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An Alternative Mesozoic Geodynamic Model for the Evolution of the Central Coastal Ranges of Peru: The Río Cañete Basin

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INTRODUCTION

Integration of detailed stratigraphic, sedimentologic and tectonic studies of the Río Cañete Basin with opening and divergence rates of the South Atlantic Ocean, overriding plate velocity, trench migration, subducting age (Fig. 1) etc. and the protracted Mesozoic Farallon Plate oblique convergence parameters provides new lines of evidence to suggest an alternative model for the evolution of the Peruvian margin. These unorthodox model departures significantly from the classic and simplistic Andean Model used in the literature. The western margin of Gondwana experience severe lithosphere extension coeval with arc magmatism since at least Middle Triassic. Actually, only the uppermost Jurassic unit is displayed along the Río Cañete Basin, however, it is important to take into account that northward the Jurassic arc sequence terminates against the accreted Amotape/Olmos Terrain and it overlies the Late Triassic to Jurassic Pucara Group. Slab stagnation in the mantle transition zone near the upper and lower mantle boundary perhaps triggered shallow subduction, which in turn caused drowning and Jurassic arc volcanism termination. Slab flattening increased upper plate stress coupling transferring the stresses eastward and causing basement-core block uplift and changing provenance to quartz-rich. Slab breakoff occurred soon after the water-bearing serpentinized slab changed to denser eclogite facies as recorded by linear alkaline volcanism with strong mantle source (low La/Nb ratio) along the high Andes. Locally, transform fault subduction enhanced fracturing during slab bending permitting the tapping of undepleted mantle by these deep faults and causing trench parallel extension coeval with explosive subaqueous volcanism with strong OIB signature (low La/Nb ratio).

Higher South Atlantic spreading rates than the trench normal convergence imparted the mechanism for trench rollback, thus enhancing the upper plate extensional deformation. Aptian increase in spreading rates coeval with protracted increase in the normal absolute plate motion terminated the active basement uplift; however, they persisted as submerged highs allowing the diachronous north-south encroaching of the Cretaceous epeiric sea in along the Marañón and Ucayali basins. Prolonged Farallón Plate oblique convergence triggered strain partitioning and set-up important strike slip deformation such as the Tapacocha and Hormigas faults. Basin development involved pervasive transtensional deformation and tectonic segmentation and each one distinguished by its own stratigraphy, geochemistry, heat flow and subsidence history. Transtensional deformation involved deep crustal faults and complex lithosphere boudinage permitting important asthenospheric mantle decompression melting magmatism that mixed with partially metasomatized subduction slab as documented by relative low La/Yb and La/Nb ratios and the occurrence of Nb-Ta negative anomalies. Two distinctive magmatic regimes are separated by an important and major plutonic regime linked to the emplacement of the Peruvian Costal Batholith (PCB) encompassing episodic multi-scale stopping, caldron subsidence and assimilation. The oldest volcanic regime (Casma Group), has higher mantle contribution and insignificant crustal contamination compare to the younger one (Quilmaná Formation). However, locally detrital zircons (DZ) and Hf isotopes support the presence of juvenile zircons supporting the absence of crustal contamination

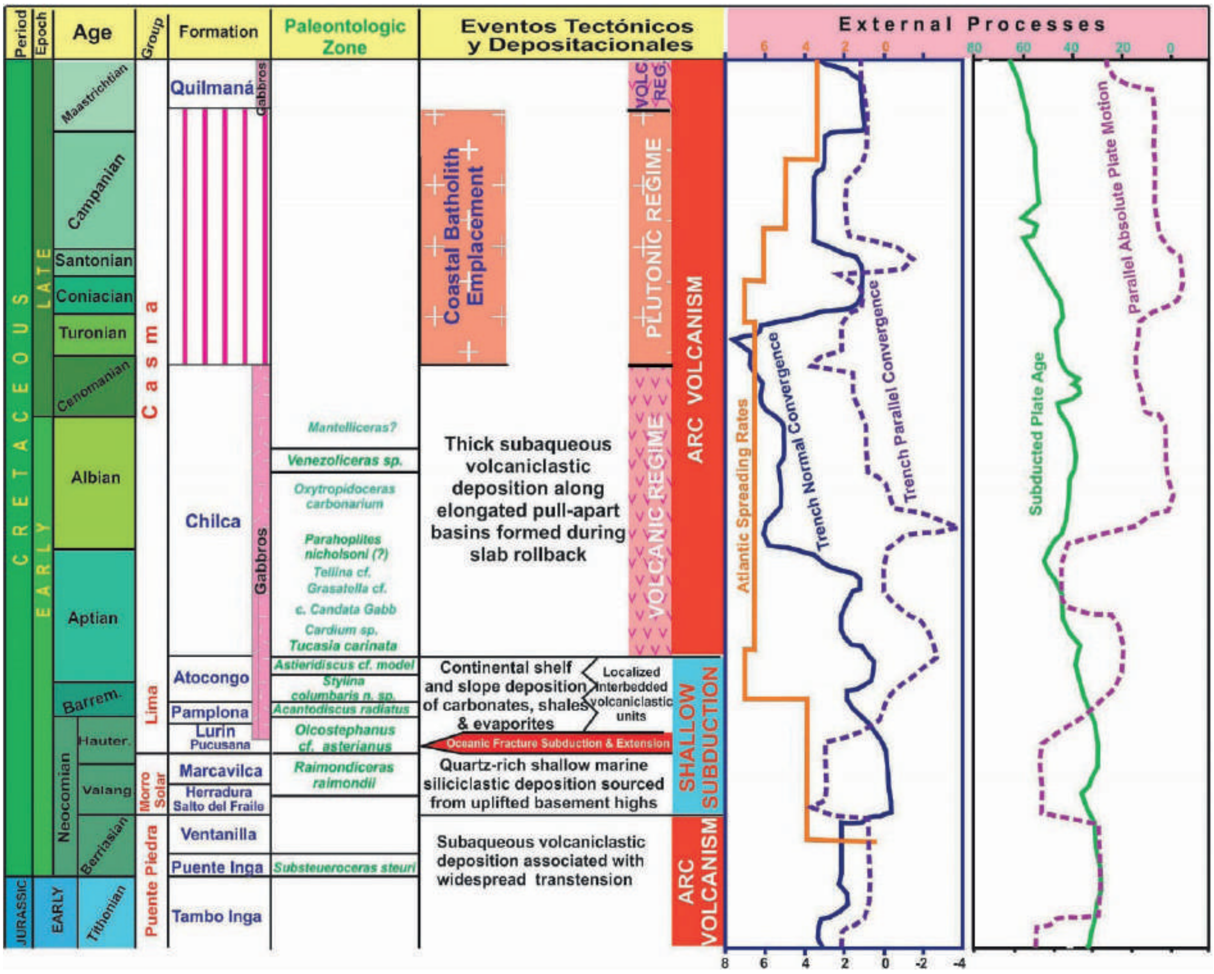

Fig.1 Tectonic events and plate velocity of the central coastal ranges of Peru: Rio Cañete Basin

OBLIQUE CONVERGENCE AND JURASSIC ARC VOLCANISM

The Puente Piedra Group symbolizes the oldest arc volcanism in the Rio Cañete Basin, ranges in age from Tithonian to Berriasian preceding the South Atlantic opening. Protracted Farallon Plate oblique convergence trigger strain partitioning developing complex strike slip bounded basins. Southward transtensional basins are broader and Jurassic Guaneros Formation volcaniclastic sequences interfinger eastward with siliciclastics and carbonates of the Yura Group. However, along the Rio Grande and northward the grabens become relatively narrow and elongated and the quartz-rich Hualhuani Formation overlies the Guaneros Formation. Indeed, along the Río Cañete Basin, the Morro Solar Group also overlies the Puente Piedra Group as the Goyllarisquizga Group overlies the Colan/Traposa Formation at the northward Jurassic arc termination.

Along the Rio Cañete Basin, the Jurassic Puente Piedra consists of subaqueous volcaniclastic units that vary from thick bedded porphyritic to aphanitic basalts and basaltic andesite lava flows interbedded with medium bedded lithic to crystal lapilli tuffs at the base followed by a varycolor tuffaceous shales interbedded with ash tuffs and thinly bedded fine grained lapilli tuffs that contain a rich Berriasian to Tithonian age fauna. The uppermost unit consist of thick bedded massive porphyritic to aphanitic lavas interbedded with coarse grained lapilli tuffs with rests of plants. Geochemically, they are mainly calc-alkaline and range from basalt to dacites representing continental arcs with important subduction enrichment. However, the normalized primitive mantle spider diagram as well as the normalized for chondrite diagram ranges between OIB and EMORB. We envision these geochemical patterns to result from important contribution of asthenospheric mantle during lithosphere extension as suggested by the relatively low La/Nb ratios that mixed with subduction slab contribution as documented by the negative Nb-Ta negative anomalies.

SHALLOW SUBDUCTION AND BASEMENT-CORE BLOCK UPLIFT

The Peruvian segment of the Gondwana margin underwent subduction flattening during the late Berriasian, thus terminating and drowning the Jurassic arc during a poorly understood contractional event that uplifted the Marañón and Coastal Cordillera blocks. This regional even also changed the source and provenance to a quartz rich shallow marine sequence known as the Morro Solar/Goyllarisquizga Group and its southern lateral equivalent known as the Hualhuani Formation (Benavides, 1956 and 1962). Recent DZ studies corroborated the meager percentage of Jurassic age zircons due to extreme arc subsidence (Chavez et al., 2021). Amid these two basement highs, a shallow basin developed and was the depositional site of these units while the upper plate stress coupling transferred the stresses eastward causing basement-core block uplift (Dickinson and Snyder, 1978, Bird, 1988). Indeed, farfield stresses caused thrust faults at both sides of this widespread basin linked along a main through-going deep crustal basal detachment described as orogenic float (Oldow et al., 1990, English and Johnston, 2004). Our early interpretation (Aleman et al, 2004, Aleman and León, 2016b) ascribed the flat slab to a hypothetical Chivaterous Plateau collision, following the proposed models for the Peruvian and Laramide flat slabs. Unfortunately, the southward migration of the Nazca Ridge may have played an important role in the flat slab in addition to some enquiries regarding the importance of aseismic ridges, since there are flat slabs without aseismic ridges, and collision of aseismic ridges without flat slab (Schellart, 2020, Schellart and Strak, 2021). Similarly, the Late Cretaceous Laramide Flat slab, initially ascribed to the subduction of a buoyant oceanic plateau, has been questioned and proposed alternatives such as the trenchward increase in North American plate motion, slab suction force due to the presence of the thick Colorado Plateau lithosphere, etc. (Liu et al., 2010). In reevaluating our old model (Aleman and León, 2016b), we realize that the aseismic ridge collision is inconsistent with the Neocomian synchronous flat slab and magmatic lull of almost 1500 km wide flat slab. Furthermore, because of the Late Triassic long-lasting subduction, we are leaning toward the model elaborated by Schellart and Strak (2021). Their numerical modelling indicates that the slab in long-lived subduction margins attaining the 660 km mantle discontinuity generates slab folding, which in turn generates recurrent variations in the upper mantle slab dip angle. The overring plate strength controls not only the shortening rate but also the duration of the flat slab subduction (Schellart and Strak 2021). During subduction flattening, the mantle wedge was squeezed and migrated outboard as the subcontinental mantle lithosphere was sheared off and removed producing thinning under the West Peruvian Trough (WPT) and thickening the crust eastward as documented by Vp/Vs studies (Condori et al., 2017).

LATE SLAB BREAKOFF

Soler (1991) reported and analyzed three early Cretaceous alkaline basalts from Cerro de Pasco and interpret them as intraplate volcanism. Later, Romero et al. (2004) described interbedded some lava flows with the shales and sandstones of the Chayllacatana Formation. Cueva et al. (2013) carried out detailed stratigraphic and geochemistry studies of these alkaline lavas interbedded with the Goyllarisquisga Group and also Chayllacatana Formation between the Cerro de Pasco/Ayacucho and La Oroya/Huancavelica fault system in the High Andes. Unfortunately, in their analysis they also included the lavas interbedded with the graben filled Sarayaquillo Formation in the eastern Cordillera lumping together in their retroarc setting interpretation (Cueva et al., 2013). Slab breakoff magmatism after the Neocomian flat slab documentation along the Peruvian margin provides an alternative interpretation. Late detachment of serpentinized and hydrous subduction took place soon after the slab increased density amidst eclogite metamorphism allowing asthenosphere mantle mixing with subtle contribution from the late phase subduction slab melting. Normalized NMORB shows slight Nb-Ta and Zr-Hf anomalies corroborating slab contribution, however its overall pattern shows pronounced LIL enrichment and shallow slope in the HFS elements. The pattern on the chondrite spider diagram strongly resembles the OIB with moderate slope in the HREE and almost flat HREE suggesting the absence of deep garnet. This OIB pattern is also observed in the normalized primitive mantle diagram that varies between EMORB and OIB. Despite the absence of isotope data, preliminary interpretation supports the absence of crustal contamination as depicted by the normalized upper crustal spider diagram showing slight Nb and Sr and slightly higher Cs, P and Ti, enrichment; nevertheless, with depleted U, K and Th anomalies. Although still in process of evaluating this model, the slab breakoff is an alternative and feasible interpretation for these alkaline basalts to basaltic nephelinites.

A NEW TYPE OF SUBDUCTION OF OCEANIC TRANSFORM FAULT

More than 800 meters of subaqueous volcaniclastics consisting of disorganized and stratified volcaniclastic breccias, thick, medium, and thin bedded volcaniclastic sandstone, and thick bedded basalts to andesite lava flows, with subordinate thin to medium bedded lime mudstone and fossiliferous packstone locally outcropping between Pucusana Beach and the Mala town, about 30 km apart. Near Mala, this volcaniclastic sequence has been documented in coreholes from the Condestable Mine overlying the Morro Solar Group and underlying the Lurin Formation. However, three kilometers south of Mala the dextral and perhaps crustal scale Calicanto Fault marks the southern depositional boundary of the Pucusana Formation which is absent along the Perico Hill continuous Puente Piedra to Casma groups stratigraphic section where the Pamplona Formation overlies the Morro Solar Group.

Initially, we interpreted this localized sequence with a strong OIB signature as a possible slab window (Aleman et al., 2004, Aleman and León, 2016a); however, its restricted distribution to a small area of 30x20 km required to review it since it was impossible also to conceive a spreading ridge that will unzipped in such a minute area without any trench migration. Although we still waiting for the results of additional geochemistry, isotope and DZ studies, we are inclined in interpreting this localized volcanism as the subduction of a transform fault during oblique convergence at the time when Pangea was separating and Gondwana was moving south compared to the Farallon Plate northeast motion (Seton et al., 2012, Maloney et al., 2013). This relative motion perhaps explains the trench parallel extension in the Pucusana area as observe in the abundant E-W oriented dykes. The transform faults added to intense fracturing reached deep into the mantle allowing upward funneling primitive mantle upwelling as well as providing large volumes of fertile water source for subduction modified magmatism and focusing the melting along the fracture zone thus explaining the alkaline to subalkaline basaltic and basaltic andesites subaqueous volcanism. This transform fault subduction is significant different from the Subduction-Transform Edge Propagator (STEP) faults described in the Mediterranean (Govers and Wortel, 2005; Rosenbaum and Agostinetti, 2015) since it took place during shallow subduction and did not involve differential slab rollback at all. Mantle upwelling is documented by the EMORB and OIB signature displayed on the chondrite REE, Primitive Mantle, NMORB and in the NMORB immobile normalized diagram and also confirmed by many other spider diagrams as well as many geotectonic diagrams.

It is important to underscored the importance of the shallow water subaqueous volcanism as documented by large scale clinoforms, the role of water in the high degree of explosiveness, and the formation of large scale calderas developed during extension and the transfer fault subduction processes. Apparently, the dextral Calicanto Fault no only represented the former trace of the transform fault but also played an important role in carrying mineralization fluids from the deeper mantle. In confirming this tectonic model, it is imperative to carry out a magnetoteluric survey from the north of the Santa Maria Beach to 10 kilometers south of the Calicanto Fault and assess the potential areas for future for ore deposits exploration.

PROTRACTED OBLIQUE CONVERGENCE, APTIAN SLAB ROLLBACK AND LITHHOSPHERE ATTENUATION

The southeast motion of the Farallon Plate during the initial acceleration spreading of the South Atlantic Ocean provides the mechanism for the oblique convergence continuation and triggered slab rollback and moderate lithosphere attenuation motion (Seton et al., 2012, Maloney et al., 2013). Extensional deformation continued as reflected by rapid thickness changes and short distance facies changes of the Lima Group. Regionally, the contractional basement uplift associated with flat subduction terminated and the Marañón Block remained as a structural high but submerged allowing the also the north-south diachronous encroachment of the Tethyan epeiric sea east of this block. The oldest Barremian gabbro emplacement reported (Martinez Ardila et al, 2019) provides the enlightenment for the restricted presence of tuffs and lavas in the Lima Group. Indeed, the Lowermost unit of this group, known as the Lurín Formation consist of interbedded muddy limestones and shales with locally chicken wire gypsum at the base and abundant slump folds and limestone boudinage that attest for block tilting during extension. The presence of gypsum may represent important pulses of extension that locally isolated this unit from the open ocean fostering higher evaporation rates and its precipitation. The type locality of the Pamplona Formation is overwhelmed by shales and subordinated muddy limestones, however, locally along the Santa Maria Beach, there are some pyroclastic breccias in a gypsum matrix that have undergone dissolution collapse, as well as some volcaniclastic sandstones showing some wave ripple marks indicating subtle and localized basin shallowing. The uppermost Atocongo Formation consist of thick bedded massive lime to packstone limestones interbedded with thin shales units and sporadic packstones toward the top and often inhibits some basaltic lava flows and discrete ash fall tuffs. Locally this unit contain abundant ahermatypic corals and some along the Perico Hill that suggest deposition within the photic zone perhaps associated with local uplift.

REKINDLING OF ARC VOLCANISM DURING APTIAN/ALBIAN SLAB ROLL-BACK SETTING OFF PERVASIVE LITHOSPHERE BOUDINAGE ALONG THE WPT

Initiation of arc volcanism with sporadic volcaniclastic deposition in the Lurin and Atocongo formations was concurrent with gabbros emplacement (Aleman et al., 2004, Aleman and León, 2018). However, it reached paroxysmic proportions during persistent lithosphere attenuation and boudinage of the WPT soon after Atlantic Ocean the spreading rates increase associated with the trench normal convergence rates and the normal absolute plate motion (Seton et al., 2012, Maloney et al., 2013). The Farallon Plate strong oblique convergence produced strain partitioning on the overriding plate developing the trench parallel Tapacocha and Hormigas dextral strike slip faults. The Tapacocha Fault setting was perhaps influenced by important Eastern Cordillera crustal growth associated to subcontinental mantle lithosphere shearing linked to the Neocomian flat slab which in turn also enhanced lithosphere thinning west of this fault.

The Hormigas Fault on other hand, developed the outer shelf basement high subparallel to the Tapacocha Fault which marked the eastern limit of Cretaceous arc deposition. The relative dextral motion of the Tapacocha and Hormigas faults resulted in transtensional deformation and accounted for the distinctive stratigraphic framework and subsidence of the Huarmey and Rio Cañete basins (Cobbing et al., 1981, Aleman, 1996, Aleman et al., 2004, Aleman and León, 2018). The magmatism involved two distinctive volcanic regimes separated by a major plutonic regime responsible for the emplacement of the Peruvian Coastal Batholith (PCB). The asthenosphere upwelling depth controlled the variable heat flow, which was a function of the crustal attenuation intensity controlling the subsidence rates and the variable volcaniclastic facies (Aleman et al., 2004, Aleman and León, 2018).

Numerous studies indicate moderated crustal contamination and assimilation and important magmatic recycling during the multiple pulses of the Plutonic Regime along the WPT. Processes of Andean crustal growth continued despite lithosphere attenuation as documented by cauldron subsidence, magmatic stopping, abundant xenoliths, enclaves, and pervasive dyking cutting some batholith units as well as the Casma Group. The shear couple set up by these two major faults develop multiple pull-apart basins in time and space as inferred regionally and locally (Pollliand et al., 2005) providing the room for the episodic emplacement of the linear PCB, an important issue to address. Evolution of the Tapacocha Fault also plays an important role in the WPT crustal extension involving pervasive lithosphere boudinage thus allowing the mixing of asthenosphere mantle upwelling with partially metasomatized subduction slab melt. The WPT magmatism is attributed to melts extracted from an enriched upper mantle and absence of old basement as documented by

Macfarlane et al. (1990). Indeed, important OIB and EMORB signatures are displayed on the chondrite REE normalized, while the low to variable La/Nb ratios suggest asthenospheric mantle contributions and the prominent Nb-Ta anomalies in the trace elements normalized NMORB and Primitive Mantle diagrams suggest subduction slab melt involvement. Termination of this regime coincides with a plutonic regime associated with a decrease in normal trench convergence concomitant with an increase in normal absolute plate motion and slight increase in the Atlantic spreading rate that decreased rapidly to a new and relative short-lived volcanic regime discussed below motion (Seton et al., 2012, Maloney et al., 2013). The aforementioned plutonic event whose discussion is beyond the scope of this paper has been discussed in detail by a myriad of papers regarding the emplacement of the Coastal Batholite Peruvian (BCP). Suffice to say that the subduction-related BCP homogeneous strontium isotopic composition (~0.704) reported between Pisco and Chimbote has been ascribed to an undepleted mantle source (OIB-type or enriched sub-continental mantle) contaminated by subducting slab derived fluids (Soler and Rotach-Toulhoat 1990) consisting we our interpretation. However, in our opinion its definition and location of the BCP should be restricted to only the intrusives older than 60 Ma and emplaced west of the Tapacocha Fault.

LATESTMOST CRETACEOUS ARC VOLCANISM, SLAB ROLLBACK AND LENGTHY LITHOSPHERE EXTENSION

Soon after the emplacement of the Coastal Batholith termination along the WPT, a new Volcanic Regime was deposited west and close to the Tapacocha Fault known as the Quilmaná Formation. This unit consists of more than 500 meters of andesite to basaltic andesite lava flows interbedded with ash and lapilli tuff changing upward to a thick sequence of hyaloclastic andesites to basaltic andesite breccias and are calc-alkaline to high-k calc-alkaline and mostly metaluminous.

These continental to calc-alkaline volcanism emplaced during a compressive orogenic characterized by a volcanic arc array (Pearce, 2008), although some diagrams suggest within plate tholeiitic volcanic arc setting perhaps coeval with the Peruvian phase of the Andean Orogeny. The heavy REE are ten times enriched with respect to chondrite while the light REE have steeper enrichment slope that rages between OIB and EMORB. The primitive mantle spider diagram also varies between OIB and EMORB with important Nb-Ta anomalies indicating important subduction slab contributions; however, the Nb negative anomaly is higher than the Ta anomaly while the K enrichment suggest either crustal contamination or late hydrothermal fluids. The NMORB immobile diagram are depleted in HFSE and enriched in LIL varying also between OIB and EMORB showing again the pronounced Nb of subduction slab input. Indeed, the upper crustal spider diagram strongly suggest the absence of crustal contamination while the Ba and K enrichment suggest contribution from subduction slab and hydrothermal fluids respectively. The Quilmana Formation Hf isotopes from zircons studies supports subordinate crustal contamination hosting several VHMS deposits such as the Perubar (Polliand et al. 2005). This finding is exceptionally important because it is a robust documentation about the role of crustal extension inhibiting potential crustal contamination during the formation of this trough. It is highly probable that the Quilmaná magmatic regime was coeval with the youngest plutonic regime of the PCB.

CONCLUSSIONS

- The evolution of the margin experienced severe lithosphere extension and boudinage during trench rollback.
- Regionally, the margin experienced two main arc volcanism episodes interrupted by subduction flattening tailed by slab breakoff as recorded by linear alkaline volcanism.
- Locally, subduction of oceanic fractures permitted the tapping of undepleted mantle causing explosive.
- The research provides new lines of evidence to propose a novel model for the evolution of the Peruvian margin. This alternative model departs significantly from the classic and simplistic Andean Model used in the literature.

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