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# **3.2** Thermal structure and source rock maturity of the North Peruvian forearc system: Insights from a subduction-sedimentation integrated petroleum system modeling.

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Research paper

Thermal structure and source rock maturity of the North Peruvian forearc system: Insights from a subduction-sedimentation integrated petroleum system modeling

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#### Abstract

Basin modeling is commonly used for the hydrocarbon potential evaluation of underexplored areas, taking into account the full basin history to assess its thermicity and fluid distributions. In the case of forearc basins, however, the influence of the subduction on the internal thermal structure is difficult to predict. The existing subduction thermal models usually focus on the present day lithosphere and do not consider the sediment infill history, while industrial modeling tools handle the thermal evolution of sedimentary basins but not the subduction process. In this paper, we propose a solution model in which the cooling engendered by the subduction is represented by the advective term of the heat conservation energy equation throughout the sedimentation. This study focuses on the Talara-Tumbes-Lancones petroleum province, part of the North Peruvian forearc system. Despite the long term exploration of the Talara Basin, the origin of its massive oil fields still remains questioned. The new subductionsedimentation integrated petroleum system modeling presented here, calibrated by numerous structural and thermometric data, allows to better constrain the thermal structure and source rock maturity history of this forearc system. We show that the exposure of the sedimentary basin to the subducting cold lithosphere, the sedimentation rate and erosion are important factors impacting the maturity of the source rocks. Consequently, even in the same subduction setting, each depocenter of the North Peruvian forearc system presents a different thermal history and maturity timing, and each basin presents an independent petroleum system.

#### Keywords

Basin modeling; thermal model; petroleum systems; subduction-related basins; North Peruvian forearc system

#### 3.2.1 Introduction

Understanding the thermal history of forearc basin systems is a challenge to better evaluate oil and gas exploration potential in subduction zones. Forearc systems are generally considered as regions with low petroleum potential due to high structural and stratigraphic complexities, polyphase tectonic histories, and depressed thermal regime (Hessler and Sharman, 2018). However, the producing Talara Basin, part of the North Peruvian forearc zone, is one of the striking exceptions to this generally held idea, as are the Cook Inlet Basin along the Alaska-Aleutian forearc zone or the Sacramento Basin along the Cascadia subduction zone of the USA (Moberly et al., 1982; Carozzi and Palomino, 1993; Higley, 2004a,b; Fildani et al., 2005; Harun et al., 2014; Hessler and Sharman, 2018). Significant hydrocarbon production occurs in these basins (Hessler and Sharman, 2018). To better understand the thermal history of the forearc regions and the dynamics of their petroleum systems, we focused on the thermal modeling of the North Peruvian forearc system across the Tumbes-Talara-Lancones basins system (Figure 3.1). The structural architecture and tectonic evolution of this forearc basins system is constrained by considerable surface and subsurface database (including more than 9 000 km of 2D seismic reflection profiles, several 3D seismic blocks and more than 14 500 wells) and exhumation data (Fernández et al., 2005; Espurt et al., 2018). The North Peruvian forearc system is characterized by a thick Cretaceous to Quaternary siliciclastic succession up to  $\sim 10$  km thick that extends onshore and offshore. It displays a complex structural and stratigraphic architecture dominated by the accretion or underplating of crustal (continental and oceanic) and sedimentary rocks since the Late Cretaceous times (Espurt et al., 2018; Brusset et al., 2018). The tectonic wedge is formed by structural highs and major forearc depocenters that are synchronously deformed by thrusts, normal growth faults and gravitational instabilities, as well as strike-slip faults.



Figure 3.1: Geodynamic settings. (a) Map of the Northern-Central Andes showing the study area of Figure 3.2. The base map is produced using elevation data from NASA (National Aeronautics and Space Administration) 30 m ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) GDEM (Global Digital Elevation Model). Plate convergence vector and velocities (mm/yr) are from Gripp and Gordon (2002). Mapping, vector, and velocities (mm/yr) of the continental slivers are from Villegas-Lanza *et al.* (2016). (b) Location of main depocenters. The location of the balanced and restored cross-section by Espurt *et al.* (2018), used in this work is shown. The sedimentary basins contours are from PERUPETRO S.A. database. BP: Banco Peru; ZH: Zorritos High; CH: Carpitas High; AH: Amotape High; PH: Paita High; IH: Illesca High; HD: Huacabamba Deflection; SR: Sarmiento Ridge; AR1-2: Alvarado Ridge 1 and 2; GR: Grivalja Ridge; WC: Western Cordillera.

The thermal regime of forearc systems is strongly controlled by the cooling effect of the cold subducting oceanic plate (Dumitru, 1988; Allen and Allen, 2005). The subduction process moves the oceanic crust, from the sea floor to deeper, warmer, conditions. This causes a negative thermal anomaly that engenders the cooling of the overlying rocks of the forearc basins system. Several authors addressed the thermal regimes of subduction areas (Peacock, 1990; Hyndman *et al.*, 1995; Molnar and England, 1995; Oleskevich *et al.*, 1999; Yoshioka and Murakami, 2007). They developed thermal models and show accurate results, in accordance with the available surface and near surface thermal data and also in coherence with the location of seismogenic zones. However, the existing subduction thermal models address interest to the temperature distribution of the lithosphere at present day, whereas in order to evaluate the thermal influence of the subduction on the petroleum system dynamics, a

model needs 1) to focus on the sedimentary basin and 2) to assess the paleo-thermal field during the entire basin history. Yet, the industrial basin modeling software that address these questions are not developed to handle the thermal cooling induced by subduction.

A solution is proposed in this paper to consider the impact of the subduction on the evolution of the source rock maturity through the basin history. The goal of this paper is to present the thermal history of the North Peruvian forearc system using an interdisciplinary approach. For that, the sequentially restored crustal scale balanced cross section previously published in Espurt *et al.* (2018) is used in an integrated petroleum system model that accounts for both the sedimentary and subduction processes. The extensive surface and subsurface data (vitrinite reflectance, thermal gradients and bottom seismic reflectors) available in the region, together with new surface vitrinite reflectance measurements, serve as calibration data for the subsurface model. The structural model was tested and its impact on the thermal maturity of the potential source rocks was analyzed using an adapted workflow in TemisFlow® 2019.1 software, from Beicip Franlab (Ungerer *et al.*, 1990; Schneider *et al.*, 2000; Willien *et al.*, 2009). The results provide insights to the thermal history of each depocenter, allow to test some of the postulated hypotheses for the origin of the Talara basin's oil accumulations, and can help develop new strategies for future exploration in this region.

#### 3.2.2 Geological and tectonic context

The development of the North Peruvian forearc system is related to the NE- to E- directed (i.e., oblique to perpendicular) post-Jurassic subduction of the Caribbean, Farallon and Nazca oceanic plates beneath the South American continental plate (e.g., Pindel and Kennan, 2009; Figure 3.1a). It is a tectonically active area with shallow and very weak interseismic coupling (Villegas-Lanza *et al.*, 2016). Somoza and Ghidella (2012) divided the Late Cretaceous-Cenozoic convergence history in western South America in three periods. (1) The Late

Cretaceous to Early Eocene (~56-47 Ma) period shows a relatively slow (4-5 cm/yr) NE motion of the Farallon plate. (2) The Early Eocene-Oligocene period (~47-28 Ma) is characterized by an almost constant convergence rate of ~9 cm/yr. The Oligocene peak of convergence and a coeval change of subduction direction coincide with the breakup of the Farallon plate into the Cocos and Nazca plates (Lonsdale, 2005; Somoza and Ghidella, 2012), and (3) the Late Oligocene to present period (~25-0 Ma) is characterized by an ENE-trending motion of the Nazca plate with convergence rates decreasing from 15 cm/yr to 7 cm/yr. This period is characterized by the subduction of the Inca Plateau (Gutscher *et al.*, 1999b) and the Carnegie Ridge in the Middle Miocene (Daly, 1989; Gutscher *et al.*, 1999a; Schütte *et al.*, 2010) and more recently, in the Quaternary, by the subduction of the Sarmiento and Alvarado Ridges (Lonsdale, 2005; Espurt *et al.*, 2018). The age of the subducting lithosphere decreases from ~70 Ma in the Paleocene to ~20Ma at present (Sdrolias and Müller, 2006).

The Tumbes, Talara and Lancones basins are part of the North Peruvian forearc system that extends from the Western Cordillera volcanic arc to the Peru-Chile trench (Figure 3.2). They result from a seaward depocenter shift from the inner Lancones Cretaceous depocenter to the Cenozoic Tumbes depocenter. Espurt *et al.* (2018) used field data, wells, seismic reflection profiles together with apatite fission-track data and thermal history modeling to build a section crossing these three depocenters (Figure 3.2). East of the Talara Basin is the Amotape high, followed by the Lancones Basin. West of the Talara Basin are the Zorritos and Carpitas basement highs, followed by the Tumbes Basin that extends northeast offshore, towards the Progresso Basin in Ecuador. The Tumbes Basin is limited westward by the Banco Peru. accretionary prism. Palinspastic restorations suggest that these depocenters were connected in the past, and the successive episodes of deformation and erosion that took place from Early Eocene to Quaternary were responsible for the basin's partitioning observed today (Espurt *et al.*, 2018). The authors interpreted a regional Early Eocene cooling/exhumation, followed by a

Middle to Late Eocene reheating/burial, and then by an Oligocene-Miocene cooling/exhumation (Figure 3.3c), as well as a last stage of cooling/exhumation during Middle Miocene (~15 Ma) for the Amotape High. These exhumation pulses are correlated with major erosional surfaces (Figure 3.4) and locally by growth strata across the forearc system (Espurt *et al.*, 2018). These vertical motion stages, as well as these major tectonic deformations in the forearc basins, are related to variations in convergence rates, as well as the plate coupling and the subduction of bathymetric asperities (Espurt *et al.*, 2018).



Figure 3.2. (a) Morphology, (b) geological map and (c) structural cross-section (modified after Espurt *et al.*, 2018) of the North Peruvian forearc system. For location, see Figure 3.1. FD: Forearc Depocenter; BPFZ: Banco Peru Fault Zone; TMFZ: Tronco Mocho Fault Zone; CFZ: Carpitas Fault Zone; CVF: Cabeza de Vaca Fault; CAF: Cuzco-Angolo Fault; EFZ: La Encantada Fault Zone.





The forearc stratigraphy is synthetized in Figure 3.4. The oldest depocenter, the Lancones Basin, involves Cretaceous strata with conglomerates at the base followed by successions of marine sequences, locally associated with small intrusive bodies (Jaillard *et al.*, 1999; Valencia and Uyen, 2002). These strata are deformed firstly by NW verging thrust-related anticlines during the Late Cretaceous (Jaillard *et al.*, 1999; Andamayo, 2008; Espurt *et al.*, 2018), and then by Cenozoic normal faults (Valencia and Uyen, 2002; Andamayo, 2008;

Espurt et al., 2018). The Amotape High is a prominent range exposing Paleozoic rocks and Triassic intrusions (Figure 3.2). The Talara Basin extends onshore and offshore (Figure 3.1b and Figure 3.2), but only its onshore part is crossed by the studied section. In this northern part, the Talara Basin is currently formed by up to 3.5 km-thick Eocene to Miocene fluvial to deep marine strata deformed by major NE trending, SE dipping listric normal faults connected at depth with the basement (e.g., Carpitas fault zone) (Séranne, 1987; Higley, 2004a; Fernández et al., 2005; ). Southward, the thickness of the Talara depocenter reaches up to 9 km. While no Cretaceous strata has yet been identified in its northern part, it has been revealed by exploration wells in the southern onshore-offshore part of the Talara Basin (Talara town and Punta Balcones areas) and in outcrops south of the Amotape High (Figure 3.4b). The offshore Tumbes Basin depicts two stacked progradational sedimentary wedge systems of Eocene to Quaternary sediments up to 11 km thick. The lower wedge consists of a seaward prograding wedge of Eocene-Early Oligocene strata. The upper wedge is formed by Late Oligocene to Quaternary strata deformed by Miocene to present syndepositional growth faults and rollovers. The basement that underlies the Talara and Lancones Basins is composed of the Amotape basement (including Paleozoic sedimentary and metamorphic rocks, as well as Triassic intrusions) whereas towards the trench, the Amotape basement gets thinner, and the Tumbes Basin ends up lying above accreted off-scrapped sediments directly exposed to the oceanic crust (Figure 3.2c; Bourgois, 2013; Espurt et al., 2018).

#### 3.2.3 Petroleum systems overview

There are at least 40 oil and/or gas fields documented in the Talara Basin, with a cumulative oil and gas production of 1680 MMBO and 340 BCF, respectively (Higley, 2004a). The rate of exploration success is not published, but amid the gathered dataset of 1118 exploratory wells, at least 45% are reported to be dry holes. The Tumbes Basin is considerably less explored than the Talara Basin and has a discovery rate of 30% (Higley, 2004b). The central

part of the Talara Basin is its most proliferous area, concentrating the oil fields. In our study area, in the northern Talara Basin and the onshore Tumbes Basin, mostly gas fields are present, sometimes associated with oil. The density of Tumbes and Talara oils varies from 18 to 48 °API. Geochemical analyses indicate they present different degrees of biodegradation, but were all originated from a same type of source rock, with probably at least two migration pulses (Higley, 2004a; Hessler and Sharman, 2018; and references therein). The Cretaceous source rocks of the Muerto and Redondo Formations (deep marine black shales with type II, II/III kerogen; Figure 3.4 and Figure 3.5) have sufficient organic matter content (1-4.5% TOC) and thermal maturity to be considered active source rocks in the Talara Basin, where they are present (Fernández et al., 2005; Table 3.1). These Cretaceous source rocks were considered as the main source of the petroleum present in the area (Higley, 2004a and references therein). But geochemical analyses using molecular biomarker analysis from oil samples and Cretaceous potential source rocks failed to establish a direct correlation between oil and source (Fildani et al., 2005). The main point for this lack of correlation was the presence of Oleanane and other age-discriminant biomarkers that point towards a Tertiary marine source for the analyzed oils. The Oligocene-Miocene Heath potential source rock or an equivalent interval in the Talara Basin, was then identified as the probable source for the analyzed oils (Fildani et al., 2005). Marine shales of the Oligocene-Miocene Heath Formation have been observed in the Tumbes Basin in wells and in outcrops along the coast, with fair potential (up to 1.85% TOC) and composed predominantly by terrestrial organic matter (Figure 3.4 and Figure 3.5; Table 3.1). This potential source rock is immature where sampled (Table 3.1Table 3.2; Fernández et al. 2005) but is expected to have generated hydrocarbon at deeper parts of the depocenter (Fildani et al., 2005, Fernández et al., 2005), where it is likely richer.



Figure 3.4. Synthetic stratigraphy of the North Peruvian forearc system showing the main source and reservoir rocks (modified from Fernández et al., 2005 and Espurt et al., 2018).

It is worth noting that the Muerto Formation samples used in these geochemical analyses did not have good source rock characteristics (Fildani *et al.*, 2005). Alternative explanations for the Oleanane presence in the Talara oils are the acknowledgment of a younger, Upper Cretaceous, age for the Muerto Formation (Fernández *et al.*, 2005) or the occurrence of locally potential Tertiary source rocks (Higley, 2004a and references therein). The available TOC measurements and pyrolysis data indicate also a locally fair source rock potential for Eocene Talara shales (Fernández *et al.*, 2005; Figure 3.3 and Figure 3.4; Table 3.1).

Table 3.1. (next page) Pyrolysis rock eval, Total organic carbon (TOC) and vitrinite reflectance (%Ro) measurements from outcrop samples in the study area. Tmax–Maturity; HI–Hydrogen Index; OI– Classical Oxygen Index; SD–Standard deviation; N–number of particles. Analyses were conducted by Energy Resources Consulting Pty Ltd (Australia)\* and LCV (Argentina). LCV data are provided by PERUPETRO S.A..

Sample name	Longitude (m)	Latitude (m)	Depocenter or structural unit	Stratigraphic age/Formation	T <sub>max</sub> (°C)	HI	01	TOC (wt%)	%Ro	Range	SD	N
TUM16-1*	538393	9588769	Zorritos High	Late Oligocene/Heath	414	152	72	0.85	0.34	0.23-0.42	0.049	25
TUM16-4*	534301	9578130	Carpitas High	Late Oligocene/Heath	428	66	31	1.75	0.44	0.34-0.59	0.062	25
TUM16-7*	534753	9575493	Carpitas High	Middle Eocene/Talara	444	12	163	0.32	-	-	-	-
TUM16-8*	540462	9572069	Talara	Early Oligocene/Plateritos	426	32	82	0.43	0.65	0.51-0.77	0.066	25
TUM16-9*	541735	9571488	Talara	Early Eocene/Mogollon	438	20	86	0.52	0.55	0.47-0.66	0.060	14
TUM16-15*	537556	9551751	Amotape High	Paleozoic/Amotape	490	34	38	0.20	-	-	-	-
TUM16-16*	512114	9546372	Amotape High	Early Eocene/Mogollon	440	102	43	0.68	0.68	0.55-0.80	0.062	25
TUM16-20*	511696	9546878	Talara	Early Eocene/Salinas	449	18	91	0.38	0.69	0.59-0.76	0.047	25
TUM16-21*	506754	9551524	Talara	Middle Eocene/Talara	433	93	29	0.70	0.61	0.48-0.73	0.067	25
TUM16-26*	504466	9554796	Talara	Early Oligocene/Mancora	441	51	73	0.20	0.53	0.44-0.66	0.053	25
TUM16-27*	504268	9559720	Talara	Late Oligocene/Heath	430	36	42	0.63	-	-	-	-
TUM16-28*	506036	9563148	Carpitas High	Late Eocene/Chira	438	25	99	0.43	0.53	0.44-0.60	0.037	25
TUM16-30*	505785	9513566	Carpitas High	Early Oligocene/Plateritos	429	47	102	0.54	0.51	0.42-0.61	0.049	25
TUM16-33*	506092	9513654	Amotape High	Paleozoic/Amotape	580	21	55	0.33	1.75	1.57-1.88	0.101	8
TUM16-34*	506230	9514009	Amotape High	Paleozoic/Amotape	580	19	24	0.32	1.75	1.58-1.87	0.094	10
TUM16-35*	506603	9514421	Amotape High	Paleozoic/Amotape	623	8	64	0.38	1.77	1.62-1.97	0.083	25
TUM16-37*	499689	9507018	Amotape High	Paleozoic/Amotape	606	15	85	0.32	1.91	1.76-2.06	0.101	9
TUM16-48*	538393	9588769	Talara	Middle Eocene/Talara	436	370	26	1.13	0.51	0.39-0.63	0.064	25
TUM-808	533815	9578677	Carpitas High	Late Oligocene/Heath	413	126	42	1.83	0.42	0.28-1.07	0.030	6
RoG1	522695	9511318	Amotape High	Paleozoic/Amotape	-	-	-	-	2.66	2.11-2.99	0.220	32
RoG2	523110	9510871	Amotape High	Paleozoic/Amotape	-	-	-	-	2.44	1.98-2.78	0.197	50
RoG3	523071	9510728	Amotape High	Paleozoic/Amotape	-	-	-	-	1.71	1.40-2.08	0.200	23
RoG6	523786	9510151	Lancones	Albian/Pananga	-	-	-	-	1.16	1.06-1.23	0.062	6
RoG7	524892	9510009	Lancones	Late Cretaceous/Encuentros	-	-	-	-	1.08	0.91-1.32	0.108	21
RoE1	554080	9525589	Lancones	Late Cretaceous/Encuentros	-	-	-	0.7	1.42	1.15-1.73	0.123	38
RoE2	554876	9553202	Lancones	Late Cretaceous/Encuentros	-	-	-	0.69	1.49	1.28-1.69	0.115	35
RoE3	555088	9522414	Lancones	Late Cretaceous/Encuentros	-	-	-	0.69	1.47	1.25-1.67	0.113	40
RoE4	555085	9521357	Lancones	Late Cretaceous/Encuentros	-	-	-	0.68	1.53	1.32-1.83	0.123	24
RoE5	554353	9520661	Lancones	Late Cretaceous/Encuentros	-	-	-	0.59	1.49	1.27-1.72	0.145	20
RoE6	554060	9519618	Lancones	Late Cretaceous/Encuentros	-	-	-	0.22	1.49	1.32-1.71	0.118	10
RoE7	554580	9519555	Lancones	Late Cretaceous/Jahuay Negro	-	-	-	0.39	1.55	1.36-1.78	0.128	20
RoE8	554819	9519352	Lancones	Late Cretaceous/Jahuay Negro	-	-	-	0.33	1.54	1.31-1.77	0.163	9
RoE9	555354	9519209	Lancones	Late Cretaceous/Huasimal	-	-	-	0.15	1.79	1.61-1.99	0.143	11
RoE10	555758	9519018	Lancones	Late Cretaceous/Huasimal	-	-	-	0.38	2.05	1.67-2.47	0.184	50
RoE11	556159	9518659	Lancones	Late Cretaceous/Huasimal	-	-	-	0.3	2.07	1.69-2.43	0.199	27
M4-C1CC	568230	9485441	Lancones	Albian/Muerto	-	-	-	0.54	3.62	2.81-4.29	0.503	14
M6-C266	568191	9485445	Lancones	Albian/Muerto	-	-	-	1.6	2.42	2.15-2.77	0.319	3
GR-01	544333	9520870	Lancones	Late Cretaceous/Jahuay Negro	-	-	-	-	1.11	0.91-1.28	0.102	16
RoJP1	545069	9484356	Lancones	Late Cretaceous/Huasimal	-	-	-	-	1.28	1.10-1.55	0.129	18
RoJP2	546150	9484293	Lancones	Late Cretaceous/Huasimal	-	-	-	-	1.24	1.08-1.37	0.093	9
GR-02	544470	9520710	Lancones	Late Cretaceous/Jahuay Negro	-	-	-	-	1.17	0.97-1.37	0.116	17
GR-03	545120	9520160	Lancones	Late Cretaceous/Encuentros	-	-	-	-	1.12	0.98-1.34	0.109	10
GR-04	546010	9519297	Lancones	Late Cretaceous/Encuentros	-	-	-	-	1.12	0.95-1.39	0.154	8
GR-05	546409	9519071	Lancones	Late Cretaceous/Encuentros	-	-	-	-	1.11	0.89-1.38	0.131	33
GR-06	547147	9518600	Lancones	Late Cretaceous/Encuentros	-	-	-	-	1.32	1.11-1.52	0.102	50
GR-07	547842	9518788	Lancones	Late Cretaceous/Encuentros	-	-	-	-	1.27	1.03-1.48	0.102	50
GR-08	548950	9518492	Lancones	Late Cretaceous/Encuentros	-	-	-	-	1.32	1.15-1.50	0.105	25
GR-15	543036	9520831	Lancones	Late Cretaceous/Jahuay Negro	-	-	-	0.31	1.22	1.00-1.39	0.122	18
SA-1	530004	9498432	Lancones	Late Cretaceous/Huasimal	-	-	-	-	1	0.82-1.17	0.100	14
SA-1A	531342	9497048	Lancones	Late Cretaceous/Huasimal	-	-	-	-	1.14	1.03-1.26	0.097	4
SA-2	529655	9499554	Lancones	Late Cretaceous/Jahuay Negro	-	-	-	-	1.04	0.90-1.18	0.105	11
SA-4	530055	9500306	Lancones	Late Cretaceous/Jahuay Negro	-	-	-	-	1.09	0.90-1.28	0.114	13
SA-5	529164	9501076	Lancones	Late Cretaceous/Encuentros	-	-	-	-	1.01	0.91-1.17	0.068	18
SA-8	528604	9501293	Lancones	Late Cretaceous/Encuentros	-	-	-	-	1.04	0.88-1.25	0.109	18
SA-9	528515	9501306	Lancones	Late Cretaceous/Encuentros	-	-	-	-	0.94	0.78-1.06	0.091	10
SA-10	527653	9501772	Lancones	Late Cretaceous/Encuentros	-	-	-	-	1.06	0.97-1.27	0.082	12
HUA-1	534973	9507886	Lancones	Late Cretaceous/Huasimal	505	35	16	0.6	1.6	1.42-1.79	0.090	50
OV-3	532580	9523601	Lancones	Albian/Lower Muerto	448	142	44	0.71	0.91	0.91-0.91	_	1
OV-4	532580	9523601	Lancones	Albian/Lower Muerto	500	51	49	1,18	0.79	0.79-0 79	_	1

The migration mechanism is also still debated (Hessler and Sharman, 2018). The hypothesis of hydrocarbon generation from the Oligocene-Miocene source rock in the offshore Tumbes depocenter (Fildani *et al.*, 2005) requires a long migration towards the onshore Talara Basin before the segmentation of the two basins. But several authors point towards a preferential vertical migration with limited lateral migration (10-50 km) in the Talara Basin onshore domain (Higley, 2004a and references therein), which is only possible if the hydrocarbon generation occurs locally within the Talara Basin boundaries, and if there is enough structure to capture enough oil to break through vertically. An intermediate alternative is proposed by Fernández *et al.* (2005), that established a correlation between the location of the oil fields, at structural highs, with the surrounding deep areas, and suggested that the known deep onshore grabens could extend offshore and allow a larger lateral migration.



Figure 3.5. Oxygen Index (OI) versus Hydrogen Index (HI) (Van Krevelen diagram; Espitalité *et al.*, 1985) with the available Rock Eval data (Table 3.1 and Table 3.2; Fernández *et al.*, 2005).

Several good quality reservoirs are present throughout the Talara Basin stratigraphic sequences (Figure 3.4). The main reservoirs are Eocene sandstones interbedded with shale seals (Fernández *et al.*, 2005). In the Tumbes Basin, potential good quality reservoirs are present from the Oligocene Mancora to the Pliocene-Quaternary La Cruz Formation. The primary reservoirs are the Miocene marine sandstones of Zorritos Formation (Fernández *et al.*, 2005). The predominant structural trap type of the Talara Basin comprises tilted fault blocks, controlled by listric basement faults and gravitational cover structures (Fernández *et al.*, 2005).

#### 3.2.4 Thermal calibration

Vitrinite reflectance (Ro) data and present-day geothermal gradient data are presented in Figure 3.3a and in Table 3.1 and Table 3.2. Part of these data is projected onto the studied cross section in Figure 3.3b. These data were used to update the structural and kinematic model of Espurt *et al.* (2018) and assure the calibration of the presented thermal model. Information concerning the presence of bottom seismic reflectors was also gathered and used to verify the model calibration in areas where no direct measurement is available.

Table 3.2. Vitrinite measurements from Tumbes basin wells (cutting) in the study area. See legend in Table 3.1. Data are provided by PERUPETRO S.A..

١	Well name	Longitude (m)	Latitude (m)	Stratigraphic age/Formation	Depth interval (mbsl)	%Ro	Range	SD	Ν
E	Barracuda 15X-1	538393	9588769	Late Miocene/Cardalitos	2469-2569	0.29	0.21-0.34	0.043	8
E	Barracuda 15X-1	534301	9578130	Early-Middle Miocene/Zorritos	4151-4179	0.32	0.26-0.39	0.034	39
[	Delfin 39X-1	534753	9575493	Early-Middle Miocene/Zorritos	1774-1856	0.30	0.26-0.35	0.030	9
(	Corvina 40-10X	540462	9572069	Late Oligocene/Heath	3008-3027	0.35	0.26-0.41	0.040	14

#### 3.2.4.1 Ro data

The Ro is a sensitive geothermometer that indicates the organic matter maturity of the rocks in sedimentary basins and can be used with caution to reconstruct the amount of burial/erosion (e.g., Kamp *et al.*, 1996; Espurt *et al.*, 2011). The Ro value is a function of the kinetic transformation of organic matter, commonly associated with temperature increase during burial (Sweeney and Burnham, 1990; Peters and Cassa, 1994). We present 57 Ro

measurements in shale outcrops of the Paleozoic-Late Miocene sedimentary succession from the North Peruvian forearc system (Figure 3.3 and Table 3.1). The first 15 measures presented in Table 3.1 were analyzed by Energy Resources Consulting Pty Ltd using a Leica MP4500P system with Hilgers DISKUS software and concern only the ones considered to represent the indigenous vitrinite population. The other measurements, provided by Perupetro S.A., were analyzed by LVC. Besides these surface Ro, measurements from four offshore wells in the Tumbes Basin were also provided by Perupetro S.A. (Figure 3.3 and Table 3.2).

The surface Ro data show a clear increasing maturity tendency from sea (Tumbes Basin) to land (Lancones Basin). Ro data from wells in the shallow offshore Tumbes Basin show immature (0.29-0.35%) Oligocene to Late Miocene rocks with more than 3 km of overburden at present day. In the outcrop area, Oligocene-Early Miocene strata of the Zorritos High show a similar Ro value of 0.34%. Quite mature values (0.53-0.65%) are found in the Late Eocene-Oligocene strata of the Carpitas High. The values increase to 0.69% in the Middle Eocene strata of the Talara Basin center. Cretaceous rocks of the Lancones Basin show higher Ro values ranging from 0.91% to 2.07%. The highest Ro values (2.66-3.62%) are found in Paleozoic rocks of the Amotape High and in lower Cretaceous rocks of the outer part of the Lancones Basin.

#### 3.2.4.2 Present day temperatures and geothermal gradients

The bottom hole temperatures (BHT) measured in 44 onshore wells were gathered from well log files. The wells located close (<10km) to the modeled section were used to support its present day thermal calibration. Additionally, the geothermal gradients were calculated using a 25°C surface temperature (Figure 3.3). Geothermal gradients presented in exploration reports provided by Perupetro S.A. (Perez Compane S.A., 2000; AIPC, no date) were also collected to help understanding and constraining their variability along the studied area (Figure 3.3).

The estimated present day geothermal gradient varies considerably with average values of 18°C/km offshore and 23°C/km onshore. The highest values observed onshore are located along the Cabeza de Vaca, Carpitas and Tronco Mocho fault zones (Figure 3.3a). The lowest onshore gradients are located south of the Carpitas High and north of the Zorritos High, under Quaternary sediments. Offshore, the lowest values correspond to the Cenozoic depocenter of the Tumbes Basin, and an increase is observed southward, when approaching the coast.

#### 3.2.4.3 Bottom seismic reflectors

The presence of methane hydrate in the Peruvian margin has been identified by Ocean Drilling Program Leg 112 along Central and South Peruvian margin (8-13°S) (Kvenvolden and Kastner, 1990) and interpreted by Auguy *et al.* (2017) through the observation of bottom simulator reflector (BSR) at the vicinity of Banco Peru, close to the trench. The presence of BSR is restricted to an area south and southwest of Banco Peru, at water depths deeper than 110m. In the inner slope of Banco Peru, i.e., inside the Tumbes-Progresso basin, no BSR is observed. Auguy *et al.* (2017) estimated the temperatures at the BSR depths using pressure-temperature curves for seawater-methane hydrate stability. The derived geothermal gradients range from 10 to  $50^{\circ}$ C/km, with an average value of  $26^{\circ}$ C/km.

#### 3.2.5 Methodology: petroleum system modeling in a subduction setting

Traditional basin and petroleum systems modeling tools simulate the thermal evolution of sedimentary basins, but they are not built to take into account the cooling effect associated with the oceanic lithosphere subduction. These models calculate the temperature and maturity evolution according to the sediments' thermal properties (e.g. thermal conductivity and heat capacity), deposition history and thermal boundary conditions. The boundary conditions are usually the temperature at the sediments' surface and either a geothermal gradient or a bottom boundary condition, that can be a basal heat flow or a crustal model with a fixed temperature at the base of the lithosphere. Relatively few petroleum systems modeling studies in forearc or

subduction-related basins have been published. In most of them (Lutz, 2011; Schultz, 2016; Burgreen-Chan and Graham, 2018), the bottom boundary condition is an inferred basal heat flow, applied at the base of the sedimentary basin, that may vary spatially and temporally in order to fit the basin's thermal data. Typical basal heat flow values for forearc basins range between 20 to 40 mW/m<sup>2</sup> according to Allen and Allen (2005). Most of the basal heat flow values defined during the subduction phase in the available studies are in accordance with this definition. Nevertheless, some locally higher or lower heat flow values are sometimes necessary to explain the thermal anomalies observed in the available data (Lutz, 2011; Schultz, 2016; Burgreen-Chan and Graham, 2018). In areas where few data are available and/or the sedimentary basin architecture is heterogeneous, using the basal heat flow as boundary condition is a source of high uncertainty for petroleum systems.

In the crustal model approach, the lithosphere thermal properties, structure, and the temperature at its base are defined (Ungerer *et al.*, 1990; Baur *et al.*, 2010; Roussé *et al.*, 2017). The calculation of the thermal model is then performed from the base of the lithosphere to the top of the sedimentary basin, integrating their geometrical evolution and thermal properties. In this case, the basal heat flow and the thermal gradients are obtained as model results, accounting for the thermal insulation caused by the deposition of cold sediments (blanketing effect). This coupled (sediment-basement) approach was used in this study. Additionally, the thermal cooling engendered by the subduction was replicated using advective heat transfer in the oceanic lithosphere, as often used in subduction thermal models (Peacock, 1990; Hyndman *et al.*, 1995; Oleskevich *et al.*, 1999; Marcaillou *et al.*, 2008).

#### 3.2.5.1 Subduction thermal structure and models

The downward motion of the subducting lithosphere brings sediments and water to deeper regions where temperature and pressure are higher. These changing conditions trigger physical and chemical reactions associated with mineral dehydration and melt generation, and consequently strong earthquakes and volcanic eruptions (Stern, 2002; Syracuse *et al.*, 2010). Since these physical and chemical processes occur in precise ranges of temperature-pressure coupling, a good understanding of the thermal structure of subducting lithosphere is crucial to define the updip and downdip limits of a seismogenic zone (Marcaillou *et al.*, 2006). McKenzie (1969) proposed the first analytical solution to this problem. He tried to predict how quick the slab would warm up while going down in a mantle that was not affected by the subduction. Even though McKenzie (1969) used an oversimplified solution, when using the conductive and advective terms of the energy equation in steady state he managed to suitably address the main processes governing the thermal evolution of the slabs (Leng, 2015). Since them, several thermal models have been proposed, all using the energy conservation equation, and getting more complex and realistic as the numerical/computational capacities increased.

The energy conservation equation for heat transfer commonly used is:

$$\rho c_p \frac{\delta T}{\delta t} = k \nabla^2 T - \rho c_p (v \cdot \nabla T) + Q \qquad \qquad \text{Equation 3.1}$$

Where  $\rho$  is the density,  $c_p$  is the heat capacity, T is the temperature, t is the time, k is the thermal conductivity. The velocity vector, represented by v, takes into account the convergence rate and the dip of the slab, and Q is a volumetric heat production, that may include radiogenic heat production or shear heating, for example.

Peacock (1996) observed that the downward advection of the oceanic lithosphere dominates the thermal structure of the lithosphere. The main factors that control the thermal structure of the lithosphere are thus the age of the lithosphere, which determines the initial temperature of the incoming lithosphere (the younger the lithosphere, the hotter it is), and the subduction velocity vector, which depends on the convergence rate and the slab geometry. In a lesser degree, shear heating, fluid migration, radiogenic heat production, mantle wedge convection and enthalpies of metamorphic reactions may also affect the temperature field. The effect of sedimentation is often neglected. Hyndman *et al.* (1995) identified that the sedimentation rate above the incoming plate could have an influence in the modeled temperatures. Later, Marcaillou *et al.* (2008) included the effects of sediment compaction in a 1D thermal model of the incoming lithosphere, which was later used as a lateral thermal boundary condition in a 2D model. The compaction was used to calculate the appropriate thermal conductivity of the sediments, taking into account the sediment's porosity evolution. Langseth *et al.* (1990) identified that the surface heat flow is lower when the sediment thickness is higher due to the blanketing effect (Lucazeau and Le Douaran, 1985). This is caused by the arrival of great thickness of cool sediments over a small time period (high sedimentation rate). Nevertheless, no subduction thermal model to date seems to take the blanketing effect into account, mainly because this effect is only observed in shallow depths and/or close to the trench, and not in the core of seismogenic zones.

#### 3.2.5.2 Integration of the subduction cooling in TemisFlow basin modeling software

The thermal modeling presented in this paper was performed with TemisFlow® commercial petroleum system modeling software (Ungerer *et al.*, 1990; Schneider *et al.*, 2000; Willien *et al.*, 2009) using its Visco calculator (Agelas *et al.*, 2001). In this calculator, the heat conservation equation  $(\frac{\partial}{\partial t}(\rho c_b T) + div(\sum_{\alpha=w,o,g}(\rho_{\alpha}\Phi S_{\alpha}c_{\alpha}T\overline{V_{\alpha}}) + \rho_s(1-\Phi)c_s T\overline{V_s} - \lambda_b\overline{GradT}) = q_h + q_r + q_{oh}$  Equation 3.2) takes into account conductive and advective heat flow, as well as radiogenic heat production, the heat transfer related to sediment deposition or erosion, and the heat engendered by fluid volume variation due to hydrocarbon generation:

$$\frac{\partial}{\partial t}(\rho c_b T) + \operatorname{div}(\sum_{\alpha=w,o,g}(\rho_{\alpha} \Phi S_{\alpha} c_{\alpha} T \overrightarrow{V_{\alpha}}) + \rho_s (1 - \Phi) c_s T \overrightarrow{V_s} - \lambda_b \overrightarrow{\operatorname{Grad}} T) = q_h + q_r + q_{oh}$$
Equation 3.2

Where:

-  $\rho c_b$  the heat capacity of the saturated porous media

-  $\lambda_b$  its thermal conductivity, which depends on the porosity, saturation and the thermal conductivity of the phase.

-  $q_h$  is the heat source linked to the sediment deposition or erosion, considering that the sediments are deposited with the same temperature as the top of the basin and that the eroded sediments take with them an amount of heat proportional to its temperature;

- q<sub>r</sub> is the radioactivity heat source;

-  $q_{oh}$  is the heat source due to the fluid volume variation by hydrocarbon generation.

-  $\alpha$  is a phase identification index with the following convention: w for water, o for the hydrocarbon liquid phase and g for hydrocarbon vapor phase;

-  $\Phi$  is the porosity;

-  $\rho\alpha$ , S $\alpha$  and c $\alpha$  the density, saturation and heat capacity of phase  $\alpha$ , respectively;

-  $\overrightarrow{V_{\alpha}}$  is the velocity of phase  $\alpha$ , obtained from Darcy law generalized in function of pressure  $P\alpha$  of phase  $\alpha$ :

$$ec{U}_{lpha} = \Phi S_{lpha} ig( ec{V}_{lpha} - ec{V}_S ig) = - \overline{\overline{K}} rac{\mathrm{kr}_{lpha}}{\mu_{lpha}} ig( \overline{\mathrm{grad}} P_{lpha} - 
ho_{lpha} ec{\mathbf{g}} ig)$$
 Equation 3.3

With, in addition,  $\vec{U}_{\alpha}$  is the Darcy velocity,  $\mu_{\alpha}$  the viscosity of phase  $\alpha$ ,  $kr_{\alpha}$  its relative permeability, and  $\overline{K}$  the intrinsic permeability of the porous media.

Since the grid of a TemisFlow® model can only move vertically when using its Visco calculator, the only lateral displacement and associated advection is related to the phase  $\alpha$ . In the lithosphere layers of the presented model, where no oil and gas generation is simulated,

the  $\alpha$  corresponds the water phase (S<sub>w</sub>=1) and all the horizontal advection is then associated to the water displacement ( $\vec{V}_w = \frac{\vec{U}_w}{\Phi S_w}$ ).

In order to use the water displacement to mimic the subduction cooling, equation 4 needs to be met:

## $\rho_{0L}c_{0L}T\overrightarrow{V_{0L}} = \rho_w c_w T\overrightarrow{U_w}$ Equation 3.4

Where OL corresponds to the subductiong oceanic lithosphere.

Consequently, the darcy velocity of the water phase needs to be :

$$\overrightarrow{U_w} = \overrightarrow{V_{OL}} * \frac{\rho_{OL} c_{OL}}{\rho_w c_w} \qquad \text{Equation 3.5}$$

The water horizontal displacement within the oceanic lithosphere was induced applying an overpressure in one of the section's lateral borders and defining the opposite border as "open", via the TemisFlow lateral boundary condition tool.

#### 3.2.5.3 The Talara-Tumbes-Lancones Basins reference thermal model

The two-dimensional TemisFlow® thermal model of the North Peruvian forearc system was performed along the 213 km-long, sequentially restored, balanced cross section of Espurt *et al.* (2018). This kinematic model has been updated (see below) with a new thermal dataset presented in this study (Figure 3.3). The thermal model takes into account the successive paleobathymetries, the thickness (and timing) of the eroded sediments, and the slab geometry from the updated kinematic model (Figure 3.6b). This section crosses the different forearc units described above, from the inner Lancones Basin to the trench. Nevertheless, some simplifications were necessary due to the type of grid (vertical shear) used in the TemisFlow® Visco Model (Figure 3.6b). For instance, the imbrication of thrust sheets that generated the Banco Peru structure was approximated by layer thickness variations. A 60 km-

thick oceanic lithosphere was defined for present day and varied in time (Figure 3.6c), taking into account the age of the Farallon (Nazca) oceanic lithosphere (Sdrolias and Müller, 2006) and the relation between the lithosphere thickness and the crust age (McKenzie, 2005).



Figure 3.6. (a) Crustal-scale sequential restoration of the cross section (modified after Espurt *et al.*, 2018). (b) Geometry model defined in TemisFlow. Dashed black line corresponds to the subduction fault. (c) Oceanic lithosphere thickness data (derived from Sdrolias and Müller, 2006; Mckenzie, 2005), and Farallon(Nazca)-South American plate projected convergence rate (Somoza and Ghidella, 2012) through Cenozoic. See Figure 3.1 for section location and Figure 3.2c for legend of the sedimentary units.

As previously mentioned, (1) the grid used for this thermal model is a vertical shear one, (2) the cooling engendered by the subduction is represented by the advective term of the heat conservation energy equation, and (3) the oceanic lithosphere displacement was modeled

using a fluid circulation inside its layer's cells. The flow velocity was defined applying a pressure gradient at the model borders. At the oceanic plate border an overpressure was applied, directing a flow towards the southeast border, which was set to be open (pressure=hydrostatic). The magnitude of the applied overpressure was selected to best represent the convergence rates defined by Somoza and Ghidella (2012) taking into account the trench, convergence and section directions (Supporting Information Figure 3.S1 and Table 3.S.1). There are some restrictions in using this functionality, primarily because it is not possible to control and change the flow rate within the section. The flow rate was chosen in order to represent the convergence rate projected at the Tumbes depocenter, where the sediments directly overlie the oceanic plate and where subduction cooling is expected to have a higher impact on the sedimentary basin.

The model thermal boundary conditions are the temperature at the base of the lithosphere and the paleo surface temperature at top. The basal temperature was defined as 1333°C constant throughout the study area and basin history. The paleo-surface temperature was estimated from the Early Cretaceous to present-day, according to the basin paleo location climate and bathymetry. The paleolatitude of the study area was estimated using paleolatitude.org (version 2.1) taking into account Torsvik *et al.* (2012) paleomagnetic reference frame. The local paleo-temperatures, as well as the pole paleo-temperatures were estimated after Wygrala (1989). Finally, the paleo-surface temperature is equal to the sea level temperature; (2) at 1500 water depth, the water temperature is the same as the pole temperature; (3) between 200 and 1500 m of water depth, the water temperature decreases linearly; (4) above the sea level, the air temperature decreases at a  $-6.5^{\circ}$ C/km rate (Wang *et al.*, 2006; Hantschel and Kauerauf, 2009).

The model thermal maturity was calculated using the BasinRo kinetic model (Nielsien *et al.*, 2017), which is a time-temperature vitrinite reflectance thermal model that uses Arhenius rate constants (Burnham and Sweeney, 1989) calibrated with basin and laboratory data. The BasinRo vitrinite is obtained as result of the thermal model, allowing the calibration with the available vitrinite measurements (Table 3.1 and Table 3.2; see chapter 3.2.4). We chose to use the BasinRo kinetic model over the more usual EasyRo model (Sweeney and Burnham, 1990) because it matches geological data better, especially for thermal maturity lower than 2%Ro (Schenk *et al.*, 2017), like is the case of the available Ro measurements used for calibration.

For numerical reasons, the continental crust was divided into five layers, the oceanic crust in three layers, and the lithospheric mantle in 10 layers. On the top of the oceanic crust, one "thin" (500 m-thick) layer of off-scraped sediments was created. One petrophysical facies was assigned for each layer (Supporting Information Table 3.S.2). The facies assigned to the continental crust and oceanic lithosphere were defined as incompressible. The compaction curves for the sedimentary facies are presented in Figure 3.S2 (Supporting Information). The density and main thermal parameters for all assigned sedimentary facies, oceanic lithosphere and water are presented in Table 3.S.3 and Table 3.S.4 (Supporting Information). The grid cells have an average horizontal size of 280 m. One additional large (5 km) cell was added at each border of the model in order to avoid border effects that could be propagated inside the section due to the advection.

#### 3.2.6 Thermal modeling results

The thermal modeling of the North Peruvian forearc system, calibrated with the above mentioned data and including the subducting oceanic lithosphere (chapter 3.2.5.3, Figure 3.6), is presented in Figure 3.7b. The complete thermal evolutionary model is presented in Figure 3.8. We also present a thermal model using the basal heat flow history used in previous

studies (Fernández *et al.*, 2005) as bottom boundary condition (Figure 3.7a). This model appears to give accurate results in the Talara Basin, where plenty calibration data are available, but overestimates considerably the thermal maturity in the Tumbes Basin, while underestimating it in the Lancones Basin. Since the available data set consists mainly of single point measurements scattered across the study area, the calibration was made rather spatially than vertically along the wells.

In the Talara Basin, the calibration of both models could only be achieved by adding around 3 km of post-Eocene erosion (Figure 3.6) to the initial structural restoration proposed by Espurt *et al.* (2018). In fact, the Ro values in the Late Eocene-Oligocene rocks of the Carpitas High area suggest post-Oligocene subsidence and heating under Late Oligocene-Miocene rocks (Heath and Zorritos Formations). We propose that this burial is followed by an erosional event preceding the deposition of the Middle Miocene Cardalitos Formation as revealed by subsurface data (Fernández *et al.*, 2005; Espurt *et al.*, 2018; Brusset *et al.*, 2018). This erosional event mainly recorded near the coastal zone may be controlled by changes in the Nazca subduction dynamic/Andean orogenic building or by the subduction of a buoyant asperity like the Inca Plateau (Gutscher *et al.*, 1999b). A Middle Miocene uplift has been also described southward in the Trujillo forearc zone by Prudhomme *et al.* (2019) related to the subduction of the Nazca ridge.



Figure 3.7. TemisFlow thermal model results for present-day calibrated with surface vitrinite reflectance (Ro) values. (a) With basal heat flow from previous studies (Fernández *et al.*, 2005). (b) With integrated subduction-sedimentation model. (c) Burial depth, temperature and Ro history extracted from (b) at the bottom of Tumbes, Talara and Lancones Basins. Dashed black line corresponds to the subduction fault. Thin dashed black line indicates the basement-sedimentary basin interface. See Figure 3.1 for section location and Figure 3.6 for model input.

Analyzing the model results, we observe that each depocenter has a different thermal history. The influence of the subduction cooling increases toward the trench where the continental crust gets thinner. The present day basal heat flow values in the Lancones Basin are around 60  $\text{mW/m}^2$ . The thick continental crust that lies under the Lancones Basin partially isolates it from the subduction cooling. The present day basal heat flow decreases to 40  $\text{mW/m}^2$  in the

Talara Basin and may be as low as 20 mW/m<sup>2</sup> in the Tumbes Basin, where the high recent sedimentation rate also generates a cooling effect (blanketing effect). At the trench, where the sedimentation rate is lower, the average present-day heat flow is 70 mW/m<sup>2</sup>, in consistence with a 20 Myr old oceanic crust, and the average geothermal gradient is  $25^{\circ}$ C/km, in accordance with Auguy *et al.* (2017). In this region, the thermal structure is mainly influenced by the oceanic lithosphere age (that may be translated into its thickness, and vice versa). The geothermal gradients follow the same trends observed for the basal heat flow in each depocenter. They are hotter in the Lancones Basin (25-35°C/km) and colder in the Tumbes Basin (~18°C/km). In the Talara Basin the geothermal gradient is higher close to the Carpitas high and to the Cabeza de Vaca fault system (25-28°C/km) and lower in its depocenter (18°C/km).

The modeled thermal structure and history of the three depocenters are also related to the changes in subduction rate and direction during the forearc deposition, and to the timing and amplitude of the erosional events. The influence of the subduction cooling is minor during deposition in the Lancones Basin until 28 Ma, when the convergence rate starts to increase in relation with the Farallon plate break-up. The maximum temperatures in the Lancones Basin are reached around 37 Ma, which also corresponds to the maximum burial depth in the depocenter (Figure 3.7 andFigure 3.8). After this period the thermal maturity of this depocenter remained overall stable.



Figure 3.8. TemisFlow thermal model results through Cenozoic time. (a) Temperature results with heat flow (brown line) extracted from the model results at the base of the sedimentary basins along the section. (b) Maturity results (Ro%) with total burial depth (blue line) of the sedimentary units along the section. Thick dashed black line corresponds to the subduction fault. Thick black line indicates the basement-sedimentary basin interface. See Figure 3.1 for section location and Figure 3.6 for model input.

The Cretaceous potential source rocks of the Lancones Basin have reached the gas generation window (Ro>1.35%) during the Oligocene, when the maximum burial of 8.5 km was reached (Espurt *et al.*, 2018). This period corresponds also to the maturity timing observed at the eastern border of the Talara Basin, close to the Amotape High, where the model shows that

outcropping Early Miocene Mogollon Formation may have Ro values equivalent to oil generation (Figure 3.7b). In these zones, the thermal maturity remained nearly constant since the end of the Oligocene erosional event (Figure 3.7 and Figure 3.8).

Two episodes of maturity increase are observed in the Talara Basin depocenter (Figure 3.7c) and related to the main burial phases (Figure 3.6). The first occurred during the Eocene (49-37 Ma), and the second during the deposition of Late Oligocene-Miocene strata (22-5.8 Ma). Since the erosion is not uniform in this depocenter, the present depth of the rocks that have reached the oil generation window (Ro=0.6%) depends highly on the amount of erosion.

In the offshore Tumbes depocenter, where the thermal maturity results are calibrated with the Ro measurements of three wells (Table 3.2), the oil generation window is reached only with 6 km of overburden for the Eocene rocks and maybe Oligocene-Miocene rocks. This occurred very recently with the deposition of Late Miocene and Pliocene Cardalitos and Mal Pelo Formations.

#### 3.2.7 Discussion

Understanding the thermal evolution of a sedimentary basin is key to assess its petroleum systems dynamics. When a large data set is available, like in the case of the Talara Basin, it is possible to construct a representative petroleum system model by adjusting its parameters in order to achieve a good calibration with the available data. But in unexplored areas, where the added value of predictive petroleum systems models is higher, the generalization of observations made in similar basins may generate significant misinterpretation, as we showed in Figure 3.7a. A well-established methodology has been integrated, implicitly or not, in most petroleum systems models of extensional basins (Ungerer *et al.*, 1990; Baur *et al.*, 2010; Roussé *et al.*, 2017), in which the McKenzie (1978) model, or variations thereof, is applied to estimate the heat flow at the base of the sedimentary basin in accordance with the lithosphere

structure and crustal thinning. But for subduction related basins, no solution was available to date to take into account the subduction cooling in their thermal evolution. In these cases, a low heat flow is usually inferred at the base of the sedimentary basin (Lutz, 2010; Schultz, 2016; Burgreen-Chan and Graham, 2018). In this study, we propose a workflow that integrates the subduction implicitly in the petroleum system model of forearc basins.

The presented integrated thermal model includes the three most important factors that rules the thermal structures of subducting lithosphere: (1) the lithosphere age, (2) the subduction rate and (3) the slab geometry (Peacock, 1996). Radiogenic heat production is also taken into account, but not the shear heating nor the fluid circulation. It is possible that fluid circulation from the subducting plate through deep-seated faults connected with the slab subduction fault could have been, at least partly, responsible for local thermal anomalies in the basins. Relationships between fluid circulation and rock maturity need to be specified and require further investigation. Downdip variations of frictional properties along the subduction fault of the North Peruvian forearc system through time have been previously speculated by Espurt *et al.* (2018) to partly explain the development of synchronous upper plate extensional faults and compressional features. The effect of the associated shear heating is neglected in this work and should be investigated in the future.

The workflow presented in this study highlighted the thermal history differences between its three depocenters of the North Peruvian forearc system: Lancones, Talara and Tumbes Basins. Even in these very correlated basins, experiencing the same subduction rates and timing, we observe that their heat flow history is not similar (Figure 3.7 and Figure 3.8). This is mainly due to the presence or absence of the continental crust together with the long-term burial and exhumation history of the prism. The Ro values are very sensitive to burial allowing us to calibrate the structural evolution of the forearc system and then its thermal model through time and space. This is particularly useful when the successive burial and

erosion phases takes place without reaching high enough temperatures that can be recorded by apatite fission-track thermochronometry.

The thermal history of the different basins allows some insight into the origin of massive oil accumulations of the Talara Basin fields (Figure 3.9). The two-dimensional characteristics of our model, located North of the main fields, preclude us from making conclusions about the volumetric hydrocarbon balance. But analyzing the maturity timing of the potential source rocks together with the structural development of the forearc system, it is possible to determine the probable origin of these hydrocarbon accumulations. The Oligocene-Miocene Heath source rock, that according to Fildani et al. (2005), is genetically connected to the Talara oil field, is immature along the modeled section. The long lateral migration hypothesis from the Tumbes depocenter to the Talara fields (Fildani et al., 2005) implies that the oil migration would have occurred before the separation of Tumbes and Talara Basins and the formation of structural traps formed by the Tronco Mocho fault system. However, in the Tumbes Basin this source rock reached the thermal maturity conditions necessary to generate hydrocarbon only in the deeper parts of the depocenter with the deposition of Pliocene-Pleistocene strata (Figure 3.7 and Figure 3.8), after the Miocene erosion event that separated the Tumbes and Talara Basins (Figure 3.6). Therefore, the assumption of a long lateral migration of oils generated by the Heath source rock in the Tumbes Basin toward the Talara fields is not possible according to our modeling results. Some hydrocarbon generation may have occurred in its deeper parts and migrated toward the coast in the Corvina and Albacora structures, but not sufficiently nor early enough to reach the Talara Basin.

The model results are more consistent with the presence of local source rocks in the Talara Basin. The observation of two maturation pulses in the model results fits the interpretation of two migration pulses from geochemical analysis (Higley, 2004a; Hessler and Sharman, 2018; and references therein). At the location of the modeled section, the Talara Formation shales

reach the oil generation window in the deeper parts of the Talara Basin depocenter. It is then reasonable to deduce that to the south, in the Talara Basin main depocenters, both these Eocene and the Cretaceous potential source rocks might have favorable maturity for oil generation. The model results suggest Cretaceous source rocks remain good candidates for the origin of at least part of the petroleum accumulations of the Talara Basin, and it is possible to conclude that where Cretaceous strata are present in Talara Basin (south of the Mancora city; Fernández *et al.*, 2005), this source rock is mature and has generated hydrocarbon. The presence of age-discriminant biomarkers suggesting a Tertiary source rock might be explained by the absence of Cretaceous strata in the main source rock kitchen, where only Tertiary source rocks would be present and mature. This might be the case at the offshore depocenters of the Talara Basin (Fernandez *et al.*, 2005; Fildani *et al.*, 2005; Figure 3.9a). Although the model results indicate that the Eocene strata at the base of Tumbes Basin's offshore depocenters, are necessary to validate this hypotheses.



Figure 3.9. (a) Potential source rock kitchens according to the model results. The base map is produced using elevation data from NASA (National Aeronautics and Space Administration) 30 m ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) GDEM (Global Digital Elevation Model). (b) North Peruvian petroleum system events chart based on the model results. Green colors correspond to Cretaceous source rocks; orange to Eocene source rocks and brown to Oligocene-Miocene source rocks.

In the Lancones depocenter, the early and high maturity of the Cretaceous source rocks, and the important uplift and consequent erosion events, do not favor the presence of conventional oil accumulations. Nevertheless, it is possible that some of the generated hydrocarbons might be trapped in low permeability layers.

#### 3.2.8 Conclusion

In this paper, we have proposed a solution model in which the cooling caused by the subduction of the oceanic lithosphere is represented by the advective term of the heat conservation energy equation throughout the basin sedimentation history. This enables the integration of both sedimentary and subduction processes in a TemisFlow thermal model, calibrated to numerous structural and thermal data of the North Peruvian forearc system. The thermal model results give clues to better understand the thermal structure and source rock maturity history of this complex forearc system, involving a poorly understood petroleum system.

The thermal structure and history of a forearc basin is influenced by the same parameters identified by Peacock (1996). However, we show that the exposure of the sedimentary basin to the subducting cold lithosphere (presence or absence of continental crust), the sedimentation rate, and erosions are major factors impacting the thermal maturity along the forearc system. We show an increasing tendency in heat flow, geothermal gradient and thermal maturity from the sea (Tumbes Basin) to the land (Talara then Lancones Basins). In the cold offshore Tumbes Basin residing above the subducting oceanic plate, the Eocene and Oligocene-Miocene source rocks (Talara and Heath shales) can be mature when Cenozoic sediments reach an additional 6 km of burial. This maturation is very recent and occurred after the formation of structural barriers separating the Tumbes and Talara depocenters. In the inner Lancones Basin, a certain preservation from the subduction cooling and early burial led

to a high maturity of the Cretaceous source rocks. Therefore, the hydrocarbon accumulations of the Talara Basin were generated locally, at least partially from Cretaceous source rocks, perhaps from intervals or facies not yet analyzed by oil-rock geochemical correlation studies, and Tertiary source rock intervals richer and mature at the Talara Basin's offshore depocenters.

Finally, we conclude that even if the histories of the Tumbes, Talara and Lancones Basins are closely related, their petroleum systems are independent due to their thermal history and maturity timing related to the main geodynamic events.

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3.2.11 Supplementary information for paper "Thermal structure and source rock maturity of the North Peruvian forearc system: Insights from a subductionsedimentation integrated petroleum system modeling."



Figure 3.S1. Calculation scheme for the projection of the subduction convergence (Vc) along the modeled 2D section (Vproj), taking into account the direction of the trench, the section and the convergence. The present day azimuths are presented in the image.





	Convo	raonco	Duciente d		
	Conve	rgence	Projected		
<u>(My)</u>	<u>rate</u>	<u>angle</u>	α	convergence rate	
	<u>(km/My)</u>	<u>(°)</u>		<u>(km/My)</u>	
49	55	60	30	67	
37	96	60	30	118	
28	90	83	7	126	
22	140	83	7	197	
11,3	110	83	7	154	
5,8	100	83	7	140	
0	67	83	7	94	

Table 3.S.1. Convergence rates projected at key time steps along the section segment crossing the
Tumbes basin. The trench direction is supposed as constant (🛛 = 45°).

#### Table 3.S.2. Facies assigned for the sedimentary layers.

Formation Name	Horizons Age (Ma)	Facies
	0	
La Cruz - Mal Pelo		70%shale; 30%sansdstones
	5.8	
Cardalitos		70%shale; 30%sansdstones
	11.3	
Zorritos		90%sandstones; 10%shale
	22	
Heath		70%shale; 30%sansdstones
	29	
Mancora		Conglomerates
	37	
Talara		70%shale; 30%sansdstones
	49	
Mongollon		Conglomerates
	56	
Lancones Cretaceous Series		70%shale; 30%sansdstones
	110	

#### Table 3.S.3. Solid density and main thermal parameters of assigned sedimentary facies.

Name	Solid density [kg/m³]	Surface matrix conductivity [W/(m·°C)]	Mass heat capacity [J/(kg·°C)]	Radiogenic production [µW/m³]	Temperature dependency [1/°C]
70%shale ; 30%sansdstones	2650	2.95	790	1.50	0.0023
Conglomerates	2692.5	3.27	812.5	1.60	0.0012
90%sandstones; 10%shale	2670	5.67	710	0.65	0.0037

Name	Density [kg/m³]	Conductivity [W/(m·°C)]	Mass heat capacity [J/(kg·°C)]	Radiogenic production [µW/m³]
Upper continental crust	2650	3.00	1150	3.00
Lower continental crust	2950	2.00	1030	0.40
Offscraped sediments	2660	3.00	900	3.00
Oceanic crust	3050	3.00	1082	0.10
Mantle	3350	3.50	985	0.00
Advecting fluid	1000		3975	

Table 3.S.4. Solid density and main thermal parameters of assigned incompressible facies and water.