presence of good reservoir is common in forearc or trench-slope basins. Forearc basins often boast more than adequate thickness of potential reservoir units due to effective structural and thermal subsidence (Dickinson, 1995). Reservoirs in forearc or trench-slope basins pose significant risk where a critical supply of volcanic lithic sediment is associated with diagenetic clays and a rapid decrease in porosity and permeability with burial depth (Bloch, 1994). Reservoir quality, in terms of sediment maturity and quartzofeldspathic composition, can vary significantly over the history of a basin. For instance,

progressive growth of the subduction complex can provide increasing volumes of sediment to the forearc from the seaward side (e.g., western Cook Inlet; Trop and Ridgway, 2007). Uplift and exhumation of the volcanic arc can result in the erosion of the granitic roots of the arc, which produces arkosic sediment that is more favorable to preserved reservoir quality, and may also expand drainages to tap into distant but favorable basement rocks or sedimentary fill inboard and/or along strike (e.g., Sacramento basin and Cook Inlet; Beyer, 1988; LePain et al., 2013; Surpless, 2014; Finzel et al., 2015; Sharman et al., 2015). Also, volcanic activity can be intermittent throughout basin deposition, resulting in alternating volcanic-rich (and lower permeability) and volcanic-poor (and higher permeability) reservoirs (e.g., Talara basin; Higley, 2004; Fildani et al., 2008), or arc volcanism can be “renewed” to provide a late influx of volcanic material to the forearc (e.g., Cook Inlet; Kortyna et al., 2013). In any case, volcanic-lithic-rich sediment can be associated with good reservoir quality provided the reservoirs are shallow (e.g., Oligocene–Pliocene reservoirs of the Cook Inlet Basin; Fig. 10) or diagenetically modified.

Basins with the highest potential for the deposition of thick, high-permeability reservoir strata are those located in forearc positions along continental margins with well-developed accretionary prisms. Continental arcs provide more detritus to the forearc than do intraoceanic arcs, generating a much thicker basin fill (Dickinson, 1995); the detritus itself is more quartzofeldspathic due to the presence of continental basement, improving the odds of higher-permeability reservoir rock. The presence of an accretionary prism, as opposed to subduction erosion of the trench slope, encourages long-term preservation of the associated forearc basin (Clift and Vannucchi, 2004). On the other hand, the Talara basin is an example of a significant petroleum basin that formed within an erosive forearc, its thick sedimentary package having filled a deep accommodation space produced by severe extension and normal faulting related to subduction erosion (Fildani et al., 2008).

The supply of clastic detritus from continental arcs and accretionary highs to forearc and trench-slope basins inhibits the precipitation of carbonate in these settings, leading reservoir units along accreting continental margins to be dominated by siliciclastic rocks (Dickinson, 1995; Underwood and Moore, 1995). However, carbonate buildups have been proposed as viable reservoirs in forearcs associated with lower-latitude intraoceanic arcs, where relatively low clastic supply and appropriate marine conditions set the stage for sizeable reef development (e.g., Simeulue forearc, Indonesia; Lutz et al., 2011; and Tonga Ridge; Scholl and Herzer, 1992).

Traps and Seals

Subduction zone settings generally offer favorable structural trap scenarios, with active faulting and folding related to accretionary prism growth or trench-front erosion. Forearc basins tend to comprise a variety of stratigraphic traps due to the rapid dip-direction changes from nonmarine to marine deposition and the along-strike interference by submarine canyons and/or fault blocks. The case studies presented here demonstrate that there is no prescriptive trap

scenario associated with subduction zones; instead the various possibilities appear evenly distributed across highly productive subduction-zone basins. In the Cook Inlet and the Talara basin, traps are largely structural but differ strongly in style due to compressive versus oblique-extensional stresses acting in each forearc, respectively. Cook Inlet traps are faulted anticlines (LePain et al., 2013), whereas those in the Talara basin are multi-stage, with anticlinal domes related to Miocene compression overprinted by normal faults related to post-Miocene extension (Zúñiga-Rivero et al., 1998). On the other hand, traps in the Sacramento basin are more diverse and include anticlinal closures, stratigraphic pinch-outs, stratigraphic abutment against mud-filled submarine canyons, and associated with volcanic intrusion doming (Fig. 12; Beyer, 1988).

While the structural variability at subduction zones provides numerous trap possibilities, that same complexity makes hydrocarbon prediction more difficult and may be the primary reason that commercial extraction from forearc basins is dominated by onshore rather than offshore production. On a very large scale, the dynamics of plate convergence are highly variable, in terms of the approach, subduction, and/or accretion of significant lithosphere features, such as spreading ridges, oceanic plateaus, and island arcs (Cloos, 1993). We see this in the Cook Inlet, where Cenozoic deformation appears to have been mostly shaped by flat-slab subduction of a spreading ridge and later an oceanic plateau (Trop and Ridgway, 2007; Finzel et al., 2016). In the Talara basin, there are particularly complex structural relationships related to changing plate convergence rates and increasingly oblique orientation (Pardo-Casas and Molnar, 1987; Jaillard et al., 1995; Silver et al., 1998) as well as the docking of island arc and oceanic lithosphere (Reynaud, et al., 1999; Spikings et al., 2005) and later collision and partial subduction of the Carnegie Ridge (Pedoja et al., 2006; Witt et al., 2006) immediately to the north along the margin of Ecuador. In response to these tectonic events, the Talara basin was partitioned into variably-sized, now-inverted fault blocks related to normal, transcurrent, and gravitational slip (Zúñiga-Rivero et al., 1998) between which occur rapid lateral facies changes (Fildani et al., 2008). This structural and stratigraphic complexity is a major reason that despite significant offshore potential, production here is mostly limited to onshore wells and is marked by very dense well spacing (>12,000 wells) across more than 42 oil and gas fields, half of which contain known recoverable resources of <1 MMBOE (Higley, 2004).

Progressive arc-ward deformation of accretionary wedges can result in suitable structural traps, as observed in ocean-ward fields of highly productive basins such as Cook Inlet (LePain et al., 2013), smaller producing basins such as the Tobago Trough (Larue et al., 1985; Schenk et al., 2012), and prospective locations such as the Bay of Bengal (Parida et al., 2011) and Nankai Trough (Ramirez et al., 2015). More often than not, however, rampant fracturing across the trench slope produces secondary porosity that can leak hydrocarbon (Underwood and Moore, 1995), and most hydrocarbons generated within an accretionary wedge may in fact seep onto the ocean floor (Larue, 1991). Notably, cold seeps associated with subduction zones often occur proximal to the accretionary wedge as observed offshore Brunei (Zielinski et al., 2007) and Barbados (Kiel and Hansen, 2015).

PROSPECTIVE SUBDUCTION ZONES

There appear to be significant recoverable reserves in subduction zones, considering various assessments using recent (since 2000) data and geologic understanding (Table 2). Particularly in already productive, mostly onshore basins such as Talara, Cook Inlet, and Barbados, the undiscovered reserve estimates largely reflect new offshore and/or deep oil and gas targets, including fractured Paleozoic basement in the Talara basin (Higley, 2004). There is new confidence in previously dismissed forearc basins that are associated with prolific backarc regions, such as the Simeulue basin in Sumatra (Lutz et al., 2011), recognizing that deep burial can counteract low geothermal gradients to generate a working petroleum system in forearc basins. There is also a new tendency to consider unconventional production and target deep source rock for oil and gas, an approach that could add significant production to the East Coast Basin in New Zealand (Campbell et al., 2008). Also, there is geopolitical motivation behind forearc exploration in the South Pacific, where island nations such as Fiji and Tonga desire energy independence and are exploring what may be considerable offshore reserves in Miocene carbonate reefs (Pflueger et al., 1989; Rodd, 1992; Scholl and Herzer, 1992). Recent exploration in Miocene–Pliocene turbidites in the Tayrona-Rancheria basin offshore Colombia was considered a commercial success for gas (Leslie and Mann, 2015), part of growing interest and confidence in subduction-related petroleum systems in Central America (e.g., Sandino basin, Costa Rica, and Nicaragua; Struss et al., 2008) and the Caribbean (e.g., Tobago Trough, Barbados; Schenk et al., 2012). The structural complexity of forearc basins has certainly raised risk as well as cost, and has significantly inhibited offshore drilling even in already productive subduction zones (e.g., Talara basin), but as regions make gains in infrastructure and data acquisition, offshore production could become routinely successful such as in the Cook Inlet basin.

CONCLUSIONS

Subduction zones are considered one of the least prospective tectonic settings, and hydrocarbon production from subduction zones has historically been limited to a few economic basins, namely the Cook Inlet and Sacramento basins (USA) and the Talara basin (Peru). These successful basins have several features in common that allowed significant petroleum generation and preservation, specifically their proximity to a continental arc, adequate time-to-maturation, thick basin fill with good arkosic reservoirs, and large-scale buried structures. In addition, each basin has a tectonic evolution (e.g., onset of flat-slab subduction or transition to a transform margin) that forced thermal and structural conditions favorable to basin preservation and hydrocarbon generation. These basins also show differences in source rock, sedimentary facies distributions, and trap mechanisms that are a testament to the complexity of subduction zone processes. As our knowledge of subduction zones has grown with marine drilling and imaging programs, our ability to predict

TABLE 2. PROSPECTIVE SUBDUCTION ZONE BASINS

Basin	Location	Arc-trench system	Arc type ¹	Geotectonic feature	Hydrocarbon potential	Maximum fill thickness (m)	Reservoirs	Source rock	Traps	References
Cook Inlet	United States	Alaska-Aleutian	Continental (I)	Forearc	19,000 BCFG/600 MMBO	17,000	Deep Jurassic coalbed; Tertiary and/or Quaternary fluvial	Marine shale	Anticlines; stratigraphic	Scheirer et al. (2006b)
Talara	Peru	Peru-Chile	Continental (I)	Forearc and trench slope	1710 MMBO/4790 BCFG; 2220 MMBO/5844 BCFG	18,000	Offshore Eocene turbidites; fractured Pennsylvanian quartzite	Marine shale	Block faults; stratigraphic	Higley (2004); Gonzales and Alarcon (2002)
Sacramento	United States	Farallon-Sierra (ancient)	Continental (I)	Forearc (ancient)	538 BCFG mean	20,000	Deep Upper Cretaceous submarine fans and deltaics	Marine shale	Anticlines; stratigraphic	Scheirer et al. (2006b)
Progreso	Peru-Ecuador	Peru-Chile	Continental (I)	Forearc	237 MMBO/695 BCFG	9000	Oligocene-Miocene marine to nonmarine sandstone	Oligocene-Miocene marine shale	Structural variety; normal faults with updip closure; paleohigh onlap	Higley (2004) (Progreso)
Andaman	Myanmar-Indonesia	Sunda-Burmese	Intraoceanic (VI)	Forearc	One gas discovery	8000	Miocene carbonate and turbidites	Paleogene-Miocene Type III	Large structural (thrusts toward ocean; normal faults toward arc); stratigraphic	Parida et al. (2011); Roy and Sharma (1993)
Tobago Trough	Barbados	Lesser Antilles	Intraoceanic (VI)	Inner forearc deformation belt	1125 MMBO/6750 BCFG (median recoverable)	10,000	Quartz arenite turbidites delivered by ancestral Rio Orinoco	Upper Cretaceous-Paleogene organic-rich marine shales	Anticlines associated with westward thrusting of accretionary wedge	Schenk et al. (2012)
Tayrona-Rancheria	Colombia	Lesser Antilles	Continental (I)	Forearc; basement high in deepwater	One exploration well, called a commercial success for gas	5000	Miocene-Pliocene turbidites	Upper Cretaceous-Paleogene (oil prone), Miocene-Pliocene (gas prone)	Large anticlinal folds	Leslie and Mann (2015)
East Coast	New Zealand	Tonga-Kermadec-Hikurangi	Intraoceanic (VI)	Exhumed forearc	>300 oil/gas seeps; estimates for north East Coast Basin area: 53.3 MMBO (conventional), 302.1 MMBO (unconventional)	4000	Paleocene Waipawa Black Shale	Paleocene Waipawa, Whangai shales	Thrust fault anticlines	Campbell et al. (2008); New Zealand Energy Corp. East Coast Fact Sheet
Simeulue	Sumatra	Sunda	Intraoceanic (VI)	Forearc	Positive seismic and seeps; proximity to prolific Central Sumatra (backarc) basin	7000	Oligocene-Miocene carbonates	Eocene and early-middle Miocene	Carbonate reefs	Lutz et al. (2011)
Sandino	Nicaragua	Central America	Continental (I)	Forearc	Oil and gas shows in four offshore wells; onshore seeps	10,000	Eocene to Miocene turbidites and carbonate reefs	Cretaceous black shales; Eocene-Miocene	Outer structural high; anticlines	Struss et al. (2008)
Tonga Ridge	Tonga	Tonga-Kermadec-Hikurangi	Intraoceanic (VI)	Forearc	Mature oil in seeps on Tongatapu	5000	Eocene to Miocene Carbonate reefs	Marine carbonate Type II kerogen from seeps; not penetrated	Reefs; fault-bound Closures	Scholl and Herzer (1992); Pflueger et al. (1989); Summons et al. (1992)
Bligh Water	Fiji	Tonga-Kermadec-Hikurangi	Intraoceanic (VI)	Transitional forearc-backarc	1700 MMBOE recoverable reserves	4000	Miocene carbonate reefs and turbidites	Oligocene-Pliocene carbonate algal Types II and III	Thrust anticlines and reef mounds	Rodd (1992)
East Timor	Indonesia	Banda	Intraoceanic (VI)	Transitional forearc to continental collision	Numerous oil and gas seeps; oil and gas shows in early wells	n.d.	Triassic-Jurassic shallow marine and turbiditic sandstones	Type II-III; Triassic-Jurassic restricted marine; mixed carbonate and clastic	Anticlines; inverted basement structures	Charlton (2002)

¹Based on categories in Dickinson (1995). I—contains mainland volcanoes within continental landmass; VI—migratory system without continental basement in arc. Abbreviations: BCFG—billion cubic feet of gas; MMBO—million barrels of oil; MMBOE—million barrels of oil equivalent; n.d.—not determined.

favorable hydrocarbon conditions in under-explored forearc and trench-slope basins should improve prospectivity in the offshore portions of successful basins and in terms of unconventional resources. Advancements with respect to the volume, distribution, and migration of subduction zone hydrocarbons will also serve global carbon models, where convergent margins are significant sites of crustal and fluid cycling.

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