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The offshore basement of Perú: Evidence for different igneous and metamorphic domains in the forearc

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ABSTRACT

As a result of new studies carried out in the offshore of Perú during the exploration and hydrocarbon evaluation of the forearc basins, new U–Pb SHRIMP and TIMS in zircons and some Ar–Ar data were obtained in the metamorphic and igneous basement. The understanding of this basement was critical to evaluate different hypotheses that have been proposed for the tectonic evolution of pre-Andean crust of Perú. Recent research performed in the basement rocks of the Marañón Massif in northern Perú, claimed that west of this area was a basement-free region in the Paleozoic, where the arc and forearc were developed in a mafic quasi-oceanic crust. However, petrographic studies and new preliminary ages indicate, for the first time, the nature and age of this sialic basement. Reconnaissance studies were performed in several offshore islands, as the Las Hormigas de Afuera Island west of Lima, and Macabí and Lobera islands along the edge of the continental platform. These data were complemented with the studies of some cutting samples obtained in recent exploration wells in northern Perú. The results of the present work show two large crustal domains in the Peruvian offshore forearc. A northern domain contains late Paleozoic igneous rocks that appear to be the southern offshore continuation of the Amotape–Tahuin block, which is interpreted as the southernmost remnant of the Laurentia Alleghenian orogen. The central offshore domain, known as the Paracas High, corresponds to the outer shelf high of previous studies. It contains orthogneisses of Grenville-age, probably recrystallized during an Ordovician magmatic episode. The new results show that the central offshore of Perú is an extension of the Grenville-age basement affected by Famatinian, early Paleozoic magmatism, well exposed in the southern domain in the Arequipa Massif along the coast of southern Perú.

1. Introduction

New studies were carried out in the offshore of Perú as part of the exploration and hydrocarbon evaluation of the forearc basins performed by Savia Perú S.A. These new studies included acquisition of new seismic data, exploration drilling, field surveys on the coastal onshore forearc and a geological reconnaissance of Hormigas de Afuera, Macabi and Lobera islands located in the offshore of Perú (see Fig. 1 for location).

The hydrocarbon exploration was complemented with the petrographic and geochronological analyses of basement cutting samples obtained in some wells done in the northern forearc, and petrographic and geochronological analyses of the rock samples obtained from different islands. Preliminary results from this study were presented by Romero et al. (2011).

The aims of this study are to present new data from the poorly known basement in the off-shore forearc of Perú, to link these data with better known areas on land, and to address some important problems in the tectonic evolution of the pre-Andean system at these latitudes. Previous work performed in the Marañón Massif in the northern Eastern Cordillera, clearly demonstrated the presence of an Early Ordovician magmatic and metamorphic belt (Chew et al., 2007). This magmatic belt that runs along the western coastal margin of the Arequipa-Antofalla basement (Loewy et al., 2004), is offset northeastward into the Eastern Cordillera in Central Perú. This offset was explained by the presence of an original embayment on the western Gondwanan margin during the early Paleozoic (Chew et al., 2007). This embayment was then filled by subsequent accretion of oceanic material, which represents the basement of the Western Cordillera (Polliand et al., 2005), probably during the Carboniferous (Mišković et al., 2005). Haeberlin et al.

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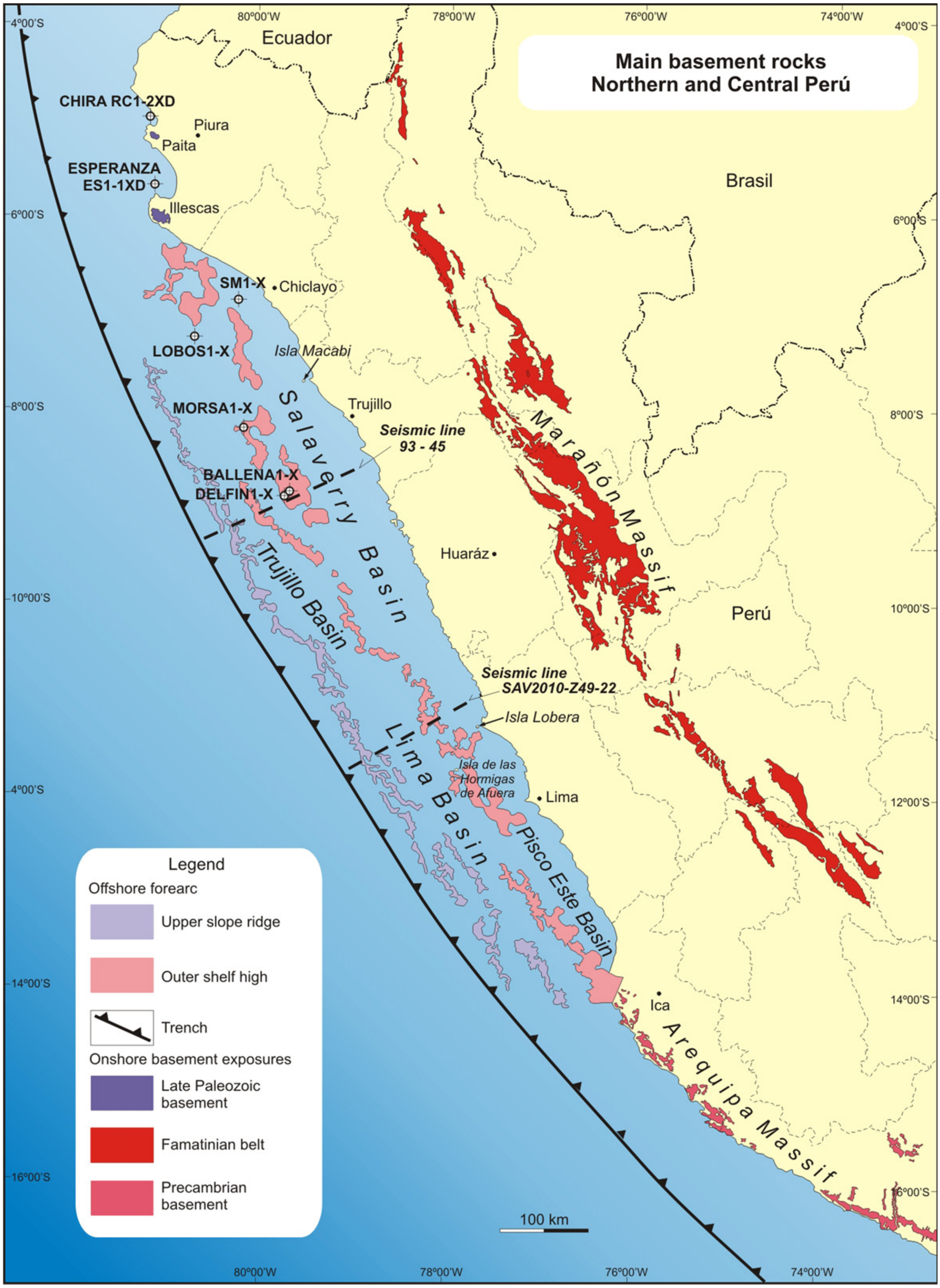


Fig. 1. Location of the study area, main exploration wells, and the islands where geological reconnaissance studies were performed. The metamorphic Precambrian rocks along the coast of the Arequipa Massif are shown (outcrops based on the Mapa Geológico del Perú, INGEOMMET, 2001) as well as the extent of the outer shelf high and the upper slope ridge after Thornburg and Kulm (1981).

(2004) also proposed a lack of sialic cratonic material below the western Peruvian trough, and the presence of oceanic crust formed during the Paleozoic through the removal and northward migration of the northern part of the Arequipa Massif.

A contrasting alternate hypothesis advanced by Ramos (2008), proposed that the basement west of the Marañón Massif was incorporated within Gondwana during the collision of the Paracas terrane in the middle Ordovician. The existence of this sialic basement was based on the metamorphic rocks exposed in the Hormigas de Afuera Island (Kulm et al., 1981), interpreted to be part of the Paracas basement arch (Ramos and Aleman, 2000) an offshore outer slope ridge. No geochronological data existed from this basement until the present study. Therefore, the objectives of the current work are to describe and present new data on these metamorphic and igneous rocks, and confirm that the offshore portion of the forearc of Perú has a series of complex basement domains as advanced by Romero et al. (2011).

2. Regional setting

The forearc basement has been extensively studied in the southern sector of Perú where good exposures along the coastal ranges of the Arequipa Massif (Fig. 1) have been known since the early reconnaissance work of Steinmann (1929). The early dating of Dalmayrac et al. (1977) and Shackleton et al. (1979) documented the Proterozoic age of these outcrops. Revised ages with higher precision were presented by Loewy et al. (2003, 2004).

North of the Paracas Peninsula, in coincidence with a large embayment along the coast between 6° and 14°S, there are no records of any basement outcrops, neither along the coast, nor in the Western Cordillera of Perú (Fig. 1). The only documented basement in the offshore forearc between 6° and 14°S latitudes was the reference of metamorphic rock exposures of unknown age in the Las Hormigas de Afuera islands (Thornburg and Kulm, 1981; Kulm et al., 1981), which motivated the present study.

2.1. Forearc structures

The Peruvian offshore forearc is characterized by dominant extensional tectonics, punctuated by some contractional episodes. This extensional regime is the result of the strong coupling between the oceanic slab and the overriding plate, controlled by the sediment-starving trench and a very desert forearc (Ramos, 2010a and cites therein). The episodic compression is related to the collision of the Nazca aseismic ridge against the trench (Pilger, 1984).

Thornburg and Kulm (1981) were the first to depict the main morphostructural units of the forearc and to recognize a series of elongated basins parallel to the coast using some offshore seismic surveys. These basins are Salaverry and Pisco Este, which are separated from the most external basins by an outer shelf high composed by a metamorphic basement (Romero et al., 2011). The outer depocenters are Trujillo and Lima basins, which are west-bounded by an upper slope ridge from the subduction complex (Kulm et al., 1981). The northern forearc is segmented by the Amotape–Tahuin block (Witt et al., 2011). This block was considered since the early work of Feininger (1987) as an allochthonous terrane that collided against the Gondwana margin.

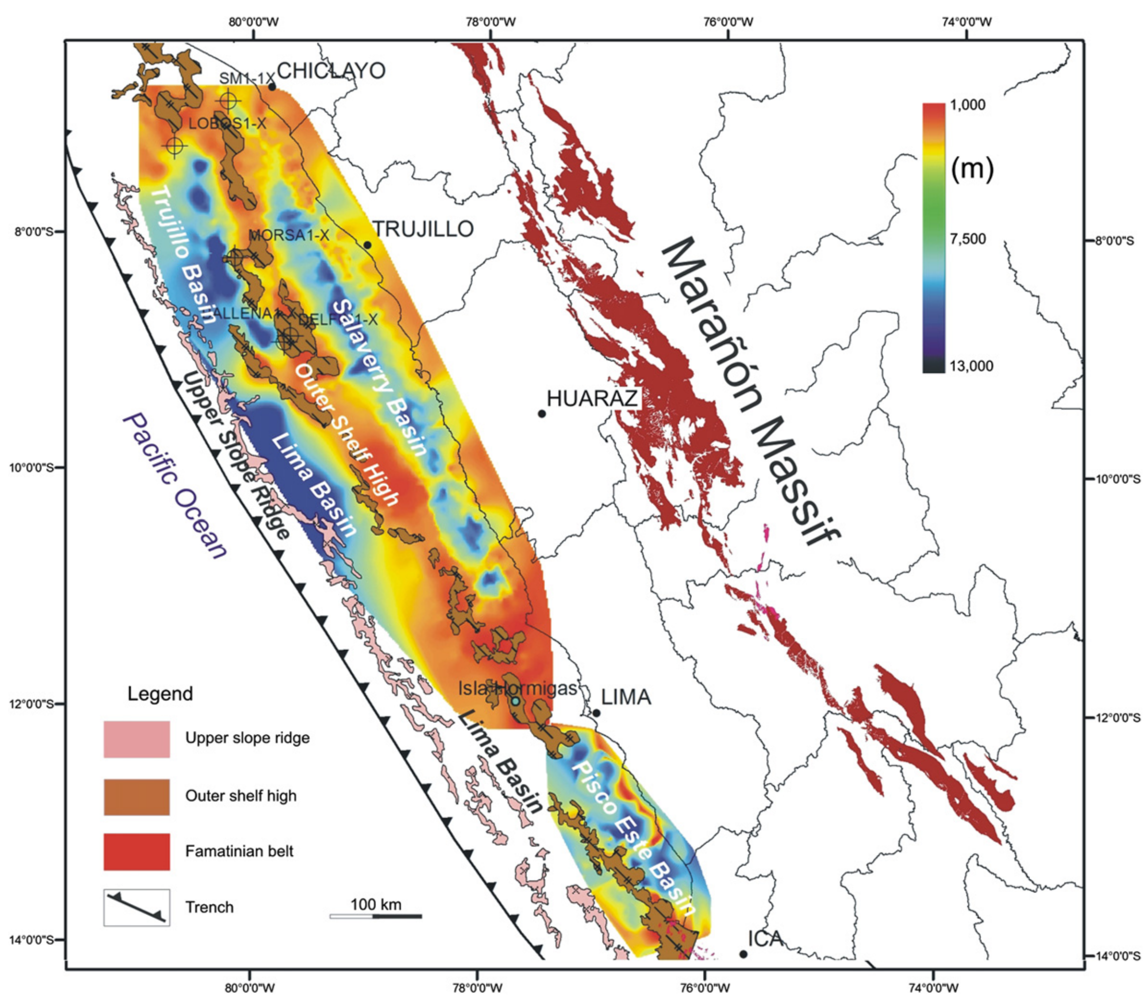


Fig. 2. Structural map to the top of the basement based on seismic interpretation; the outline of the outer shelf high, and upper slope ridge was based on gravimetric data of the northern forearc with main basins (after Thornburg and Kulm, 1981; gravimetric anomalies after Romero, 2010). The metamorphic and igneous basement of the Marañón Massif in the Eastern Cordillera is indicated as reference based on Benavides (1999) and the Mapa Geológico del Perú, INGEMMET (2001).

Benavides (1956) in his early analysis of the provenance of the Cretaceous deposits inferred a western source land, as an offshore continental positive area parallel to the coast, which fed the western basin (Benavides, 1956, Fig. 2). This basement high was also postulated by Wilson (1963) and Myers (1974) west-bounding the west Peruvian trough along the offshore. These authors in their analysis of the Cretaceous tectonic framework of Perú recognized this high as uplifted during Late Cretaceous as a consequence of the "Peruvian deformation" of Steinmann (1929). This high was interpreted as originally formed by normal faults and it was named Paracas block by Myers (1975). Several subsequent studies recognized the sialic nature of this high later known as the Paracas arch, based on geological and geophysical grounds (Atherton et al., 1983; Soler and Bonhomme, 1990; Benavides, 1999; Ramos and Aleman, 2000).

The outer shelf high coincides with the Paracas Arch of Benavides, 1999. This author defined this basement high as the western border of the late Jurassic–early Cretaceous Huarney-Cañete Basin, based on the provenance of the sediments. This early Cretaceous basin was developed during an extensional regime that dominated the continental margin in early Mesozoic times as result of the negative roll-back of the subduction (Ramos, 2010a).

The seismic line 93-45 has been selected to depict the different structural styles and morphostructural units of the offshore forearc (see location in Fig. 1). The section illustrates the upper slope ridge and the outer shelf high that corresponds to the Paracas arch, bounding the Trujillo and Salaverry basins. The Cenozoic fill was deposited on an attenuated crust over the Jurassic and Cretaceous sequences formed in an extensional regime (Fig. 3). Stratigraphic control is provided by the projection of the Delfin 1-x and Ballena 1-x exploration wells onto the seismic line. These wells indicate that Paleogene and Neogene sediments unconformably overlie Paleozoic rocks. The Paleocene to Eocene beds were deposited in an extensional setting covered by Miocene to Pliocene deposits (see for stratigraphic details Romero et al., 2011). It is interesting to remark that the Pliocene deposits show synextensional wedges that enhanced the Trujillo Basin roll-over structures (Fig. 3a–c).

In the eastern sector of the seismic line 93-45 a contractional anticline is observed in the Middle Miocene sequences, which are unconformably covered by Late Miocene deposits. This exceptional structural setting is seen in the central Salaverry Basin where an anticline is controlled by a reverse fault. This fault is interpreted as tectonic inversion of a previous normal fault based on its high cut-off angle (Fig. 3c).

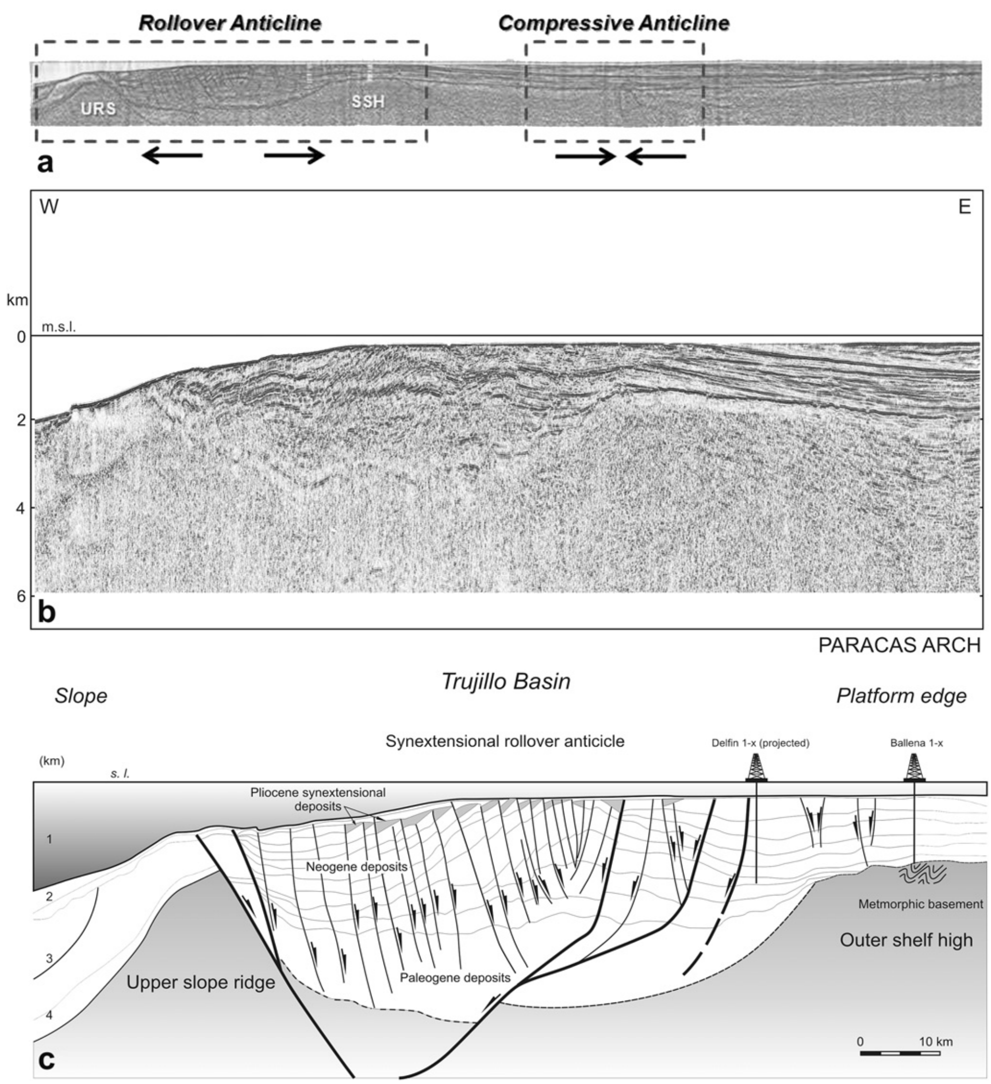


Fig. 3. a) Regional seismic line 93-45 (USR: upper slope ridge and OSH: outer shelf high) (see location in Fig. 1); b) Western sector where normal faults are heavily attenuating the crust between the upper slope ridge and outer shelf high; c) Structural interpretation of the western sector dominated by normal faults in the outer Trujillo Basin, and location of Delfin 1-x and Ballena 1-x wells that have intersected metamorphic basement in the platform edge.

As pointed out by Romero et al. (2011) and Witt et al. (2011) the offshore Peruvian forearc is dominated by extensional structures. The normal faults are originated by crustal subduction erosion along the Pacific margin (see von Huene et al., 1996; Ramos, 2010a). This extensional regime is only interrupted at the studied latitudes in Middle Miocene times by the collision of the Nazca aseismic ridge against the trench, which produced the tectonic inversion of the normal faults (see Fig. 4a and b). As several authors have established, the ridge collision between Chiclayo and Lima was produced during Middle Miocene times (Gutscher et al., 2000; Hampel et al., 2004; Alemán, 2006; Aleman and Ramos, 2000). The sweep of the ridge along the margin is responsible of the tectonic inversion of some previous normal faults.

These compressional structures are observed further south in the outer slope where backthrusts have been described by von Huene et al. (1996). These structures are seen in the new seismic line Z49-22 (Fig. 4a and b, location shown in Fig. 1).

These backthrusts have an eastern vergence, which is opposite to the typical thrust vergence toward the trench in accretionary prisms (von Huene et al., 1996). These authors have identified the backthrusts in poor-quality, old seismic lines, and attributed the contraction to the collision of the Nazca ridge. This diachronous collision started in the north around 15 Ma (Alemán, 2006), reached the latitude of Lima close to 10 Ma, and is affecting the continental margin at the latitude of Nazca now (Hampel et al., 2004). The new seismic data clearly show that this contraction is affected by a later Pliocene extension as shown in Fig. 3.

These examples indicate that the Peruvian forearc was dominated by normal faults during Neogene times, which produced a heavily attenuated crust, and the present expression of the outer shelf high or the Paracas Arch (Ramos and Aleman, 2000). Compression and partial inversion of these structures are related with the collision from north to south of the Nazca Ridge.

2.2. New exploration

Prior to this study the outer shelf high which separates the Salaverry and Pisco Este basins from the Trujillo and Lima outer basins has been considered as the offshore extension of the basement exposed in the Paracas Peninsula. The only offshore exposure between Illescas Massif in the north and Paracas Peninsula in the south lies on Las Hormigas de Afuera Island 65 km west of El Callao port. The basement has also been intersected in the northern offshore by Delfín 1-x and Ballena 1-x exploratory wells drilled by Occidental Oil Company in 1971 (see location in Fig. 1) and the Morsa 1-x well, drilled in the SK Energy contract area in 1999 by Repsol.

This fragmentary information was the only knowledge previous to the present work of Savia Perú S.A. in Las Hormigas de Afuera Island (Fig. 5) and other new exploration wells.

The first lithologic description of rocks from Las Hormigas de Afuera Island was based on the samples collected by Antonio Masias (Petroperú S.A., in Kulm et al., 1981). In this study two different lithologies were recognized. A quartzite with lenses of muscovite and garnet, and a quartz–feldspatic schist, with a poor schistose texture, indicated by bands of biotite intercalated by bands of elongated crystals of quartz and feldspar. The dominant mineralogy was quartz, plagioclase, biotite and garnet. The texture and the mineralogy indicate quartz–feldspatic schist, which was probably a granulite. The high content of anorthite, together with the absence of low grade minerals suggest that it is a high grade metamorphic rock (Kulm et al., 1981). The cores of the Ballena 1-x and Delfín 1-x wells yield gneisses and phyllites.

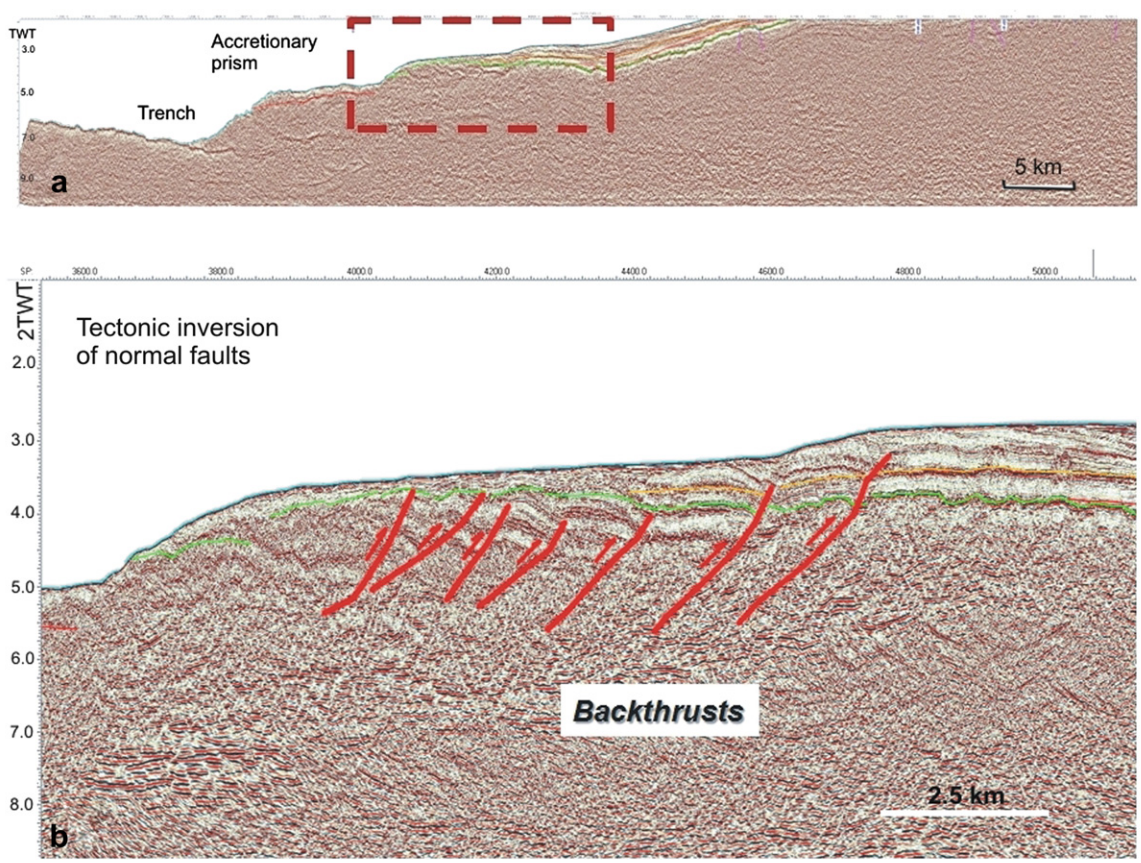


Fig. 4. a) Seismic line Z49-22 (location in Fig. 1); b) Western sector of the seismic line with backthrusts, probably related to the inversion of previous normal faults.

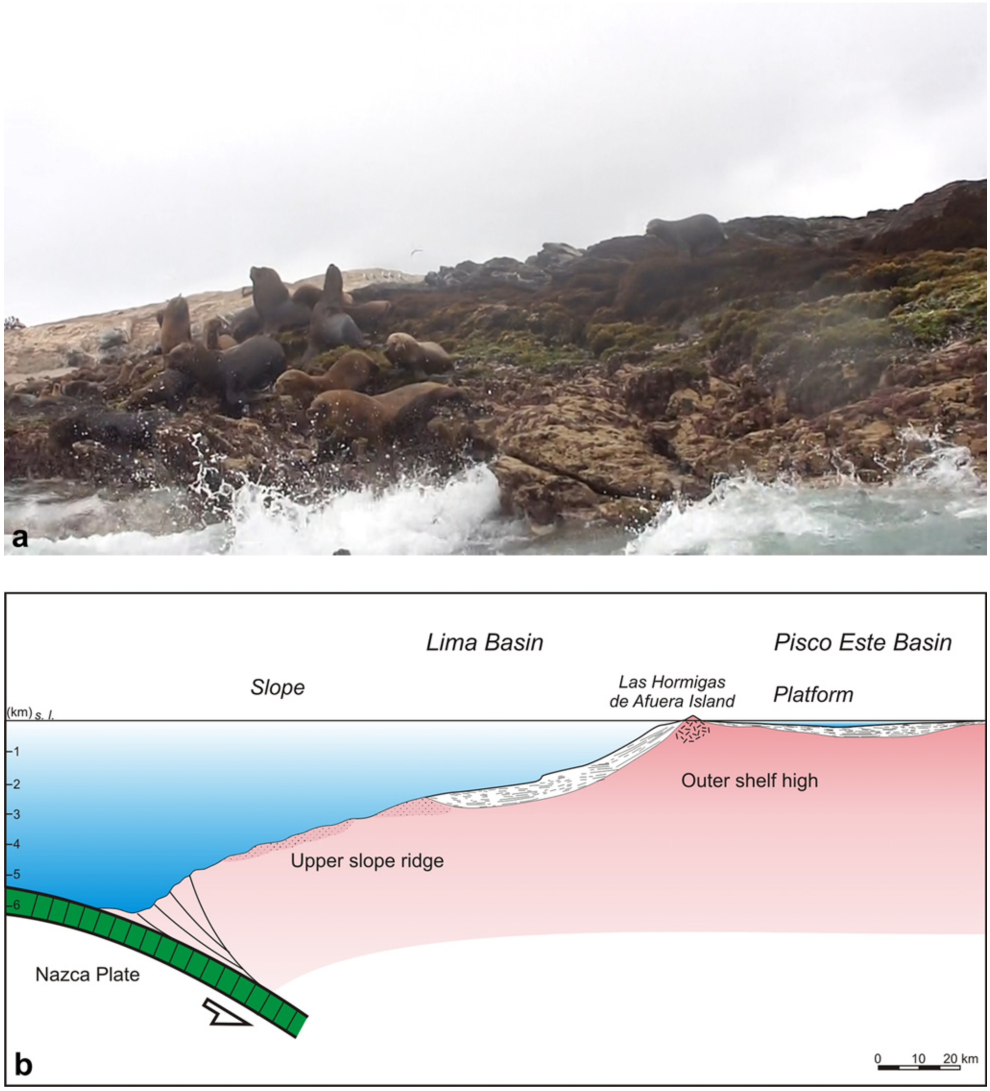


Fig. 5. a) View of the Las Hormigas de Afuera Island, where sampling by Daniel Peña (Savia Perú S.A.) was performed. Note foliation of metamorphic rocks dipping to the east. b) Section of the forearc along the island based on Thornburg and Kulm (1981).

2.3. New geochronological data

New studies have been performed in Las Hormigas de Afuera, Lobera and Macabí islands and in cutting samples from the exploration drillings San Miguel 1-x, Chira RC1-2XD, and Esperanza1-1XD, performed by SAVIA Perú S.A. (location shown in Fig. 1). The geochronological analyses have been done by U–Pb SHRIMP and TIMS in zircons and Ar–Ar methods by Activation Laboratories (ACTLABS), Canada. The dating and results will be presented by location. Implications and relevance of these ages will be discussed in chronological order to understand the geologic history of the forearc basement.

2.3.1. Las Hormigas de Afuera Island

The petrographic examination in thin sections of a few samples obtained from this island by Savia Perú S.A. shows the presence of high grade metamorphic rocks dominated by hypersthene gneisses. These gneisses have been affected by a retrograde metamorphism as evidenced by secondary biotite. As the survey boat was unable to land due to the rocky nature of the coast, the only way to get the samples was to swim to the shore. This is the reason of the reduced size of samples obtained, and therefore the limited amount of zircons. A reconnaissance geochronological study was then performed in the orthogneiss of sample YK-9, which provided only 19 concordant zircons which were analyzed by U–Pb SHRIMP. The results are illustrated in Fig. 6 and Table 1.

The cathodoluminescence images of the zircons analyzed show that most of them correspond to euhedral crystals with oscillatory zoning of igneous origin, possibly plutonic rocks as indicated by their morphology, with inherited nuclei. Ages between 2600 and 1400 Ma of these nuclei are slightly discordant, but younger ages are concordant. Some inherited zircons as the 9.5.1 and 9.4.1 yield ages between 1812 ± 31 and 1988 ± 11 Ma, show an outer thin edge with low luminescence typical of a younger metamorphism. These are similar to the Arequipa orthogneiss zircons, with reported ages of 1793 ± 6 Ma (Loewy et al., 2004). These zircons also have Mesoproterozoic ages (1200–1000 Ma), which correspond to the Grenville Orogeny, an age population that is common in most of the accreted terranes to the proto-Pacific margin of South America (Ramos, 2010b). Some zircons, such as the 9.1.1 do not have an oscillatory zoning, and are characterized by a patchy texture typical of metamorphic zircons with concordant values about 1001 ± 10 Ma (Fig. 7a), similar to the Grenvillian ages reported in granulite-facies

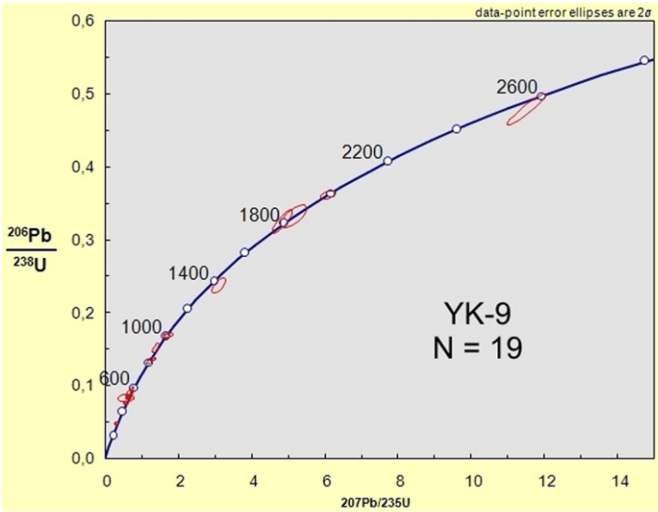


Fig. 6. Tera-Wasserburg concordia diagram of the new U–Pb SHRIMP zircon-dating of hypersthene gneiss from Las Hormigas de Afuera Island.

metamorphism in the Arequipa basement by Wasteneys et al. (1995) and Loewy et al. (2004) further south.

The most external oscillatory zoning in these zircons with a mean age of 467.9 ± 4.5 Ma, corresponding to the middle Ordovician, is interpreted as the crystallization age of these orthogneisses. These ages are also similar to the San Nicolás batholith zircons along the coast of the Arequipa Massif. In similar rocks, Loewy et al. (2004) have reported ages of 468 ± 4 Ma.

Some preliminary conclusions can be advanced even though only a few zircons were analyzed. This rock contains zircons of predominantly three ages. The most external oscillatory zoning seems to indicate a middle Ordovician age in prismatic zircons attributed to plutonic rocks by their morphology. The Ordovician concordia age of 467.9 ± 4.5 Ma is a typical Famatinian age that is very common in different terranes along the proto-Gondwana margin of South America (see Pankhurst et al., 1998; Quenardelle and Ramos, 1999; Dahlquist et al., 2008; Bahlburg et al., 2009; Reimann et al., 2010, and cites therein). The nearest granitoids in the Arequipa Massif have similar middle Ordovician ages reported by Loewy et al. (2004). These ages are also within the time range obtained by Chew et al. (2007) for granitoids of the Marañón Massif belt located hundreds of kilometers further to the east.

There are zircons that formed during the Grenvillian event that may represent the age of the metamorphism of these orthogneisses, and some younger zircons that may be related to the Rodinia break-up. These data, together with some older Paleoproterozoic ages (Fig. 8), indicate striking similarity to the ages of the basement of the Arequipa Massif. Previous hypotheses related the Paracas arch to the northern morphological continuation of the Paracas Peninsula (Kulm et al., 1981; Aleman and Ramos, 2000). As this peninsula is the northern end of the Arequipa Massif, it is almost straight forward to postulate that both basements have similar geological histories.

In addition to the data obtained from the metamorphic and igneous rocks of the Arequipa basement, the recent detrital zircon data from Paleozoic sediments deposited on the Arequipa Massif presented by Reimann et al. (2010) yield a similar age distribution to those in the basement of the Las Hormigas de Afuera Island (Fig. 8).

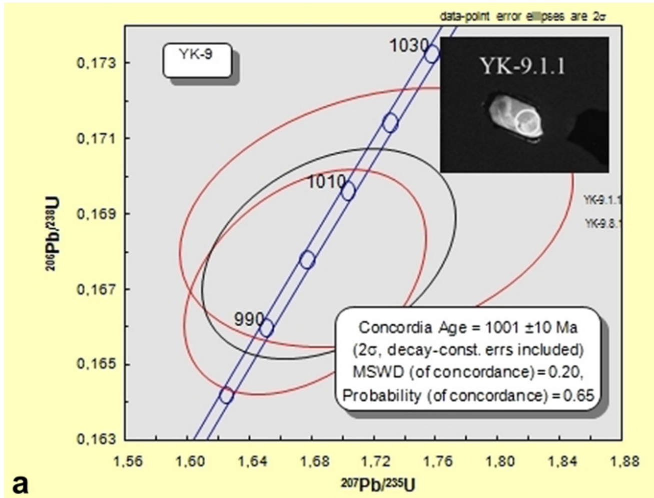
2.3.2. Basement of the San Miguel 1-x well

The location of the SM 1-x well in the northern offshore of Perú is indicated in Fig. 9. The well site is along the trend of the Illescas and Paita massives, located some kilometers to the north as part of

Table 1
Analytical results of Isla de Las Hormigas U–Pb SHRIMP data.

	Spot	$\%^{206}Pb_c$	ppm U	ppm Th	$^{232}Th/^{238}U$	ppm $^{206}Pb^*$	(1) $^{206}Pb/^{238}U$ Age		(1) $^{207}Pb/^{206}Pb$ Age		%Discordant	Total $^{238}U/^{206}Pb$	±%	Total $^{207}Pb/^{206}Pb$	±%	(1) $^{238}U/^{206}Pb^*$	±%	(1) $^{207}Pb^*/^{206}Pb^*$	±%	(1) $^{207}Pb^*/^{235}U$	±%	(1) $^{206}Pb^*/^{238}U$	±%	errcorr	(1) $^{206}Pb^*/^{238}U$	±
1	YK-9.12.2	1.29	1316	136	0.11	55.3	304	±5.3				20.460	1.8	0.05800	2	20.730	1.8	0.04760	5.5	0.316	5.8	0.04823	1.8	0.308	304	5
2	YK-9.3.1	0.21	806	350	0.45	51.9	465	±2.8				13.352	0.61	0.05799	1.1	13.381	0.62	0.05625	1.7	0.580	1.8	0.07473	0.62	0.347	465	3
3	YK-9.6.2	0.73	314	58	0.19	20.8	474	±3.8				12.990	0.79	0.06120	1.7	13.090	0.84	0.05530	4.5	0.582	4.6	0.07637	0.84	0.182	474	4
4	YK-9.11.1	1.75	63	33	0.54	4.53	513	±12				11.850	2.3	0.06470	4.4	12.070	2.5	0.05030	16	0.575	16	0.08280	2.5	0.157	513	12
5	YK-9.9.1	0.51	257	266	1.07	18.4	514	±4.3				11.984	0.83	0.06080	1.8	12.050	0.87	0.05660	3.9	0.647	4.0	0.08299	0.87	0.219	514	4
6	YK-9.7.1	0.57	116	63	0.56	8.45	523	±5.7				11.760	1.10	0.06030	2.7	11.830	1.10	0.05570	5.1	0.649	5.3	0.08454	1.10	0.214	523	6
7	YK-9.10.1	0.25	1876	264	0.15	141	539	±8.9				11.430	1.7	0.06102	0.8	11.460	1.7	0.05902	1.3	0.710	2.1	0.08730	1.7	0.802	539	9
8	YK-9.2.2	0.51	328	35	0.11	25.5	556	±9.8				11.040	1.8	0.05820	2.2	11.100	1.8	0.05400	3.8	0.671	4.2	0.09010	1.8	0.436	556	10
9	YK-9.14.1	0.24	682	118	0.18	55.3	580	±9.8				10.590	1.8	0.05830	1.3	10.620	1.8	0.05630	1.9	0.731	2.6	0.09420	1.8	0.681	580	10
10	YK-9.6.1	0.26	226	99	0.45	25.7	801	±5.9				7.540	0.77	0.06837	1.4	7.560	0.78	0.06620	2.1	1.207	2.2	0.13220	0.78	0.352	801	6
11	YK-9.2.1	0.10	487	182	0.39	57.1	824	±5.4				7.329	0.69	0.06980	2.5	7.336	0.69	0.06900	2.6	1.296	2.7	0.13630	0.69	0.253	824	5
12	YK-9.12.1	0.15	479	115	0.25	62.4	909	±15				6.590	1.8	0.06760	1.6	6.600	1.8	0.06630	1.9	1.385	2.6	0.15150	1.8	0.683	909	15
13	YK-9.8.1	0.03	632	184	0.30	90.8	997	±6.7				5.980	0.73	0.07300	1.7	5.982	0.73	0.07270	1.7	1.676	1.9	0.16720	0.73	0.388	997	7
14	YK-9.1.1	0.43	121	78	0.66	17.7	1006	±7.8				5.893	0.81	0.07750	1.8	5.918	0.83	0.07390	2.9	1.722	3.0	0.16890	0.83	0.278	1006	8
15	YK-9.5.2	0.06	252	69	0.28	51.4	1371	±23	1533	±34	12	4.216	1.8	0.09580	1.7	4.219	1.8	0.09520	1.8	3.112	2.6	0.23700	1.8	0.714	1533	34
16	YK-9.5.1	0.13	116	77	0.69	32.3	1812	±31	1767	±22	−3	3.076	2.00	0.10920	1.0	3.080	2.00	0.10810	1.2	4.840	2.3	0.32460	2.00	0.848	1767	22
17	YK-9.13.1	0.29	136	43	0.33	38.9	1847	±30	1841	±37	0	3.003	1.9	0.11510	1.8	3.012	1.9	0.11260	2.1	5.150	2.8	0.33190	1.9	0.674	1847	30
18	YK-9.4.1	0.06	283	145	0.53	87.9	1988	±11	1992	±22	0	2.767	0.65	0.12300	1.2	2.768	0.65	0.12240	1.2	6.097	1.4	0.36120	0.65	0.470	1988	11
19	YK-9.15.1	0.14	314	81	0.27	129	2519	±37	2603	±9.9	3	2.088	1.8	0.17599	0.54	2.091	1.8	0.17470	0.59	11.520	1.9	0.47810	1.8	0.948	2603	10

Errors are 1 – sigma; Pb_c and Pb^* indicate the common and radiogenic portions, respectively.
Error in Standard calibration was 0.6% (not included in above errors but required when comparing data from different mounts).
(1) Common Pb corrected using measured ^{204}Pb.



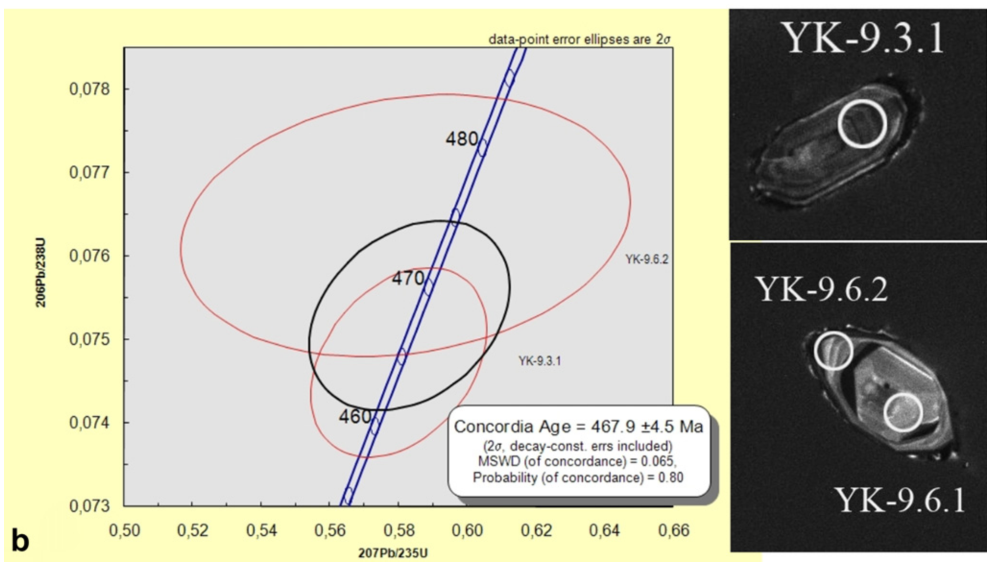


Fig. 7. Details of the Tera-Wasserburg concordia diagram of Fig. 6: a) Grenvillian ages of metamorphic zircon YK-9.1.1 with 1001 ± 10 Ma age; b) External oscillatory zoning of igneous zircons YK-9.3.1 and 9.6.2 with middle Ordovician ages of 467.9 ± 4.5 Ma. Zircon 9.6.1 has a Proterozoic nucleus.

the Amotape–Tahuin domain of Romero et al. (2011) and Carlotto et al. (2011) (see location in Ramos, 2009).

The Illescas Massif comprises a metamorphic basement exposed near the city of Piura. The age of these metamorphic rocks is controversial due to the lack of geochronological data (Mourier et al., 1988; Palacios et al., 1992; Haeberlin et al., 2004). These authors considered these rocks as metamorphic remnants of Precambrian–early Paleozoic continental margin, although Mourier et al. (1988) proposed that this basement was allochthonous to the Central Andes based on paleomagnetic data. The rotation of 90° of the Amotape–Tahuin range during Neocomian times was interpreted as evidence of the accretion of the Tahuin terrane already postulated by Feininger (1987). Mourier et al. (1988) recognized that the major coastal metamorphic massifs of Paita and Illescas, as part of the Amotape–Tahuin block, have undergone a geological evolution different from the sedimentary sequences of that age in the stable craton to the east. This block has been interpreted as a para-autochthonous terrane and apparently its suture orthogonal to the continental margin has controlled the Huancabamba lineament according to Carlotto et al. (2011).

This basement consists of polyphase metamorphic rocks that contrasted with the Devonian to Permian marine and continental sedimentary series exposed further east. The recent studies of Sánchez et al. (2006), Cardona (2006) and Cardona et al. (2008) showed that in Illescas there are exposed gneisses and migmatites of tonalitic composition with garnet, plagioclase and biotite with a heterogeneous texture (Fig. 10). The basement rocks of Silla de Paita further north (Fig. 10) are characterized by an orthogneiss dated by Ar–Ar in 221.5 ± 1.2 Ma, similar to the Higuerón Orthogneiss, close to the boundary with Ecuador in the Amotape block, which also yielded an age of 220 ± 1.2 Ma by the same method (Sánchez et al., 2006). These rocks are intruded by granitoids of Middle Jurassic age.

The first geochronological data of the Illescas Gneiss were done by Cardona (2006) and Cardona et al. (2008). The U–Pb SHRIMP in zircons analyses of this author recorded metamorphic overgrowths that were dated in the outer border in 257 ± 8 Ma. The zircon cores with oscillatory zoning range from 280 Ma to 1690 Ma are somewhat different from the ages observed in the zircons of the Las Hormigas de Afuera Island basement.

The samples obtained from cutting of the San Miguel 1-x well have an igneous character with a dioritic composition in transition to gabbro, composed of amphibole, plagioclase and quartz (Valencia, 2009). The samples are quite altered, but the abundance

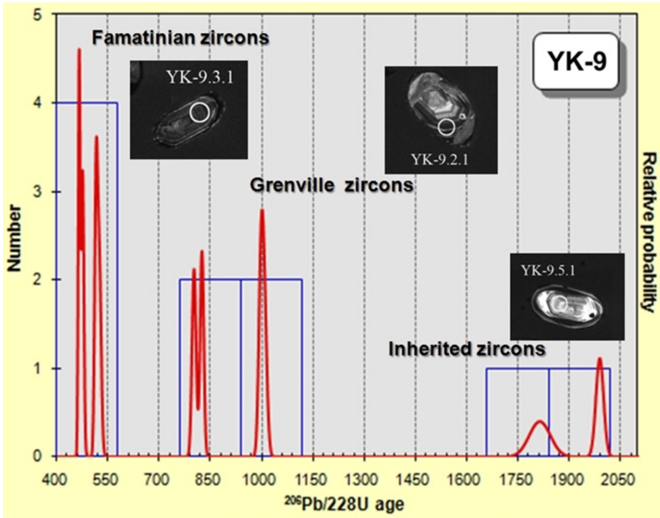


Fig. 8. Summary of the main zircon ages of the Las Hormigas de Afuera Island where three important episodes can be recognized in spite of the exiguous amount of zircons: a Famatinian magmatic igneous peak, a probable Grenvillian protolith with some younger ages probably related to Rodinia break-up, and some older Paleoproterozoic inherited zircons.

of amphibole and the presence of overgrowths may indicate a superposed metamorphic episode. The amphiboles have been analyzed by Ar–Ar and the obtained results are indicated in Fig. 11. The most probable mean age for these minerals is 259.5 ± 12.3 Ma, which could be related to crystallization of the sample. This age is striking similar to the metamorphic U/Pb SHRIMP zircon age of 257 ± 8 Ma obtained by Cardona et al. (2008) for the gneisses of the Illescas Massif. Based on the Ar–Ar data of San Miguel 1-x well, and the U–Pb metamorphic and inherited ages of Illescas obtained by Cardona et al. (2008), it is interpreted that a metamorphic episode took place in Late Permian times, superimposed to a previous igneous event close to 272.9 ± 30.5 Ma as inferred from the Ar–Ar isochrone, which may correspond to an intrusive of Early Permian age.

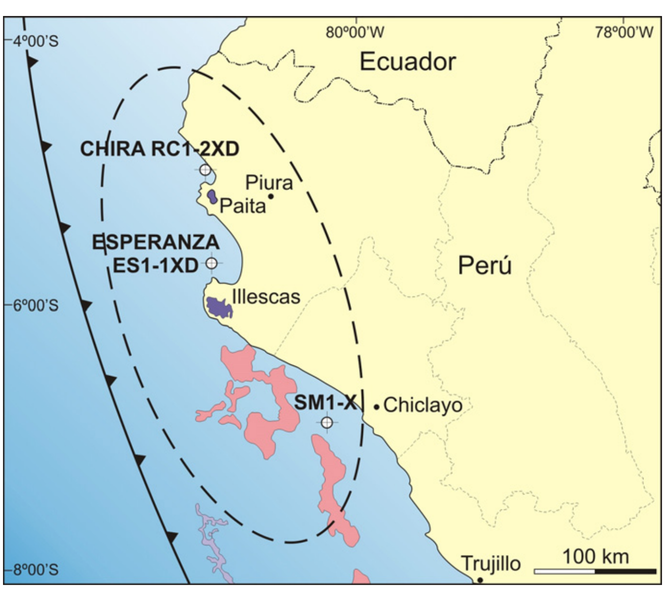


Fig. 9. Location of the San Miguel 1-x well along the basement trend outlined by the Paita and Illescas massives with polyphase gneisses. There are also indicated the location of Chira RC1-2XD and Esperanza ES1-1XD wells where late Paleozoic basement has been intersected.

The Amotape–Tahuín region between Ecuador and Perú records an important anatectic episode, which has been recognized from northern Central Cordillera of Colombia to the southern Eastern Cordillera of Ecuador (Aspden et al., 1992; Spikings et al., 2011). U–Pb LA–ICP–MS analyses of zircons extracted from migmatitic leucosomes and S-type granites, combined with geochemical analyses reveal a belt of peraluminous, crustal anatectites formed during 247–228 Ma (Spikings et al., 2011). This thermal episode affected orthogneisses as the Tres Lagunas and Jubones foliated granitoids as well as other orthogneisses of the El Oro Region of Ecuador (Aspden et al., 1992) and the Higuerón and Paita orthogneisses, with slightly younger Ar–Ar ages in Perú (Sánchez et al., 2006). These rocks were interpreted as derived from a pre-Late Permian metamorphic protolith with a strong ductile deformation formed by the collision of Laurentia during Alleghenian Orogeny, affected by partial anatexis during the Triassic break-up of Pangea (Ramos, 2009).

In some wells of the northern offshore of Perú studied by Savia Perú S.A., as in the Esperanza ES1-1xd well, some low metamorphic grade is evident in Paleozoic quartzites, which reaches a higher grade in the older units, as seen in Chira RC1-2xd well (see location in Fig. 9).

2.3.3. *Macabí Island basalt*

This island is located in the Libertad department, 7 km from the coast (7°47′35″ S; 79°29′40″ W, see location in Fig. 1). The basalts exposed in this island were so altered that they could only be dated by U–Pb TIMS in zircons (Fig. 12). Like typical basalts, the basalt sample from Macabi Island, only provide a few zircons which yielded ages between 1059.3 ± 5.4 Ma and 217.5 ± 0.9 Ma, indicating a possible maximum Triassic crystallization age. Most probably these zircons are xenocrystals incorporated to the basaltic magma from the country rock. Two zircons gave concordant ages of 243 ± 0.1 and 243.5 ± 0.2 Ma.

These ca. 217–243 Ma ages suggest that the basalts probably were emplaced through igneous or metamorphic rocks of Late Permian–Early Triassic age, a southern extent of the Amotape–Tahuin domain of Romero et al. (2011). The location of these basalts is near the Huarmey-Cañete marginal basin (see Benavides, 1999), such that these basalts could have been part of this Jurassic–Early Cretaceous basin. The maximum Triassic age for the Macabi basalt is similar to the ones reported by Spikings et al. (2011) further north.

2.3.4. *Lobera Island diorites*

The Lobera Island belongs to a series of islands that form the offshore extent of Punta Salinas, a few kilometers south of Huacho (see Fig. 1 for location). It is one of the five islands that extend up to 25 km orthogonal to the coast. The Lobera Island is at 8 km from the coast and it is composed of diorites (Fig. 13).

The analyzed rock is an altered diorite, partially recrystallized. The rock consists of plagioclase with phenocrystals of clinopyroxene, amphibole and abundant magnetite. The matrix has fine grained quartz, granular epidote and clinopyroxene. Plagioclase is partially sericitized and replaced by clays.

The rocks have provided enough zircons to be dated by U–Pb SHRIMP. The concordant zircons yielded an age of 127.2 ± 1 Ma (Fig. 14), which indicates Barremian crystallization (Early Cretaceous).

These intrusives are observed in the seismic lines unconformably covered by the Salaverry basal sequences, where satellites stocks occur west of the main batholith (Fig. 15). The present location of these stocks, close to the trench, shows the amount of crustal erosion by subduction that affected the continental margin since the Early Cretaceous.

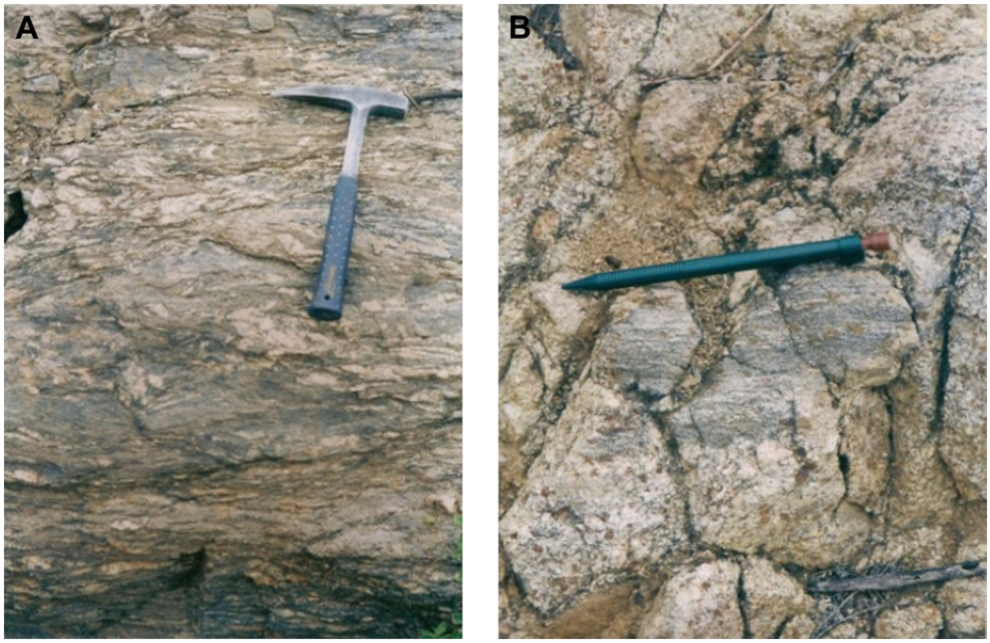


Fig. 10. Representative exposures of the Illescas Gneisses and tonalites with polyphase deformation (photo after Cardona, 2006).

3. Discussion

In order to discuss and analyze the obtained results, the data will be discussed in chronological order to evaluate the different hypotheses.

3.1. Precambrian–early Paleozoic basement

The Precambrian–early Paleozoic ages of the metamorphic basement of the Las Hormigas de Afuera Island provide the first evidence of a pre-Jurassic sialic crust in the forearc of central and northern Perú. Although the amount of sample obtained was very limited, and therefore the amount of zircons only permits a kind of reconnaissance geochronology, results are very interesting when compared with data from the adjacent Arequipa Massif. The first important fact is that this basement has also a Grenville signature with mean concordant values around 1001 $\pm$ 10 Ma, values common in the Arequipa Massif (Wasteneys et al., 1995; Loewy et al., 2003, 2004) and elsewhere from Colombia to Patagonia in the proto-continental margin of South America (Ramos, 2010b). The petrographic analysis of the sample was not conclusive, but it may indicate that hypersthene gneiss was an orthogneiss. The metamorphic high grade is the same as the Arequipa gneisses, and the presence of euhedral prismatic zircons with oscillatory zoning, with ages of 467.9 $\pm$ 4.5 Ma are almost identical to the San Nicolas Batholith crystallization ages obtained by Loewy et al. (2003, 2004). Correlation even improves with some inherited ages of these zircons with Paleoproterozoic ages. As a whole it is possible to affirm that correlation with the Arequipa Massif based on the metamorphic grade of the gneisses, the ages and characteristics of the analyzed zircons, and the topographic continuity between Paracas Peninsula and the outer-shelf high in the offshore, is highly positive, in spite of the limited amount of zircons analyzed. This correlation between the outer-shelf high and the Arequipa Massif was evident for Atherton et al. (1983) when comparing the gravity sections analyzed along the coast. These authors emphasized the important crustal change north and south of the Abancay lineament, which represented for them a change in the pre-Mesozoic crust (see location in Ramos, 2009).

Since the early work of Atherton et al. (1983, 1985), most of the authors accepted the hypothesis that the Western Cordillera is composed of Pre-Mesozoic continental crust while trying to explain

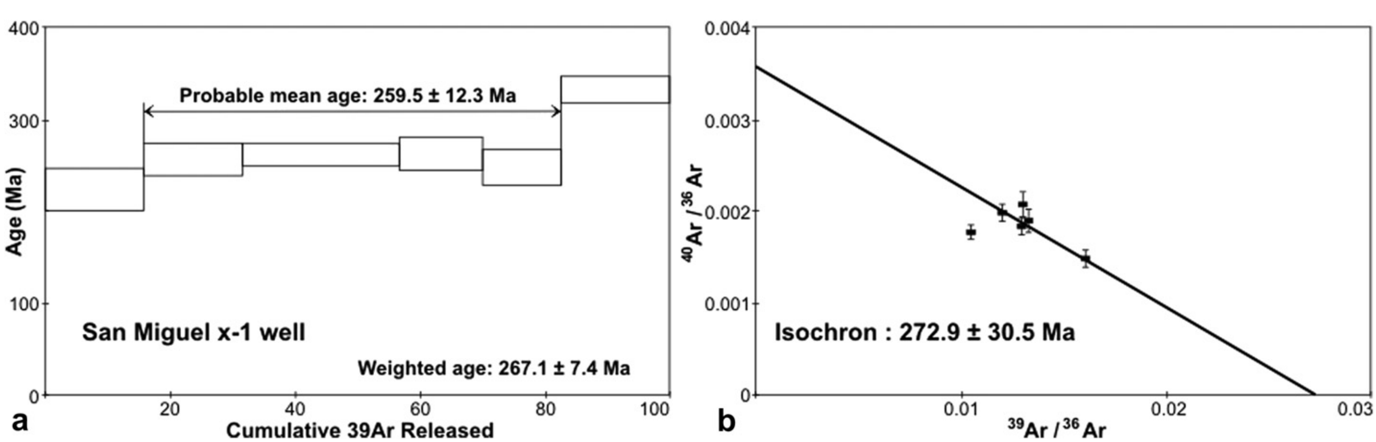


Fig. 11. Ar–Ar ages of the diorite of San Miguel 1-x well.

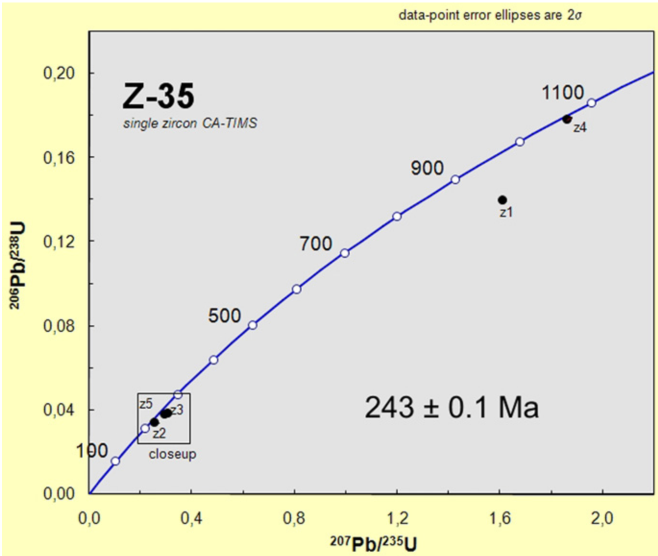


Fig. 12. Concordia diagram of Macabí Island Basalt zircons dated by U–Pb TIMS method.

the large volume of younger granitic juvenile magmas. The evolution of the Cretaceous basins was interpreted as some kind of aborted back-arc basin developed in attenuated continental crust (Aguirre et al., 1989; Atherton and Webb, 1989; Atherton and Aguirre, 1992; Cobbing, 1998). These models were improved by the proposal of an intra-arc setting dominated by extension during oblique subduction (Soler, 1991a,b). However, Haeberlin et al. (2004) proposed an alternative explanation for the lack of evidence of sialic cratonic material below western Perú: the high density basement is thought to correspond to a piece of oceanic crust formed during the Paleozoic through the removal and northward migration of the northern part of the Arequipa Massif. Polliand et al. (2005) presented interpretations based on U–Pb, Hf, and geologic data from the eastern part of the western Peruvian trough at the latitude of Lima that are in agreement with the intra-arc extensional model of Soler (1991b) and support the lack of sialic basement underlying this part of the Peruvian coast (De Haller et al., 2006).

Based on the data presented in the Las Hormigas de Afuera Island, plus the evidence of metamorphic rocks in several wells along the outer-shelf high, the proposal of removal and northern

Fig. 13. Granitoids of Lobera Island, western offshore margin of the coastal batholith of Perú. Note the homogeneous structure of the diorite in the upper part of the island.

migration of the northern part of the Arequipa Masif should be discarded. There are sialic pre-Jurassic gneisses in the offshore basement. In addition, the lack of evidence of a continental crust based on U–Pb, Hf, and other geologic data, is easy to reconcile with an extensional regime as the one proposed by Soler (1991b). Most of the continental margin of South America has been affected by extension during Late Jurassic and Early Cretaceous times, and as result of that, poorly evolved igneous rocks of juvenile nature were erupted in these intra-arc settings (Mpodozis and Ramos, 1989; Ramos, 2010b).

Once established that in the forearc there is a metamorphic sialic crust with ages similar to the Arequipa Massif, another essential problem arises, the existence of an early Paleozoic magmatic arc along the Marañón Massif, more than 600 km away from the present trench (Chew et al., 2007; Cardona et al., 2005, 2007; Mišković et al., 2009). Besides the present distance to the early Paleozoic batholith of more than 420–440 km, it is necessary to take into account more than 140 km of minimum Andean shortening at these latitudes (Cabassi and Introcaso, 1999), and at least 100 km of subduction erosion along the Peruvian forearc (Von Huene and Lallemand, 1990). To avoid this problem, several authors proposed a freeboard hypothesis, since they considered necessary to have only oceanic crust west of the Marañón Massif, and postulated an oceanic embayment north of the Abancay lineament (Chew et al., 2007). The alternative hypothesis considered the collision of a Paracas sialic terrane in Ordovician times (Ramos, 2008). This hypothesis was supported by the recognition of a suture with an NMORB to EMORB ophiolitic assemblage in the western margin of the Marañón Massif by Castroviejo et al. (2009, 2010) and Fanlo et al. (2009). The recognition of high pressure metamorphic conditions in garnet amphibolite from this collisional shear zone by Willner et al. (2010) also favor the hypothesis of a collisional scenario. This high pressure belt together with the metamorphism of low to middle pressure and high temperature above the magmatic arc of Marañón described by Chew et al. (2007) constitute a typical metamorphic pair as those described by Miyashiro (1961) and Brown (2010) in other subduction zones elsewhere. These ophiolites represent oceanic crust formed during the break-up de Rodinia (~720 Ma) and tectonically emplaced at some stage in the Late Ordovician (~450 Ma) according to Tassinari et al. (2011).

It is interesting to remark that the 467–477 Ma ages of the Ordovician episode in the Marañón Massif, in the Las Hormigas de Afuera Island, and in the Arequipa Massif are similar, and denote a typical Famatinian magmatism that dominated the continental margin of the Central Andes. This fact implies subduction beneath the Marañón Massif as well as beneath the Paracas and Arequipa terranes with a similar tectonic setting to the Antofalla terrane in northern Chile (Ramos, 2008). The Paracas terrane was detached during the Rodinia break-up and recollided during the Ordovician, while Arequipa stayed welded to Gondwana since the Mesoproterozoic as proposed by Loewy et al. (2004).

3.2. Late Paleozoic basement

The late Paleozoic age of the metamorphic rocks of the Illescas Massif, together with a series of granitoids and metamorphic rocks as the Higuerón and Paita orthogneisses in northern Perú, as well as other similar rocks in the Cordillera Real of Ecuador (Aspden et al., 1992; Sánchez et al., 2006), outline a dismembered orogen that was correlated with the Alleghenian by Ramos (2009). Many of these S-type peraluminous granites have Triassic ages between 239 and 220 Ma (U–Pb zircon ages of Bellido et al., 2009) and were explained by these authors as a Paleozoic crustal thickening followed by Permo-Triassic thinning and rifting. Similar ages were obtained along southern Ecuador and Colombia by Spikings et al.

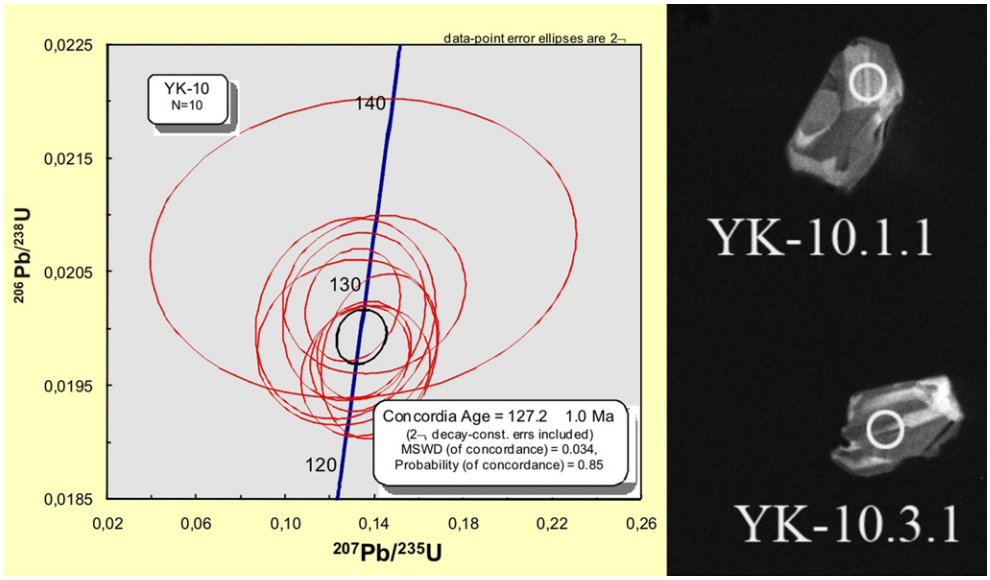


Fig. 14. Concordia diagram of U–Pb SHRIMP in zircons from the diorite of Lobera Island, near Punta Salinas, south of Huacho.

(2011), which yielded 247 and 228 Ma (U–Pb in zircons), associated with an anatectic episode that postdates the ductile deformation that foliated these rocks. The new data from San Miguel 1-x confirm and extend this belt to the south. The data of Macabi Island here presented, although scant, show a possible further extent of the late Paleozoic domain to the south.

The presence of metadiorites and younger S-type granites as described by Bellido et al. (2009) and Spikings et al. (2011), emplaced in the metamorphic rocks indicate the existence of a magmatic arc as inferred by the geochemical data presented by Bellido et al. (2009), and a subsequent regional anatexis along the northern coast of Perú affecting a Grenvillian-age basement, with a similar tectonic setting as the Tahami, Tres Lagunas, and Tahuin terranes. These terranes have been formed during the Alleghenian late Paleozoic collision and were interpreted as detached pieces of Laurentia left in the Gondwanian side after break-up of Pangea (Ramos, 2009).

The fact that metamorphic rocks in northern Perú coexist with equivalent sedimentary rocks of the same age may indicate a tectonic contact between these units, already proposed by Bellido et al. (2009) to explain the juxtaposition of middle and upper crustal rocks. These authors postulated a listric middle crustal shear zone that detached the upper crust and a subsequent thrusting and wrenching to the present position. This could be explained by the allochthonous origin of the Tahuin block proposed by Feininger (1987) and Mourier et al. (1988). Although these authors proposed a younger Cretaceous age for the docking of this terrane, the Cretaceous collisions further north could have displaced parts of the previous Paleozoic proto-margin of Gondwana as envisaged by Bellido et al. (2009).

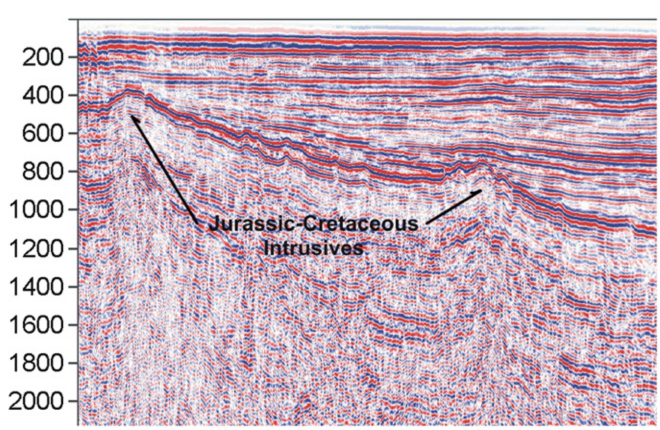


Fig. 15. Seismic expression of the Mesozoic intrusives similar to the Lobera Island diorite in the Salaverry Basin along the eastern side of seismic line 93-45 (two-way time msec). Location in Fig. 1.

3.3. Northern extent of the Huarmey Basin

The Macabi Island Basalts may represent the northwestern offshore margin of the Huarmey Basin as defined by Atherton and Webb (1989) based on the basalt's characteristics and maximum age. The U–Pb ages obtained in very scarce zircons indicate a Triassic maximum age, as these volcanic rocks are likely younger. The new outline of the basin in the paleogeographic reconstruction of Romero et al. (2011), indicates that the extensional processes extended further into the offshore than previously known.

3.4. Western margin of the coastal batholith

The new ages of Lobera Island diorite proved the existence of calcalkaline granitoids offshore of the Coastal Batholith defined by Cobbing and Pitcher (1972) and Pitcher et al. (1985). The precise 127.2 ± 1.0 Ma age obtained indicates the location of the magmatic arc front for the Barremian at these latitudes. The location of this island, plus the evidence of some other stocks along the eastern border of the Salaverry Basin as depicted in Fig. 15, shows that magmatic activity is less than 150 km away of the present trench. This fact confirms important crustal erosion by subduction since the Barremian, in the order of 100 km postulated by Von Huene and Lallemand (1990), and von Huene et al. (1996), which explains the important extension seen in Figs. 3b and 4b, a dominant feature all along the forearc of Perú.

4. Concluding remarks

The reconnaissance geochronological studies conducted in the forearc offshore of northern and central Perú demonstrate for the first time the existence of a cratonic basement of Precambrian–lower Paleozoic age. The obtained zircon ages from Hormigas de Afuera Island and the results of the existing drilling of Ballena 1-x, Delfín 1-x, and Morsa 1-x, together with gravimetric data presented in Fig. 2, permit the correlation of the outer shelf high with the Arequipa Massif of southern Perú. These data corroborate previous assumptions of the existence of a Precambrian–early Paleozoic metamorphic basement almost all along the Peruvian forearc.

The new Permian ages from the San Miguel 1-x well identify for the first time in the offshore the extent of a late Paleozoic basement further south than the Illescas Massif. These data and the existence of metadiorites in that well permit identification of the Tahuín terrane in the offshore forearc of northern Perú, as part of the Tahuin–Amotape domain.

The dates on the Macabí Island basalts only indicate a maximum Triassic age for these rocks of possible Jurassic–Cretaceous age. Their presence in this area can extend in the offshore the extensional Huarmey Basin.

The granitoids of the Lobera Island, together with other offshore stocks identified in the seismic lines in the eastern Salaverry Basin, permit inference of more than 100 km of crustal erosion by subduction at these latitudes since the Lower Cretaceous. This would explain the prevailing extensional regime in the Peruvian continental margin during the Andean cycle.

As a whole, the new reconnaissance geochronological data are an important step for the knowledge of the offshore forearc basement, a poorly known area prior to the present studies.

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References

Aguirre, L., Levi, B., Nyström, J.O., 1989. The Link Between Metamorphism, Volcanism and Geotectonic Setting During the Evolution of the Andes, vol. 43. Geological Society of London, Special Publication, pp. 223–232.

Alemán, A., 2006. Collision of aseismic ridges in Perú. Backbone of the Americas Symposium, Geological Society of America and Asociación Geológica Argentina, Abstracts with Programs, Special Meeting 2, Mendoza, p. 21.

Aleman, A., Ramos, V.A., 2000. The Northern Andes. In: Cordani, U.J., Milani, E.J., Thomaz Filho, A., Campos, D.A. (Eds.), Tectonic Evolution of South America, 31° International Geological Congress, pp. 453–480. Río de Janeiro.

Aspden, J.A., Fortey, N., Litherland, M., Viteri, F., Harrison, S.M., 1992. Regional S-type granites in the Ecuadorian Andes: possible remnants of the breakup of western Gondwana. Journal of South American Earth Science 6, 123–132.

Atherton, M.P., Aguirre, L., 1992. Thermal and geotectonic setting of Cretaceous volcanic rocks near Ica, Peru, in relation to Andean crustal thinning. Journal of South American Earth Sciences 5, 47–69.

Atherton, M.P., Webb, S., 1989. Volcanic facies, structure and geochemistry of the marginal basin rocks of Central Perú. Journal of South American Earth Sciences 2, 241–261.

Atherton, M.P., Pitcher, W.S., Warden, V., 1983. The Mesozoic marginal basin of central Peru. Nature 305, 303–306.

Atherton, M.P., Warden, V., Sanderson, L.M., 1985. The Mesozoic marginal basin of Central Peru: a geochemical study of within-plate-edge volcanism. In: Pitcher, W.S., Atherton, M.P., Cobbing, E.J., Beckingsale, R.D. (Eds.), Magmatism at the Plate Edge: the Peruvian Andes. Blackie, Glasgow, UK, pp. 47–58.

Bahlburg, H., Vervoort, J.D., Du Frane, S.A., Bock, B., Augustsson, C., Reimann, C., 2009. Timing of crust formation and recycling in accretionary orogens: insights learned from the western margin of South America. Earth-Science Reviews 97 (1–4), 215–241.

Bellido, F., Valverde, P., Jaimes, F., Carlotto, V., Díaz-Martinez, E., 2009. Datación y caracterización geoquímica de los granitoides peraluminicos de los cerros de Amotape y de los Macizos de Illescas y Paita (Noroeste de Perú). Boletín Sociedad Geológica del Perú 103, 197–213.

Benavides, V., 1956. Cretaceous of Northern Perú. Bulletin of the American Museum of Natural History 108 (4), 353–494.

Benavides, V., 1999. Orogenic evolution of the Peruvian Andes: the Andean cycle. In: Skinner, B. (Ed.), Geology and Mineral Deposits of Central Andes. Society of Economic Geology, Special Publication, vol. 7, pp. 61–108.

Brown, M., 2010. Paired metamorphic belts revisited. Gondwana Research 18, 46–59.

Cabassi, I., Introcaso, A., 1999. Los Andes peruanos y argentino-chilenos: un estudio cortical preliminar comparativo. 14° Congreso Geológico Argentino, Salta, Actas 1, pp. 295–297.

Cardona, A., 2006. Reconhecimento da evolução tectônica da proto-margem Andina do centro-norte Peruano, baseada em dados geoquímicos e isotópicos do embasamento da Cordilheira Oriental na região de Huánuco-La Unión. PhD thesis, Universidade de São Paulo, unpublished, 196 p., São Paulo.

Cardona, A., Cordani, U.G., Ruiz, J., Valencia, V., Nutman, A.P., Sanchez, A.W., 2005. U/Pb detrital zircon geochronology and Nd isotopes from Paleozoic metasedimentary rocks of the Marañon complex: insights on the proto-Andean tectonic evolution of the eastern Peruvian Andes. 5° South American Symposium on Isotope Geology, Proceedings, Punta del Este, pp. 208–211.

Cardona, A., Cordani, U.G., Sanchez, A.W., 2007. Metamorphic, geochronological and geochemical constraints from the pre-Permian basement of the eastern Peruvian Andes (10°S): a Paleozoic extensional-accretionary orogen? Colloquium Latin American Earth Sciences, 20th, Kiel, pp. 29–30.

Cardona, A., Cordani, U.G., Nutman, A.P., 2008. U.Pb SHRIMP circón, 40Ar/39Ar geochronology and Nd isotopes from granitoid rocks of the Illescas Massif, Peru: a southern extension of a fragmented Late Paleozoic orogen? 6° South American Symposium on Isotope Geology, Proceedings, Abstracts, Bariloche, p. 78.

Carlotto, V., Acosta, H., Mamani, M., Cerpa, L., Rodríguez, R., Jaimes, F., Navarro, P., Cueva, E., Checaltana, C., 2011. Los dominios geotectónicos del Perú: Aportes para la interpretación de la evolución de los Andes. 14° Congreso Latinoamericano de Geología and 13° Congreso Colombiano de Geología, Memorias, Medellín, p. 109.

Castroviejo, R., Rodrigues, J.F., Acosta, J., Pereira, E., Romero, D., Quispe, J., Espí, J.A., 2009. Geología de las ultramafitas pre-andinas de Tapo y Acobamba, Tarma, Cordillera Oriental del Peru, vol. 46. Sociedad Geológica Española, Geogaceta, Madrid, pp. 7–10.

Castroviejo, R., Macharé, J., Castro, P., Pereira, E., Rodrigues, J.F., Tassinari, C.G., Willner, A., Acosta, J., 2010. Significado de las ofiolitas neoproterozoicas de la Cordillera Oriental del Perú (9°30′–11°30′). Sociedad Geológica del Perú, 15° Congreso Peruano de Geología, Publicación Especial 9, Cusco, pp. 51–53.

Chew, D.M., Schaltegger, U., Košler, J., Whitehouse, M.J., Gutjahr, M., Spikings, R.A., Miškovíc, A., 2007. U–Pb geochronologic evidence for the evolution of the Gondwanan margin of the north-central Andes. Geological Society of America, Bulletin 119, 697–711.

Cobbing, E.J., 1998. The coastal batholith and other aspects of Andean magmatism in Peru. Boletín de la Sociedad Geológica del Perú 88, 5–20.

Cobbing, E.J., Pitcher, W.S., 1972. The coastal batholith of central Peru. Journal Geological Society London 128, 421–460.

Dahlquist, J.A., Pankhurst, R.J., Rapela, C.W., Galindo, C., Alasino, P.H., Fanning, C.M., Saavedra, J., Baldo, E.G., 2008. New SHRIMP U–Pb data from the Famatina complex: constraining early-mid Ordovician Famatinian magmatism in the Sierras Pampeanas, Argentina. Geologica Acta 6 (4), 319–333.

Dalmayrac, B., Lancelot, J.R., Leyreloup, A., 1977. Two-billion-year granulites in the late Precambrian metamorphic basement along the southern Peruvian coast. Science 198, 49–51.

De Haller, A., Corfu, F., Fontboté, L., Schaltegger, U., Barra, F., Chiaradia, M., Frank, M., Zúñiga Alvarado, J., 2006. Geology, geochronology, and Hf and Pb isotope data of the Raúl-condestable iron oxide–copper–gold deposit, central coast of Peru. Economic Geology 101, 281–310.

Fanlo, I., Gervilla, F., Castroviejo, R., Rodrigues, J.F., Pereira, E., Acosta, J., Uribe, R., 2009. Metamorphism of chromitites in the Tapo Ultramafic Massif, Eastern Cordillera, Peru. 10th Biennial SGA Meeting, Proceedings, Townsville, Australia, pp. 161–163.

Feininger, T., 1987. Allochthonous terranes in the Andes of Ecuador and northwestern Peru. Canadian Journal of Earth Sciences 24, 266–278.

Gutscher, M.A., Spakman, W., Bijwaard, H., Engdahl, E.R., 2000. Geodynamic of flat subduction: seismicity and tomographic constraints from the Andean margin. Tectonics 19, 814–833.

Haeberlin, Y., Moritz, R., Fontboté, L., Cosca, M., 2004. Carboniferous orogenic gold deposits at Pataz, Eastern Andean Cordillera, Peru: geological and structural framework, paragenesis, alteration, and 40Ar/39Ar geochronology. Economic Geology 99, 73–112.

Hampel, A., Kukowski, N., Bialas, J., Huebscher, C., Heinbockel, R., 2004. Ridge subduction at an erosive margin: the collision zone of the Nazca Ridge in southern Peru. Journal of Geophysical Research 109 (B02101). http://dx.doi.org/10.1029/2003JB002593.

Kulm, L.D., Prince, R.A., French, W., Johnson, S., Masias, A., 1981. Crustal structure and tectonics of the central Perú continental margin and trench. Geological Society of America, Memoir 154, 445–508.

Loewy, S.L., Connelly, J.N., Dalziel, I.W.D., Gower, C.F., 2003. Eastern Laurentia in Rodinia: constraints from wholerock Pb and U/Pb geochronology. Tectonophysics 375, 169–197.

Loewy, S.L., Connelly, J.N., Dalziel, I.W.D., 2004. An orphaned basement block: the Arequipa-Antofalla basement of the central Andean margin of South America. Geological Society of America, Bulletin 116, 171–187.

Mišković, A., Schaltegger, U., Chew, D., 2005. Carboniferous plutonism along the Eastern Peruvian Cordillera: implications for the Late Paleozoic to early

Mesozoic Gondwanan tectonics. In: Barcelona, 6th International Symposium on Andean Geodynamics. Institut de Recherche pour le Développement, Paris, pp. 508–511.
Mišković, A., Spikings, R.A., Chew, D.M., Košler, J., Ulianov, A., Schaltegger, U., 2009. Tectonomagmatic evolution of Western Amazonia: geochemical characterization and zircon U–Pb geochronologic constraints from the Peruvian Eastern Cordilleran granitoids. Geological Society of America Bulletin 121 (9/10), 1298–1324. http://dx.doi.org/10.1130/B26488.1.
Miyashiro, A., 1961. Evolution of metamorphic belts. Journal of Petrology 2, 277–311.
Mourier, T., Laj, C., Mégard, F., Roperch, P., Mitouard, P., Farfan, M., 1988. An accreted continental terrane in northwestern Peru. Earth and Planetary Science Letters 88, 182–192.
Mpodozis, C., Ramos, V.A., 1989. The Andes of Chile and Argentina. In: Ericksen, G.E., Cañas Pinochet, M.T., Reinemud, J.A. (Eds.), Geology of the Andes and its Relation to Hydrocarbon and Mineral Resources. Earth Sciences Series, vol. 11. Circumpacific Council for Energy and Mineral Resources, Houston, pp. 59–90.
Myers, J.S., 1974. Cretaceous stratigraphy and structure, Western Andes of Peru between latitudes 10°–10°30″. American Association of Petroleum Geologists Bulletin 58 (3), 474–487.
Myers, J.S., 1975. Vertical crustal movements of the Andes in Peru. Nature 254, 672–674.
Palacios, O., Caldas, J., Vela, Ch, 1992. Geología de los cuadrángulos de Lima, Lurín, Chancay y Chosica; hojas 25-i, 25-j, 24-i, 24-j. INGEMMET. Carta Geológica Nacional, Boletín Serie A 43, Lima, 163 pp.
Pankhurst, R., Rapela, C., Saavedra, J., Baldo, E., Dahlquist, J., Pascua, I., Fanning, C.M., 1998. The Famatinian magmatic arc in the Central Sierras Pampeanas: an early to mid-Ordovician continental arc on the Gondwana margin. In: Pankhurst, R.J., Rapela, C.W. (Eds.), The Proto-Andean Margin of Gondwana. Geological Society of London, Special Publication, vol. 142, pp. 343–367.
Pilger, R.H., 1984. Cenozoic plate kinematics, subduction and magmatism: south American Andes. Journal Geological Society of London 141, 793–802.
Pitcher, W.S., Atherton, M.P., Cobbing, E.J., Beckinsale, R.D., 1985. Magmatism at a Plate Edge: the Peruvian Andes. Blackie, Glasgow and London, 289 pp.
Polliand, M., Schaltegger, U., Frank, M., Fontboté, L., 2005. Formation of intra-arc volcanosedimentary basins in the western flank of the central Peruvian Andes during Late Cretaceous oblique subduction; field evidence and constraints from U–Pb ages and Hf isotopes. International Journal of Earth Sciences 94, 231–242.
Quenardelle, S., Ramos, V.A., 1999. The Ordovician western Sierras Pampeanas magmatic belt: record of Argentine Precordillera accretion. Geological Society of America, Special Paper 336, 63–86.
Ramos, V.A., 2008. The basement of the Central Andes: the Arequipa and related terranes. Annual Review on Earth and Planetary Sciences 36, 289–324.
Ramos, V.A., 2009. Anatomy and global context of the Andes: main geologic features and the Andean orogenic cycle. In: Kay, S.M., Ramos, V.A., Dickinson, W. (Eds.), Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision, Memoir 204. Geological Society of America, pp. 31–65.
Ramos, V.A., 2010a. The tectonic regime along the Andes: present settings as a key for the Mesozoic regimes. Geological Journal 45, 2–25.
Ramos, V.A., 2010b. The Grenville-age basement of the Andes. Journal of South American Earth Sciences 29 (1), 77–91.
Ramos, V.A., Aleman, A., 2000. Tectonic evolution of the Andes. In: Cordani, U.G., Milani, E.J., Thomaz Filho, A., Campos, D.A. (Eds.), Tectonic Evolution of South America, 31° International Geological Congress, pp. 635–685. Río de Janeiro.
Reimann, C.R., Bahlburg, H., Kooijman, E., Berndt, J., Gerdes, A., Carlotto, V., López, S., 2010. Geodynamic evolution of the early Paleozoic Western Gondwana margin 14°–17°S reflected by the detritus of the Devonian and Ordovician basins of southern Peru and northern Bolivia. Gondwana Research 18, 370–384.
Romero, D., 2010. Informe del procesamiento digital de imágenes y cartografía digital de área del litoral peruano entre las ciudades de Chiclayo y Paracas. Savia Perú S.A., Unpublished report, 38 p., Lima.
Romero, D., Valencia, K., Alarcón, P., Ramos, V.A., 2011. Geología de la costa pacífica del Perú central entre Chiclayo y Paracas (7°–14° Sur). 14° Congreso Latinoamericano de Geología, Memorias, Medellín, pp. 110–111.
Sánchez, J., Palacios, O., Feininger, T., Carlotto, V., Quispesivana, L., 2006. Puesta en evidencia de granitoides triásicos en los Amotapes–Tahuín: deflexión de Huancabamba. 13° Congreso Peruano de Geología, Sociedad Geológica del Perú, Resúmenes Extendidos, Lima, pp. 312–315.
Shackleton, R.M., Ries, A.C., Coward, M.P., Cobbold, P.R., 1979. Structure, metamorphism and geochronology of the Arequipa massif of coastal Peru. Journal of Geological Society 136, 195–214.
Soler, P., 1991a. Contribution à l'étude du magmatisme associé aux marges actives – petrographie, géochimie et géochimisme isotopique du magmatisme Crétacé à Pliocène le long d'une transversale des Andes du Pérou central-Implications géodynamiques et métallogéniques. PhD. thesis, Université Pierre et Marie Curie, Paris VI, Unpublished, 846 p.
Soler, P., 1991b. El volcanismo Casma del Perú Central: cuenca marginal abortada o simple arco volcanico? Sociedad Geológica de Perú, 7° Congreso Peruano de Geología, Resúmenes Extendidos, Lima, pp. 659–663.
Soler, P., Bonhomme, M., 1990. Relations of magmatic activity to plate dynamics in Central Peru from Late Cretaceous to present. In: Kay, S., Rapela, C.W. (Eds.), Plutonism from Antarctica to Alaska. Geological Society of America, Special Paper 241, pp. 173–191.
Spikings, R., Villagómez, D., Cochrane, R., Van der Lelij, R., Winkler, W., 2011. The tectonic history of the northern Andean segment (North of 5°S) since the Early Triassic: a geochronological and thermochronological study. 14° Congreso Latinoamericano de Geología, Memorias, Medellín, p. 107.
Steinmann, G., 1929. Geologie von Peru. Karl Winter ed., Heidelberg, 448 pp.
Tassinari, C.G., Castroviejo, R., Rodrigues, J.F., Acosta, J., Pereira, E., 2011. A Neoproterozoic age for the chromitite and gabbro of the Tapo ultramafic Massif, Eastern Cordillera, Central Peru and its tectonic implications. Journal of South American Earth Sciences 32, 429–437.
Thornburg, T., Kulm, L.D., 1981. Sedimentary basins of the Peru continental margin: structure, stratigraphy, and Cenozoic tectonics from 6°S to 16°S latitude. Geological Society of America, Memoir 154, 393–422.
Valencia, K., 2009. Estudio petro-mineragráfico de muestras de canaleta y pared del pozo exploratorio San Miguel 1-x. Informe Savia Perú S.A. (unpublished), Lima, 14 pp.
Von Huene, R., Lallemand, S., 1990. Tectonic erosion along the Japan and Peru convergent margins. Geological Society of America, Bulletin 102, 704–720.
von Huene, R., Pecher, I.A., Gutscher, M.A., 1996. Development of the accretionary prism along Perú and material flux after subduction of Nazca Ridge. Tectonics 15 (1), 19–33.
Wasteneys, A.H., Clark, A.H., Farrar, E., Langridge, R.J., 1995. Grenvillian granulite-facies metamorphism in the Arequipa massif, Peru: a Laurentia-Gondwana link. Earth Planetary Science Letters 132, 63–73.
Willner, A.P., Castroviejo, R., Rodrigues, J.F., Acosta, J., Rivera, M., 2010. High pressure metamorphic conditions in garnet amphibolite from a collisional shear zone related to the Tapo ultramafic body, Eastern Cordillera of central Perú. 15° Congreso Peruano de Geología, Resúmenes Extendidos, Sociedad Geológica del Perú, Publicación Especial 9, Cusco, pp. 87–90.
Wilson, J.J., 1963. Cretaceous stratigraphy of central Andes of Peru. Bulletin of the American Association of Petroleum Geologists 47 (1), 1–34.
Witt, C.A., Alarcón, P., Valencia, K., Lajo, A., Fuentes, J., Romero, D., 2011. Segmentación tectono-estratigráfica y superposición de cuencas de antearco cenozoicas en la margen andina entre 6°S y 2°S (Norte Perú – Sur Ecuador). 14° Congreso Latinoamericano de Geología, Memorias, Medellín, pp. 248–249.