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Deformation and domains of the central Peruvian Andes: A spatial approach using surface data

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ABSTRACT

Mapped folds and faults are used in a GIS approach that interpolates measured spaces between these features to define the nature of deformation in central Peru. The combined results indicate variable deformation and distinct zones of concentrated strain within the major structural domains of the Cordillera Occidental and Oriental. Characterization of mapped structures by area analysis provides a different context in which to evaluate the tectonic evolution of the Andes. This method provides an alternative structural analysis to the frequently unsatisfying construction of balanced cross-sections, in which a number of serious errors typically are present.

A total of 5,089 structures were used to delineate areas of more densely spaced folds and faults, which define four distinct zones of greater intensity of strain. Folds and faults in Mesozoic units statistically are closer together than those in Cenozoic units, and structures in the Cordillera Occidental are more closely spaced than those in the Cordillera Oriental.

Zones of greater structural intensity correlate with regions of large mineral deposits and active hot springs.

RESUMEN

Los pliegues y fallas mapeados son usados en SIG (*GIS*), enfocados en una medida interpolar entre los espacios que definen la naturaleza de la deformación en el Perú central. La combinación de los resultados indica una deformación variable en las distintas zonas de la deformación concentrada en los principales dominios estructurales de la Cordillera Occidental y Oriental. La caracterización de las estructuras mapeadas bajo el análisis de un área provee un contexto diferente en la que se evalúa la evolución tectónica de los Andes. Este método proporciona un análisis estructural alternativo a la construcción de secciones transversales equilibradas, en el cual el número de errores están típicamente presentes.

Un total de 5,089 estructuras fueron utilizadas para delinear las áreas de pliegues y fallas que contienen un espaciado más denso, los cuales definen 4 zonas distintas de mayor intensidad de deformación. Pliegues y fallas en unidades mesozoicas están estadísticamente más apretados que en unidades cenozoicas. Las estructuras en la Cordillera Occidental son más apretadas que las en la Cordillera Oriental.

Las zonas con mayor intensidad de deformación se correlacionan con áreas de grandes depósitos minerales y aguas termales activas.

Palabras claves: espaciamiento de pliegues, intensidad estructural, zonas de deformación, Perú.
Keywords: fold spacing, structural intensity, deformation zones, Peru.

1. Introduction

The topic of rock deformation of the Andes has greater than 100 years of limited and discontinuous geological studies in an attempt to understand the amount of horizontal contraction, to place constraints on the timing of events, and ultimately relate this information to the processes of mountain building. Geologists are in general agreement that the major deformational features observed in Phanerozoic rocks of the Peruvian Andes were formed through a series of major contractional events during the Cenozoic (Mégard, 1978; Noble et al, 1979; Noble et al., 1985; Benavides Cáceres, 1999; Wise et al., 2008). Nonetheless, realization of a reasonably complete structural model has been hampered by several factors; these include the size of the study area, making it nearly impossible for short-term studies to comprehend the nature of the complex structure; the difficult access for field studies; the limitation imposed by the quality and amount of data present on the government geological quadrangle maps; the long periods of political instability; and the varying quality of rock exposure, ranging from excellent in the dry coastal regions to Amazon catchment high jungles which hide much of eastern part of the Andes. In this context of these challenges many early studies contributed greatly to the development of the structural framework of central Peru; in particular those of Harrison (1943), Szekely (1969), Coney (1971) and, to a greater extent, Mégard (1978).

This paper takes the next step in the characterization of deformation in central Peru based on more than 15 years personal field experience, combined with the results of more than 60 years of mapping by numerous geologists of the Servicio de Geología del Perú (now INGEMMET); published studies by a number of geologists, both Peruvian and foreign, from academia, industry and government agencies over period of more than 100 years, and intensive interpretation of satellite images and aerial photography to correct, augment, and provide more detail on the locations of folds and faults. A brief description of the upgraded structural data is first presented; additional information is given as required when discussing various features throughout the paper.

The Andes is subdivided into major structural domains to facilitate the analysis and provide a coherent framework for data interpretation. Many recent structural studies of the Andes, and particularly the sub-Andean belt, have relied on the use of balanced cross-sections (e.g., Baby et al., 1997; Sheffels, 1990; Kley, 1999; McQuarrie et al., 2008; Gotberg et al., 2010). Plane section modeling of structure typically is difficult to execute with area preservation when material transfers in and out of the section; such standard interpretation is particularly difficult in the present high Andes, where there is very little subsurface data and the thickness of some geological units change markedly over short to moderate distances. A new approach is presented in this paper to draw conclusions about the character of deformation; this methodology, however, is limited to map analysis and cannot, at least at this time, be used to estimate the percent shortening across the orogeny.

The structures of central Peru are considered from a GIS perspective, making quantative derivatives that clearly characterize the patterns present in the deformed rocks. The resultant zones of greater rock deformation identified have several important implications that are summarized at the end of this paper; these relationships maybe used to guide future research, critique the shortfalls of estimates of shortening based on balanced cross-sections, and may even be useful in inferring the most likely regions for mineral exploration.

2. Description of fold and fault data

Seventeen years ago, at the beginning of this study, there was no "off the shelf" GIS-based datasets that were suitable for studying geological features. Existing information on folds were on printed 100,000 scale geological quadrangle maps that fortunately, over time, became available as raster images that could be georeferenced and used to digitize the location of folds. The country-level compilations of Peruvian geology produced by INGEMMET included only faults at the 1:1,000,000 scale, and these were incomplete and contained many interpretative errors. Many quadrangle maps do not have a single fold mapped, and many others that did show fold hinge lines were incomplete. Other typical errors are the map boundary discontinuities where faults or folds from adjoining sheets do not continue, or are plotted in different places. As an example, the major syncline in the Sicuani 100k quadrangle map, located at –71.297, –14.312, was drafted as a fault despite the bedding symbols clearly indicating the presence of a fold (Audebaud and Pecho, 1970). The area here has remarkable parallel bedding with excellent exposure so that the existence of a tight upright fold is unmistakable. Furthermore, many faults shown on the quadrangle maps are not internally consistent with the mapped geology in that the lithologic contacts are shown without displacement. Information on fault dips, sense of slip, and other structural features such as nature of the fault zones were not given. Fold information on the published maps in many cases are not supported by measured bedding orientations, and were presented with no information on the fold interlimb angles, and in many cases, vergance direction. Some map sheets do indicate presence of recumbent folds, and rarely, overturned folds.

New traces of folds and faults were identified from field observations in the Santa Barbara, Castrovirreyna, Huachocolpa, and Julcani districts in central Peru. These were augmented by a study of the Ayacucho intermontane basin (Wise, 2004). In the field, three major transects were studied in reconnaissance at the latitude of Huancayo-Huancavelica, with one extending to Satipo, and the canyons of Churin, Rimac, Cañete, San Juan, Mala, and Pisco were explored. Upgrading the fold data obtained from maps and field observation began with interpretation of LandSat TM, and fortunately transitioned to the detailed, but variable quality, images provided by Google Earth (GE). Repeated image inspection over the years has discovered the location of many previously unmapped folds and faults, and through use of the oblique GE inclination tool (air photos draped on DEM) to observe the fold geometry and amount of fold closures or interlimb angles has developed qualitative understanding on the character of deformation for many areas. In Peru, a total of 6,636 folds and 3,370 faults were assembled (Fig. 1). Newly mapped folds during this study accounts for 1,030 of the total. For various data quality issues, and to avoid some other deviate superimposed structural complications of southern Peru, the study area presented in this paper includes 3,090 folds and 1,719 faults, or roughly half of the dataset. In addition, this study area encompasses the region of most of my first hand field experience (Fig. 2), and likewise avoids the increased vegetation in northernmost Peru and the mantling volcanic deposits of southern Peru. The study area boundary in the south intentionally excludes the Abancay deflection, and the major area of EW-oriented folds near Cusco that pertains to a superimposed major oroflexure extending northeastward through Machu Picchu (Roperch et al., 2006, 2011).

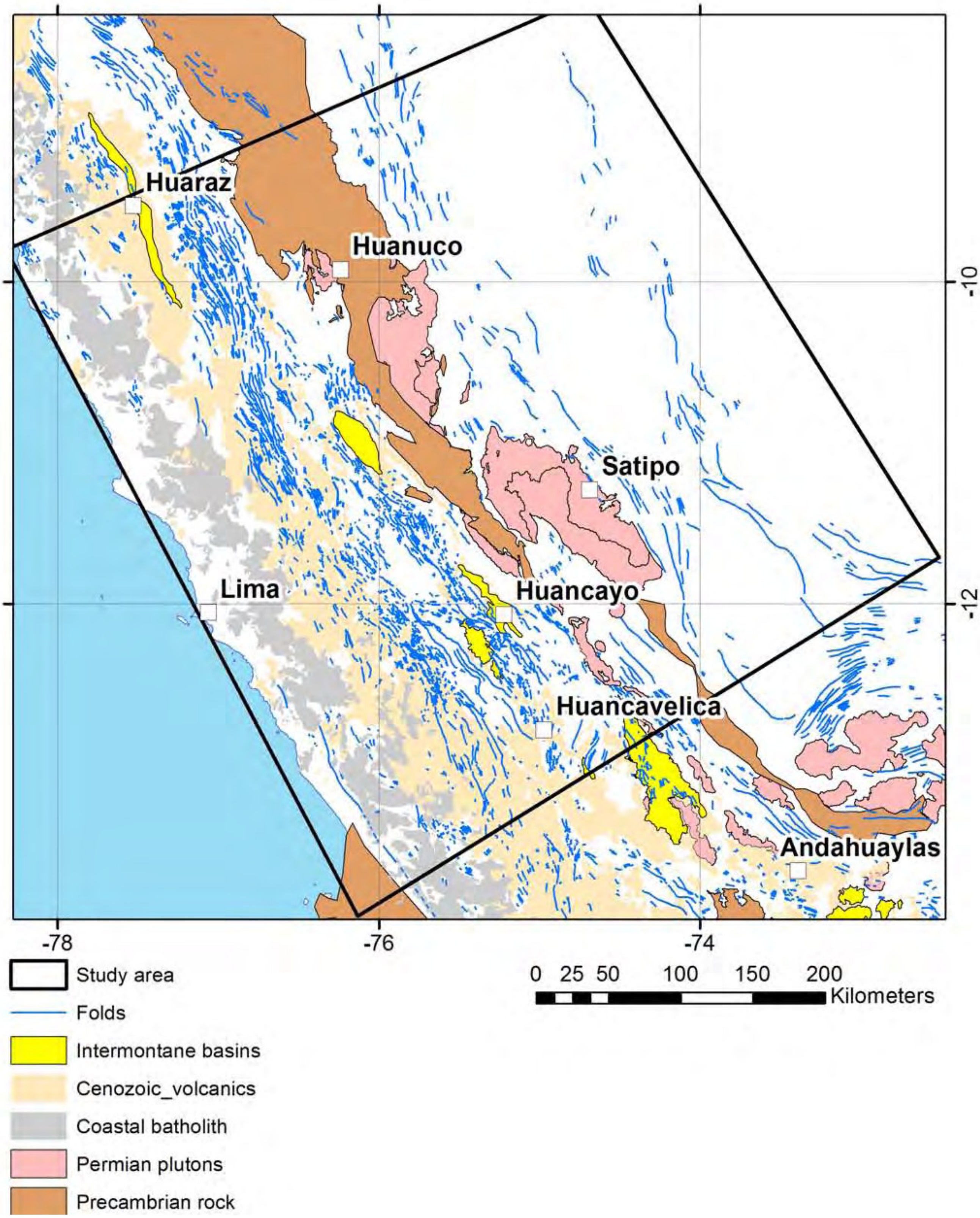

Figure 1. Map showing distributions of fold hinge lines covering 8°S to 14°S and box outline of study area for detailed fold analysis. The areas left white generally correspond to regions of pre-Cenozoic rocks. The selected colored lithologic units are shown for subdividing the study area into major structural domains. The intermontane basins mark the transition between the Cordilleras Occidental and Oriental. The Precambrian and Permian plutons define areas of crystalline bedrock that, while deformed, do not readily present mappable large scale folds from remote sensed data.

Figure 2. Photograph gallery of selected fold styles. A. View north from Churin at a slightly west-tilted upright closed anticline in the Chimú Formation- Ticlio zone. B. View south at upright chevron style folds in the Jumasha Formation limestone cropping out southwest of Laguna Lauricocha, east of Raura- Ticlio zone, C. View north of an upright tight large-scale syncline in the Chulec Formation, Santa Barbara district, Huancavelica- Huanca zone, D. View south of the major east vergent fold pair in the Pucara Group limestone, south canyon wall to Rio Mantaro, along the Huancayo-Huancavelica road- Huanca zone. Thin blue lines mark hinge surface traces, yellow lines used to emphasis bedding in the fold limbs.

The selected structural domains used in this study, while similar to the traditional terminology summarized by Mégard (1978), amongst numerous others, needs a little clarification. The region encompassing the Cordillera Occidental domain (COD) is everything west of the centerline of the zone of intermontane basins and going up to the stable Coastal Batholith block. The Cordillera Oriental of Peru includes at least two major structural domains, these are the crystalline basement core (CBD) that generally runs along the divide and is largely comprised of gneiss, lesser schist, and widely intruded by a complex Permian plutons, and to the east structurally simpler domain of Mesozoic formations in the foreland fold and thrust belt (FFTB). A series of parallel reference lines were drawn perpendicular to the orogenic fabric and used to take spacing measurements of the folds and faults; these data points were classified by the above domains, and by formation era. Results are discussed in the next sections below.

3. Fold spacing

The distances between folds were measured along the section lines in Figure 3 and mostly represent estimates of the fold wavelength. Where each reference line crosses the folds the spacing measurement was taken as close to perpendicular between the two folds hinges, meaning the distance measured is not that right on the reference line. Fold hinges are not perfectly straight features, they curve and waver, and the general trend of folds may converge. No attempt was made to take the maximum distance between the measured folds. In truth, the fold spacing character could be considered a range of distances. With higher number of fold spacing measurements these vagrancies should average out. A total of 712 fold spaces were measured within the study area. Furthermore, the measurements did not directly take into consideration faults that in some places truncate the folds, nor the position of the CBD and other intruding plutons that artificially increase the apparent fold spacing. The term "fold spacing" is a more accurate description of the features measured because of fault interruptions, although in many cases what indeed was measured were the fold wavelengths. The fault data is accounted for later in a separate analysis. About thirty percent of the fold spaces are impacted from intervening faults. The zone of increased apparent spacing caused by the CBD is easy enough to interpret in the later interpolation maps, and the control stations falling within this domain were separated out while tallying the spacing data of folds shown in Table 1. Overall, the COD has median fold wavelengths that are approximately half those in the FFTB. Within the COD, the Cenozoic fold spacing mean of 3.73 km is almost twice that of spacing of 1.78 km in the Pre-Cenozoic formations. The parameters that feed into these numbers are a combination of both the intensity and amount of shortening and the varying competency of the units being folded. Furthermore, the pre-Eocene rocks were affected by the major Incaic phase of deformation whereas the middle Eocene to recent volcanic and sedimentary rocks were deformed by several less intense events of contraction.

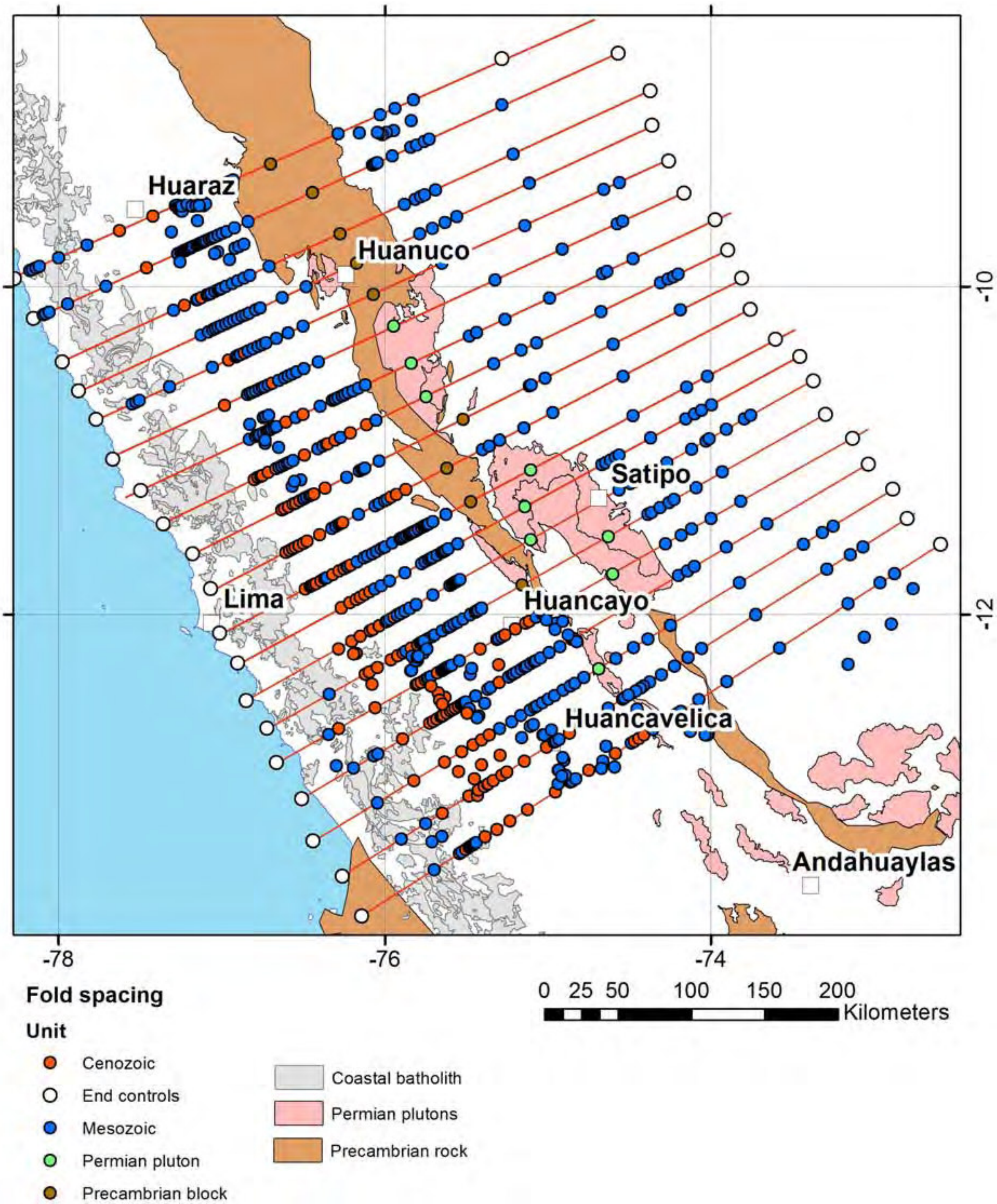

Figure 3. Map showing cross Andean fabric reference lines along which fold spacings were measured. The stations are color coded by major rock age units. The summary of fold spacing was separated according to age of units and by structural domains that were intervened by the Precambrian gneiss-Permian plutonic rock basement block. Other noteworthy structural domains comprise the Coastal batholith, or Coastal Batholith block that essentially has no Cenozoic volcanic-hosted folds, and older pre-batholith folds in the Mesozoic Western Peruvian trough strata.

Table 1. Structural estimates from measured stations

Domain	Count	Max. (km)	Mean (km)	Median (km)
Fold spacing				
Peru*				
Cordillera Occidental				
Cenozoic volcanic	149	54	6.43	3.73
Paleocene-Mesozoic	432	44.7	3.15	1.78
Cordillera Oriental				
Mesozoic	131	116	17.64	6.75
Fault spacing				
Cordillera Occidental	180	102.4	12.46	7.44
Cordillera Oriental	142	112	17.53	9
Bolivia fold spacing**				
Pre-Cenozoic	1262	57	4.82	3.7

*Peru study area measures 438 by 490 km.
**Bolivia study area was 600 by 770 km.

For comparison purposes, the fold spacing in Bolivia was measured using a similar approach. The fold data set used was the country level information by SERGEOTECMIN, which consists of 2,324 folds. This data has not been refined or even field examined in this study. A total of 1,262 measurements were taken along similarly spaced transect lines as from Peru, but covering a larger study area (Table 1). The Bolivian median fold spacing value, 3.7 km, which includes mostly folded sedimentary formations, is similar to the number from folded Peruvian Cenozoic volcanic units. A range of 3.7 to 6 km can be considered typical for Andean fold spacing.

Deformation in the Peruvian Andes is not evenly distributed. Figure 4 shows an interpolated surface generated using ESRI Spatial Analyst. The interpolated fold spacing grid was calculated through a spline function set to tension mode and used 12 nearest neighbors of measured spacing. Early interpolations using the IDW method resulted in rougher images that had less infill of the trends between adjacent transect lines. The spline method tends to smooth out the extreme highs and lows, yet generates surfaces that in this analysis better represent the regional scale patterns. Initial pass at interpolation used half the number of cross-Andean transect lines to an unsatisfactory result that included marked computer generated deviations that obviously were from data edge effects. The present transect line spacing of about 25 km produces sufficient detail with respect to the fold hinge lines despite the folds having an average length of 5 km. Only 93 folds exceeded 25 km length, which in these cases would be measured more than once on adjacent transect lines. Both outer sides of the study areas used control stations set to an arbitrary high number of 500 km to place boundaries to the model (these numbers were excluded from all summary statistics). For the western limit this edge is the modern coast; undocumented deformed rocks are certainly present beneath the ocean going up to the trench. The eastern line of control stations are beyond the main frontal fault and mark the edge of the orogeny.

Contouring the measured stations for fold wavelength yields a map that shows the distribution of more abundant folds, with the map units being in kilometers. This is not the same as a fold density map, or abundance by area analysis, which would have its units as features counted per square area. Without having the fold interlimb angles, the amount of shortening cannot be calculated. Again, the fold spacing varies and groups into distinct domains that reflect both the intensity of deformation and the competency of the rock. One could reasonably conclude that shortening is not evenly distributed.

Results indicate coherent zones of similarly spaced folds that are consistent with the median numbers for the larger structural domains. The FFTB has two parallel NNW-trending subzones of more closely spaced folds. The eastern subzone in the FFTB corresponds to leading edge deformation hangingwall to the frontal faults. The western FFTB subzone occurs as a belt between the major piggyback basin, the Pachitea and Ene basins (Espurt et al., 2008) at Satipo, and is buttressed to the west by the rigid bedrock in the CBD. The Cordillera Occidental domain shows subzones with the most intense area of closely spaced folds running the length of the topographic divide, and secondary subzone running just west of Huancayo on the range east of the Incahuasi depression.

4. Folds compared to faults

There is a general correspondence to the areas of shorter fold wavelengths to the location of faults (Fig. 5). The same cross-orogeny reference lines were used to measure the distance between faults and the results were then interpolated using the same spline calculation settings (Fig. 6), accounting for a total of 456 control points. Both the median and mean fault spacing in the Cordillera Occidental is greater than in the FFTB of the

Cordillera Oriental (Table 1). The number of measured stations is nearly half of the data used in the fold calculation, yet the mapped pattern is similar. Processing the fault spacing has a similar feature comparison issue as in the fold data, but this time the estimate includes faults of all styles, normal, strike-slip, and reverse, both high and low angle faults. Useful to consider as a next step in this analysis would also be measured displacements on the faults, a measurement that is more problematic in obtaining than the fold interlimb angles.

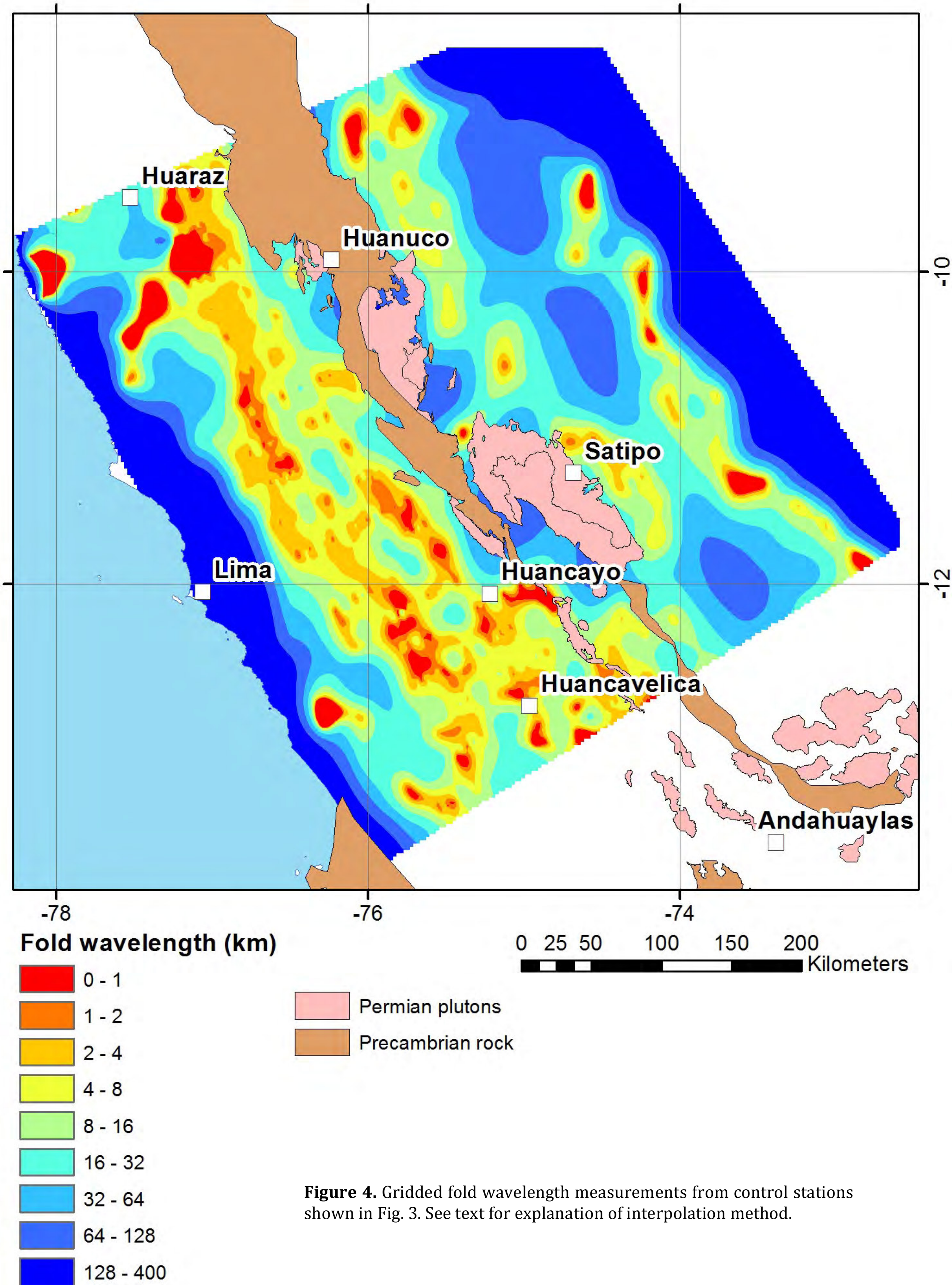

Figure 4. Gridded fold wavelength measurements from control stations shown in Fig. 3. See text for explanation of interpolation method.

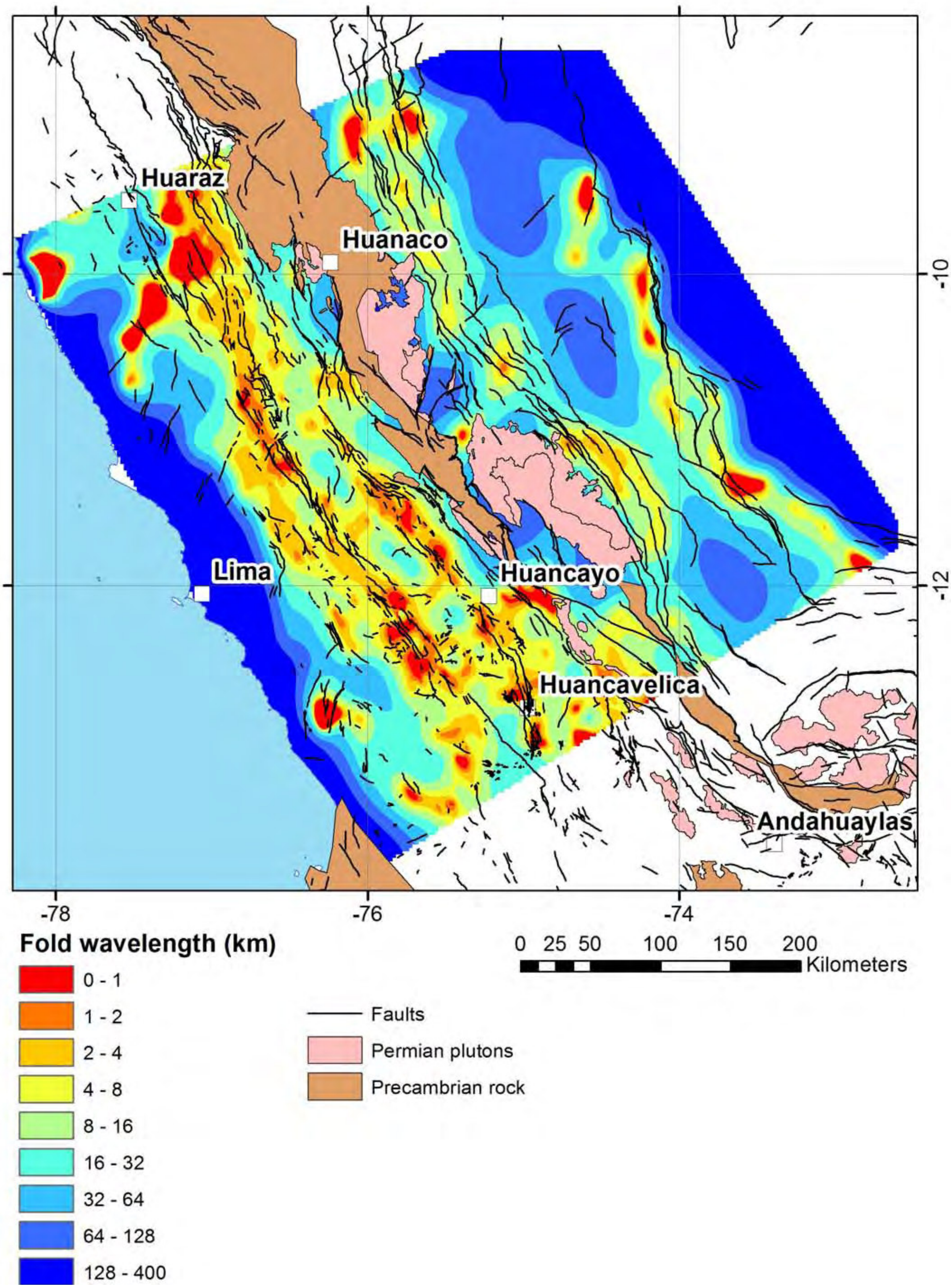

Figure 5. Map showing the same fold spacing interpolation from Fig. 4 with faults overlain to further illustrate distinct zones of concentrated deformation.

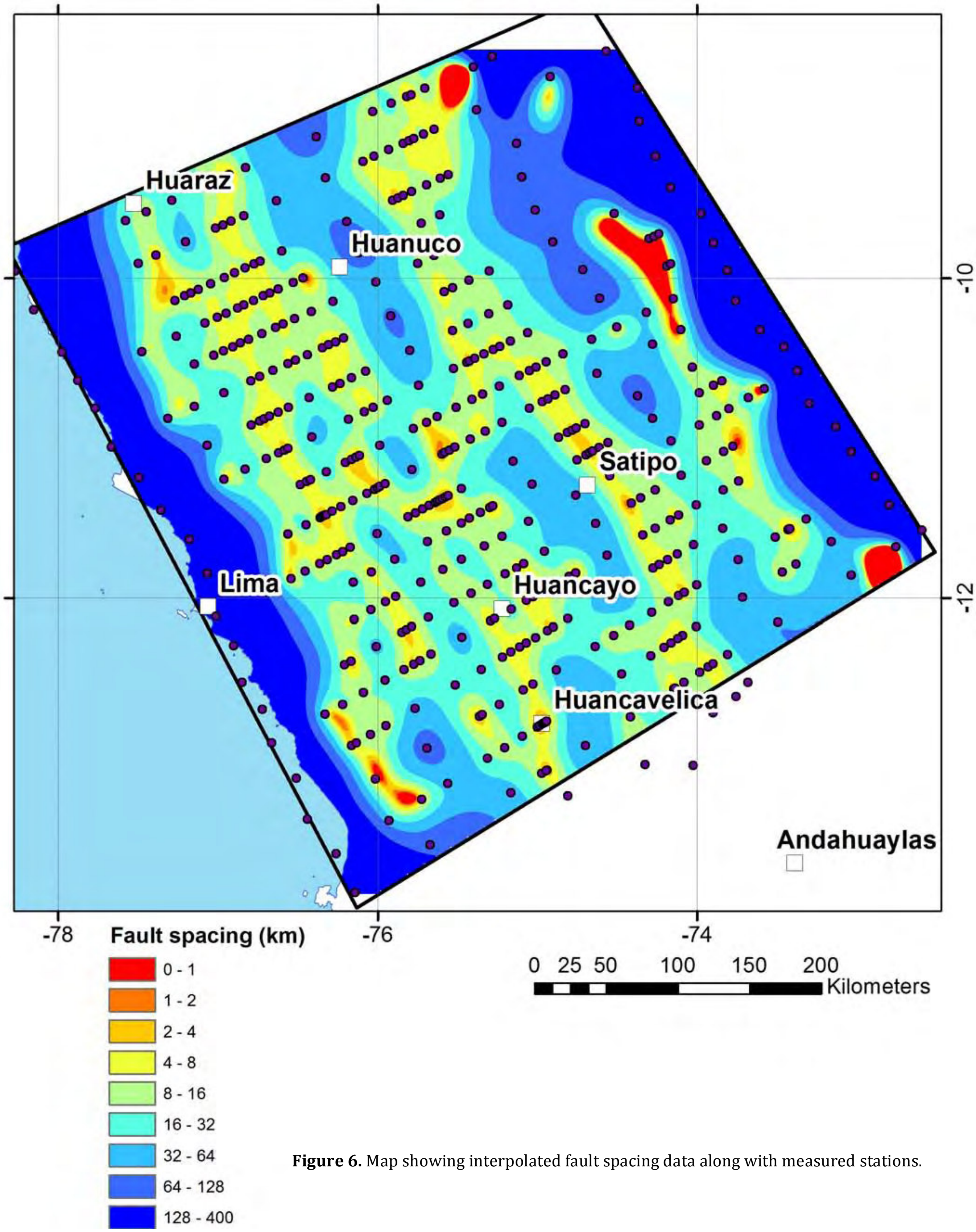

Figure 6. Map showing interpolated fault spacing data along with measured stations.

Combining the fault and fold spacing gridded data, both of which have units in kilometers, and then dividing by two, yield a new gridded structure spacing map (Fig. 7) that further enhances the areas where rock deformation is present. This layer was interpreted to outline the most significant areas of closer spaced structures.

The here termed Ticlio zone runs the length of the continental divide, making a corridor that is 20 to 47 km wide and extending at least 700 km in strike length. Most of the belt is closer to the 20-km width. The zone widens north of 10.52°S latitude where it passes to the east of the Cordillera Blanca. Key areas within the belt that exhibit tight to closed folding include a fold train located 35 km NW of Yauricocha, and the deformed sections at Churin that provide the qualitative impression of significant strain. The Chonta fault that defines part of the southern segment of the zone was described previously (Wise & Noble, 2002) as a reverse fault with a strong Miocene left-lateral strike slip reactivation. While fold interlimb angles are not yet compiled, many of the folds are tight to closed with rounded hinge zones and separated by subvertical faults, such as illustrated by Szekely (1969) for the Alis-Quillcasca imbricate zone. Given the close spaced nature of structures and the fold geometries it is suspected that the Ticlio belt marks one of the greater areas of deformation in the Peruvian Andes.

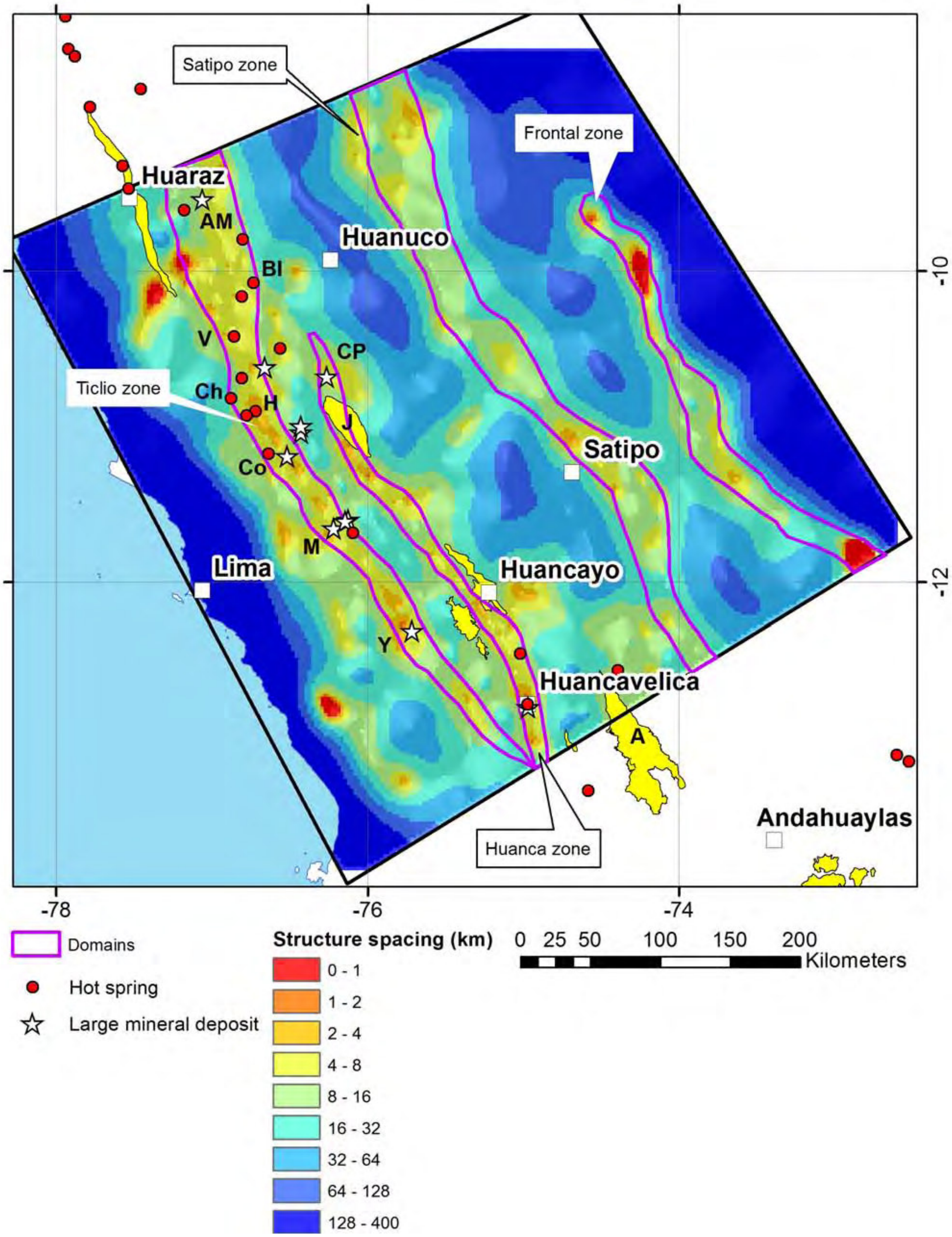

Figure 7. Structure spacing map that was calculated from the grids shown in Fig. 4 and 6. High-intensity deformation subdomains are outlined in purple. Yellow polygons are intermontane basins (A= Ayacucho, J= Junin). Mining camps: AM = Antamina, CP = Cerro de Pasco, M = Morochoca, Y = Yauricocha. Hot springs: BI = Baños del Inca, Ch = Churin, Co = Collpa, H = Huancahuasi, V = Viconga.

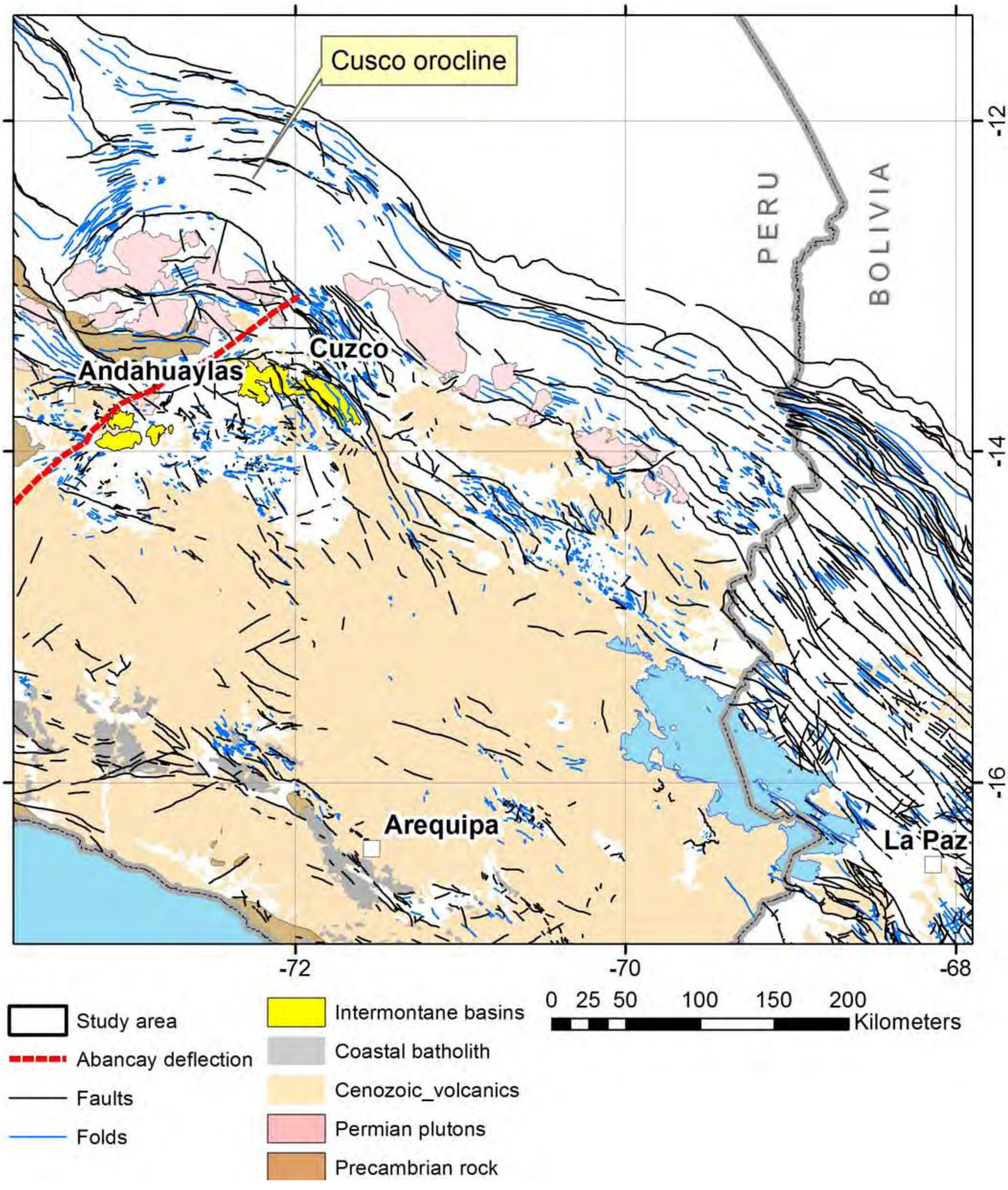

Figure 8. Fold pattern in southern Peru, showing the location of the Cusco oroflexure, the Abancay deflection, and contrasting fold and fault abundance across the border with Bolivia.

The Huanca zone of closely spaced faults and folds runs between Huancavelica and Cerro de Pasco. The southern end of this zone terminates or merges with the Ticlio zone and the Chonta fault at the Huachocolpa mining district. The Huanca zone is shorter than the Ticlio zone, having an extent of about 375 km. This zone is narrower, averaging 12 to 15 km wide. The Huanca zone is comprised of many steeply west dipping reverse faults and associated east vergent large-scale fold pairs. Where the belt approaches Huancavelica the faults are vertical, the folds are little preserved, and instead the zone consists of numerous fault-bounded vertical panels of Mesozoic units. These faults were likely mainly formed during the Incaic II phase. The faults were clearly reactivated during the Quechua phases where they are truncating early Miocene volcanic deposits. To the north, the structural corridor probably plays a part in the boundary conditions for both the Huancayo and Junin intermontane basins. In part, this zone is one of the structural elements that marks the transition between the two cordilleras. Steeply dipping faults focused Miocene mineral deposits. The entire corridor accounts for an important amount of translational deformation of unknown amount. The horizontal shortening is believed to be mainly accounted for during the Incaic II phase. The nature of combined east-directed reverse faults with segments splaying into vertical configuration of dismembered Mesozoic strata defines a structural pattern not amenable to restoration methods using balanced cross-sections.

The Satipo zone runs east of the divide of the Cordillera Oriental, here clearly marked for 600 km strike length, however, the belt likely continues into Ecuador, and may be present southeast of Cusco, but faces additional structural complications. The Satipo zone runs just east of this town, and is present at a similar distance east of Oxapampa and Tingo María. The zone averages 25 to 45 km in width, spanning the elevations of 600 to 2,600 meters. North of 10.31°S the zone directly faces the foreland basin and shares in common many structural and geomorphic features of the Frontal zone.

The Frontal zone averages 20-km wide and lies along the very base of the Andean orogeny. A cross-section just south of Satipo by Espurt et al. (2008) illustrates a west-rooted thrust duplex; using reconstructions of balanced sections, a shortening estimate of 28 % was derived for the segment extending east of the Cordillera Oriental basement rock. Folds in the Frontal zone are significantly more open and widely spaced than those found in the Cordillera Occidental.

5. Comments on the structure of southern Peru

The geology south of the study area goes through some major changes from that of central Peru. At about the latitude of Cusco, the NW-Andean orogenic fabric becomes rotated E-W. Units are disrupted across the Abancay deflection, which also marks the southern exposure of Precambrian rocks in the Cordillera Oriental (Fig. 8). The orogenic belt significantly widens and is accompanied by the development of the Altiplano geomorphic domain. The structural domains defined in central Peru either become rotated and modified in the east, and to the west are buried by younger volcanic rocks. The amount of folding documented in the Cordillera Occidental decreases. The widening of the orogenic belt and variations of the units into oroclines, such as north of Cusco, generally follows the development of the Arica bend. The Cusco orocline appears to have the regional pattern that suggests tectonic escape developed about an impactogen, which generally implies a component of left-lateral shearing along the break north of the Cusco intermontane basin.

The Cusco intermontane basin follows an interesting complex structural corridor that continues southward to Lake Titicaca. While some authors call for this region to have ongoing contraction during the Oligocene basin sedimentation (Carlotto et al., 2013; Horton et al., 2014), units within the sequence of the San Jerónimo Group are remarkably parallel overall, and fine-grained. The corridor does contain strong folding developed after 29 Ma and before deposition of the late Miocene Paruro Formation, that likely correlates to the Quechua 1 phase of folding.

The amount of documented folds drastically changes across the Peru-Bolivia border. The number of folds in Peru has clearly been underestimated, as I have shown with nearly 20 percent addition to the database. On the other hand, one may ask if the number of folds and faults in Bolivia been over-interpreted and reported? Granted the more arid conditions moving southward across the border will invariably lead to more easily mapped structures. Does drawing balanced cross-sections in Bolivia better satisfy the conservation of area in the sections? More importantly, with the total shortening estimates, do similar zones of greater intensity of structures in the Cordillera Occidental continue southward through Bolivia and are buried beneath the Central Volcanic Zone? If true, how good are the shortening estimates? One must ask if the selection of the balanced cross-section method from the very beginning of a structural study determines the type of results? For example, fold geometries in this method are typical angular with straight fold limbs, whereas sketched real folds in the Cordillera Occidental are more typical rounded with variable limb thickness and more complex fault truncations and hinge zone collapses (Szekely, 1969; Coney, 1971; Vicente, 1989). If off-the-shelf fold data in Peru contains at least 20 percent less number of structures should that not equate to estimates of shortening being 20 percent, well, short?

6. Discussion and conclusions

Features described here are missing the attendant measurements that are needed to make strain calculations. The spacing method presented is straightforward, and later can be built upon with information on fold interlimb angles to calculate the amount of shortening. The average spacing of folds in Mesozoic rock is significantly less than those hosted in Cenozoic volcanic rocks. It is not surprising that the older units have seen more folding events, whereas much of the younger volcanic section missed the major contraction caused by the Incaic events. It is also worth noting that areas with folded Cenozoic volcanic rocks, showing one characteristic spacing, are certainly underlain by Mesozoic formations with tighter fold spacing. The field observations from the Cordillera Occidental subdomains of deformation mark tight to isoclinal folds in the Ticlio zone accompanied by steep to vertical dipping faults, suggesting this is a major area of shortening that does not contain geometric features used by the balanced cross-section approach. From several quick traverses through the Subandean fold and thrust belt of central Peru, it appeared that overall bedding was gentle to moderately dipping, implying folds there are more open for their interlimb angles than in the Cordillera Occidental.

Calculating shortening across many segments of the

Andes remains only borderline science. Any structural methods working out the geology of a region should be reproducible. Structures studies in country have not broadly applied description of fold geometries using Ramsay dip isogon classes or Hudleston's (1973) shape and amplitude classification. Most descriptions of fold shapes come from photographs and sketches without much analysis. The balanced cross-sections have so many arbitrary assumptions about fault dips, cut-off angles, and geometry of fold shapes, nearly always leave out vertical fault zones and areas of crystalline rock, and oversimplify composite stages of contraction that was interspersed with periods of extension. A method that uses preservation of area in section cannot be applied in situations where material is transferred in and out of the section plane. The Ticlio and Huanca zones clearly have strike-slip movement and fragments of folds contained in fault slices. Because the timing of fault exhumation of the Cordillera Oriental basement rock to surface remains unknown, how can one possibly sequence a balanced cross-section across this complex structural domain?

The map data presented Gotberg et al. (2010) for their northernmost balanced cross-section located near Cusco, and those in Bolivia, provide no information on the number of folds present, or that there is a major discrepancy on the number of folds across the Peru-Bolivia border. Similarly, illustrated geology in Pfiffner & González (2013) barely shows a fold axis, or faults, in their "structure" maps in their figures 6 and 7. This brings us to the crux of the situation with geological reporting in journals showing structure information as cartoons. Cartoon maps lead to cartoon cross-sections, none of which are science. The omission of the bulk of the data, showing the remaining features with inadequate descriptions of coordinates or map projections, and then attempting to make everything a layer cake does little to improve our structural understanding of the Andes. In contrast, the detailed map in foldout 1 of McQuarrie et al. (2008), showing a transect east of Lake Titicaca across the northern arc of the Bolivia orocline, provides a positive example of how the cross-section methodology should be presented. Their result of 40 % shortening perhaps represents a reproducible calculation; it is at least comparable to the ranges reported in other studies. Their section line faces the "Bolivian problem" of the estimate only covering half of the Andes; the western half lacks the geological exposures of deformed rocks to measure.

Further concerns regarding balanced cross-sections is the fact that the method leads researchers into making flat faults, many times beneath areas where only steeply dipping structures are present. This expectation of what a thrust complex should look like — I suspect — becomes favored many times over how the rocks really express their architecture. For this reason, and others, the regional cross-sections shown by the studies of Mégard (1978, 1987) appear geologically more probable. The amount of shortening estimated across the Andes is always a cumulate number. The data simply is not there to break apart the various contractional events. And within each phase of contraction the shortening must have been spatially variable, just like the mapped structures today have distinct zones. This observation requires that shortening was variable. Is an across-orogeny average cumulate number on shortening meaningful in terms of describing crustal thickening and structural evolution of the belt?

An estimate on shortening done at the latitude of Huaraz would first be including most deformation happening during the Incaic phase, with folding and faulting concentrated to the east of the Coastal batholith block. Any crustal thickening at this time likely was accompanied by erosion and isotasy. How thick did the crust remain after this equalization? Then additional major folding during the Quechua 1 event happened, clearly deforming the Early Miocene volcanic section of the Cordillera Negra, likely reactivating the Incaic fold and thrust belt, but how far east would such deformation extend? There are neither units nor dated horizons covering the Cordillera Oriental to provide any constraints. Had the Precambiran crystalline rocks been eroded to surface at this time? The cumulate balance cross-section of this hypothetical transect would emphasis the more widely spaced structures in the Satipo and Frontal zones, likely showing flat faults that would root westward and ignore the flowering steep curved reverse faults interpreted by Mégard (1978). The Ticlio zone, now a composite structural belt with several reactivations, having folds limbs and units all rotated into steep positions, that locally were dismembered and translated laterally, could not be reasonably restored. Finally, this transect would have to account for a domain of extension across the Cordillera Blanca. Early tensional events between the main phases of contraction would not be considered in a cumulate balanced cross-section. And then a percent number would be reported, such as 40 %, or 28 %, but what really would that say about the structure?

The GIS approach taken in this study, while having issues fully disclosed in the presentation of the data, is at least working with data. Geological mapping is the foundation of geology in many respects. In contrast, the figure format in journals force cartoon representations of the geology. The zones of deformation interpolated in this study gave similar results between the folds and faults datasets. Both features occur together and combining them into a single thematic layer of structures emphases the areas with greater abundance of structures. This in part may represent the data quality, particularly with the Cordillera Oriental being incompletely mapped. At least in the Cordillera Occidental, where exposure quality is similar across the range, the structural data does show variation in the number of features or occurrence density. This result is certainly expected given the tendency of strain to accumulate into narrow zones with increasing deformation through time. The evolution of Peruvian structures into focused zones still requires explanation. The Ticlio zone in part may be influenced by the rigid Coastal Batholith block to west (Wise et al., 2014), and a similar process may explain the Satipo deformation zone forming along the boundary area of the belt of Permian plutons and older basement rock (CBD). It is likely that the Ticlio, Huanca, and Satipo zones all developed during the Incaic deformation events whereas the more widely spaced and less geomorphically developed Frontal zone likely formed during the Neogene. The very fact that the structures were concentrated may be characteristic for areas undergoing thick-skinned deformation whereas the rather evenly distributed folding and thrusting of Bolivia results from thin-skin deformation. Acknowledging that the number of folds and faults have never been completely mapped in previous studies combined with the twenty percent addition contributed here, and an estimate of still another twenty percent additional structures remaining to be documented, plus the varying intensity of deformation and important role of strained rock between high-angle faults, qualitatively imply that all previous shortening calculations in Peru underestimated it by fifty percent.

To conclude in a more concrete note, discussing the data worked in this study, Figure 7 marks the location of major mines and hot springs. Understanding the structure of Peru has real world economic implications for the distribution of metal resources. The large mining camps at Antamina, Morococha, and Yauricocha lie in the Ticlio zone, amongst many other late Miocene polymetallic mining camps (Ward, 1959; Love et al., 2004). The Huanca zone includes several major mineral districts: 1) the middle Miocene Cerro de Pasco camp (e.g., Baumgartner et al., 2009), 2) the world's third largest mercury deposit at Santa Barbara, which is of late Miocene age (Noble & Vidal, 1990; Wise & Féraud, 2005), and farther south the medium-scale late Miocene polymetallic mining camp of Huachocolpa (Wise, 2010). Both of these structural corridors apparently provided zones of weakness that focused Cenozoic stocks and hydrothermal cells. No cross or transverse Andean structure or lineaments are required to explain the location of the mining camps. Instead, the distribution of deposits within the structural corridors have natural along-arc spacing similar to that which controls the distribution of modern volcanoes in the Andes. The continuation of these domains north and south out of the study area is likely to account for the spatial control on other mining camps. In addition to controlling the location of major metal deposits, the structural zones defined here are clearly seen in Figure 7 as being important channels for active hot springs, such as at Churín and Huancahuasi, which have temperatures that range from 38 to 61°C. The Cordillera Oriental structural zones are not mineralized, the domains are less structurally complex than those in the Cordillera Occidental, and were backarc to the area of magmatism, further explaining their barren aspect for metal deposits. The Frontal zone, however, should have important controls on petroleum reserves.

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