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Kinematic Reconstruction of the Subandino Thrust-Fold Belt (Bolivia)

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Abstract—Two- and three-dimensional models of geological structures of the Subandino thrust-fold belt (Bolivia) have been constructed using structural-kinematic modeling and the balanced cross-section method. Main stages of deformation have been identified. These stages were compared with the geological history of Andean orogeny.

Keywords: balanced cross-sections, kinematic reconstruction, South America, Andes

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INTRODUCTION

The purpose of this research is to reconstruct pre-deformation relationships between the beds and the history of THE formation of structures in the southern part of the Subandino fold belt (Bolivia).

Information about the structure of the thrust-fold structures of the Subandino belt was obtained by combining seismic exploration, drilling, and field geological observation data. Seismic profiles make it possible to record gently sloping western limbs of anticlines and adjacent areas of piggy-back basins, and well data can be used to reconstruct the structure of the apical parts of anticlines. However, the geological structure cannot be described unambiguously, since the wave pattern often becomes chaotic in seismic sections, the dynamic pattern of reflecting horizons becomes less distinct, the correlation of reflections becomes complicated, and well data are point-like in this case. Therefore, the most effective methods for reconstructing the geological structure are to construct geological sections based on geological maps, taking into account drilling, seismic exploration, and gravity survey data and check the sections using the balancing and kinematic reconstruction method.

The balanced cross-sections and volumetric models were constructed using the Move software package. The process of building the reconstructed cross-sections (volumes) included the removal of consequences of fault displacements, unfolding, and replenishment of the volume and length of compacted or eroded layers.

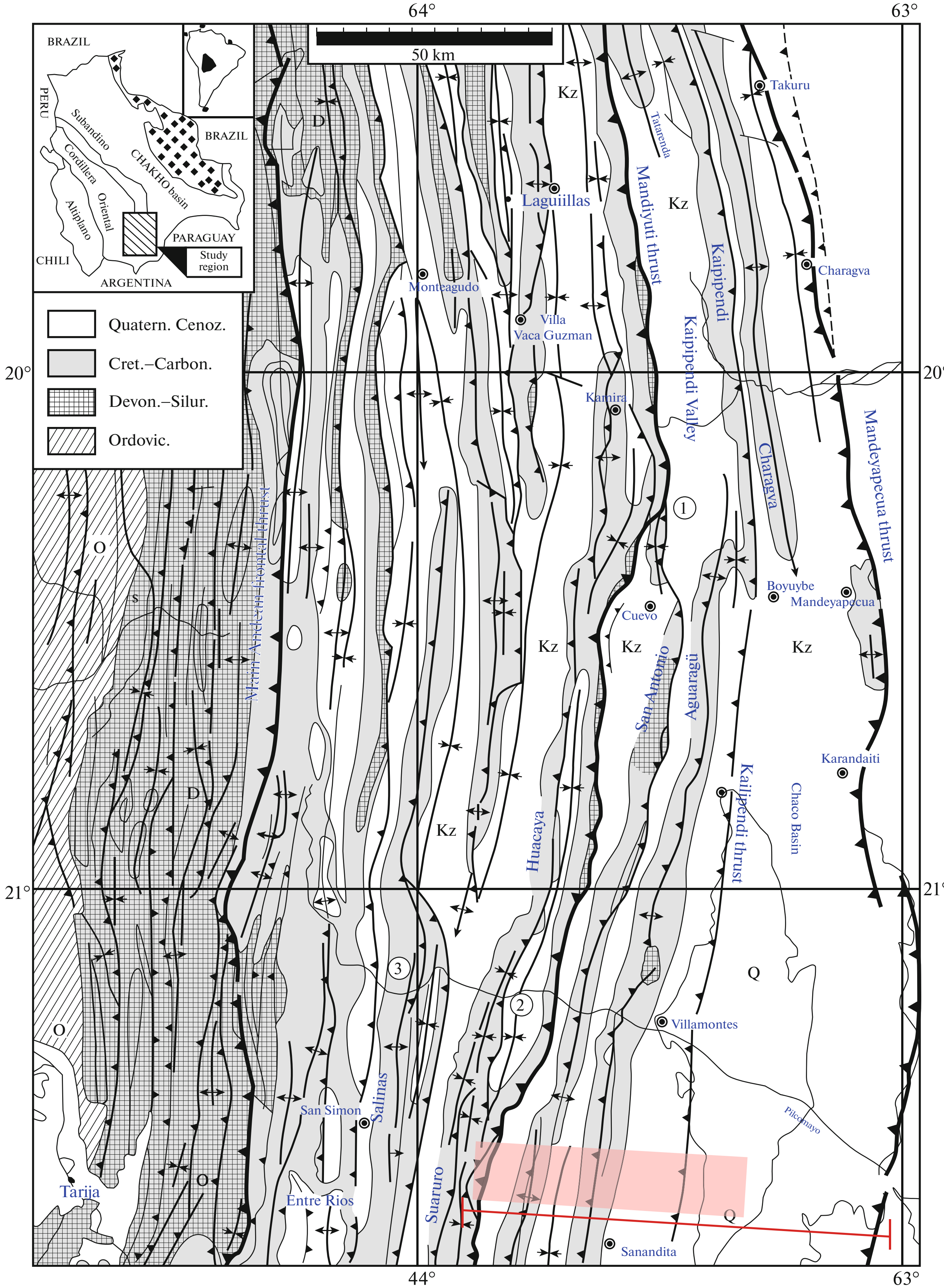
MATERIALS AND METHODS

Geology of the Subandean Zone

The southern part of the Subandean thrust-fold belt (Fig. 1) forms the outer (eastern) part of the Andes and is located at a latitude of 18 to 13° S; it has a length of about 500 km (Fuentes et al., 2018). The Subandino zone is an active fold-and-thrust belt developing according to the mechanism of “thick-skinned tectonics”; i.e., the deformation involves the rocks of the crystalline basement in the western parts of the belt. The main level of detachment has been recorded in the Ordovician and Silurian deposits (Brooks et al., 2011; Weiss et al., 2015).

In the southern part of the Subandino belt, the stratigraphic section of deposits from the Precambrian to the Cenozoic is represented most completely. Four sedimentary cycles have been reliably established: Taksarian (it combines Cm–O_1 deposits), Cordilleran (O_3–D), Subandean (C–T), and Andean (MZ–KZ) cycles. The deposits of the latter three cycles are exposed to the surface and opened by wells (Dunn et al., 1995; Starck, 1995; Fuentes et al., 2018).

Fig. 1. Tectonic scheme of the southern part of the Subandino Sur zone (Dunn et al., 1995). The red line is the regional geological section used for the kinematic reconstruction (Fig. 9) and the red rectangle indicates the area of three-dimensional reconstruction (Fig. 10).


64°
63°
50 km
BRAZIL
PERU
Subandino
Cordillera
Oriental
Altiplano
CHAKHO basin
BRAZIL
PARAGUAY
Study region
CHILI
ARGENTINA
Quatern. Cenoz.
Cret.–Carbon.
Devon.–Silur.
Ordovic.
Takuru
Tatarenda
Kz
Mandiyuti thrust
Kaipipendi
Laguiillas
Charagva
Monteagudo
Villa
Vaca Guzman
Kaipipendi Valley
20°
Kamira
Charagva
Mandeyapecua thrust
Main Andean frontal thrust
1
O
S
Boyuybe
Mandeyapecua
Cuevo
San Antonio
Aguaragüi
Karandaiti
D
Kailipendi thrust
Chaco Basin
Huacaya
21°
3
2
Q
Villamontes
O
Pilcomayo
San Simon
Salinas
Tarija
O
Entre Rios
Suaruro
Sanandita
44°
63°

The formation of thrusts and folds in the Subandino Sur zone began in the west and gradually moved east and covered increasingly new areas. The folds are mostly concentric and rounded; they are characterized by a significant amount of interlayer sliding. In plan view, the folds are linear and very extended, from dozens to hundreds of kilometers. This geometry is explained by the absence of significant regional changes in stratigraphy (Dunn et al., 1995).

Three main tectonic provinces separated by major regional faults are identified in the Subandino region: the main Andean frontal thrust separates the Andes from the Subandino zone; the Mandiyuti thrust divides the Subandino belt into the western and eastern provinces; and the Mandeyapecua thrust separates the Subandino fold-thrust zone from the Chaco foreland basin (Dunn et al., 1995).

The western and eastern provinces of the Subandino Zone differ from each other in the structural style of deformation. Step-type faults predominate to the west of the Mandiyuyti fault, while thrusts are more planar to the east. In the western province, the allochthon contains Ordovician deposits, while they are absent in the eastern province. In the western part, a local detachment level may be formed within the Ipaguazu Formation (T–J) in areas where the section contains gypsum rocks.

The section of the sedimentary cover can be divided into three structural levels (Fig. 2).

The lower structural level includes the Silurian deposits (Ordovician deposits in the western province) and Devonian deposits of the Santa Rosa, Icla, and Huamampampa formations. The lower structural level is bounded by the footwall and roof (within the Los Monos (D) Formation) detachments and has a constant thickness of about 2500 m (Starck, 1995; Fernandez Seveso et al., 2000).

The middle structural level includes the middle part of the Los Monos Formation, with a thickness of 600 to 1000 m. The deformations within the middle structural level determine the spatial structure of the upper structural level, in particular, the features of the bedding of layers observed on the daylight surface in the Subandino zone.

The beds of the upper structural layer form concentric anticlines with rather steeply dipping limbs; the angle of their inclination depends on the vertical increase in the thickness of the rocks, i.e., on the degree of compression of the middle structural layer. Anticlines can be asymmetrical; the western limbs usually have inclination angles from 30° to the subvertical one; the eastern limbs dip more steeply, up to overturned bedding (Starck et al., 2002).

Methodology for Constructing Balanced Cross-Sections

A balanced cross-section is a cross-section that consistently explains the observed structural situation on a surface, in wells, and on seismic profiles and allows for a geometrically correct version of the reconstruction of the primary horizontal bedding of layers (Dahlstrom, 1969; Woodwart et al., 1985; Gaiduk and Prokopiev, 1999; *Geologicheskii*..., 2010).

The main limitations of the method are as follows:

— the volume of rocks is preserved after deformation;

— the volume of rocks changes only during sediment compaction and erosion;

— brittle deformations are dominant and folds are genetically related to faults; and

— the loss of rock volume due to dissolution under pressure and tectonic compression is considered minimal.

The process of constructing a balanced cross-section, shown in Fig. 3, includes the following sequence of actions (Woodward et al., 1985):

(1) Data collection.

(2) Selecting a profile line.

(3) Imposing a topographic surface and plotting geological data.

(4) Projecting information from the adjacent area.

(5) Reconstructing the paleostratigraphic section.

(6) Estimating the depth to the autochthon.

(7) Estimating the depth of the rear edges of the scales.

(8) Selecting a vertical reference line or a pin-line.

(9) Depth projection of the surface structure.

(10) Filling the "holes."

(11) Measuring the length of the beds.

(12) Construction of a reconstructed (palinspastic) section.

(13) Checking the reconstructed section.

Algorithms used to perform two-dimensional and three-dimensional palinspastic reconstructions can be divided into two groups:

(1) Unfolding (the relationship between the geometry of faults and the configuration of beds is not taken into account; this algorithm is used for residual deformations).

(2) Move on fault (the influence of fault geometry on the structure of the hanging wall was taken into account; this algorithm is used in the reconstruction of deformations associated with movement along the surface of the fault plane.

The reconstructions performed in this study were built using the Move software package based on the following algorithms.

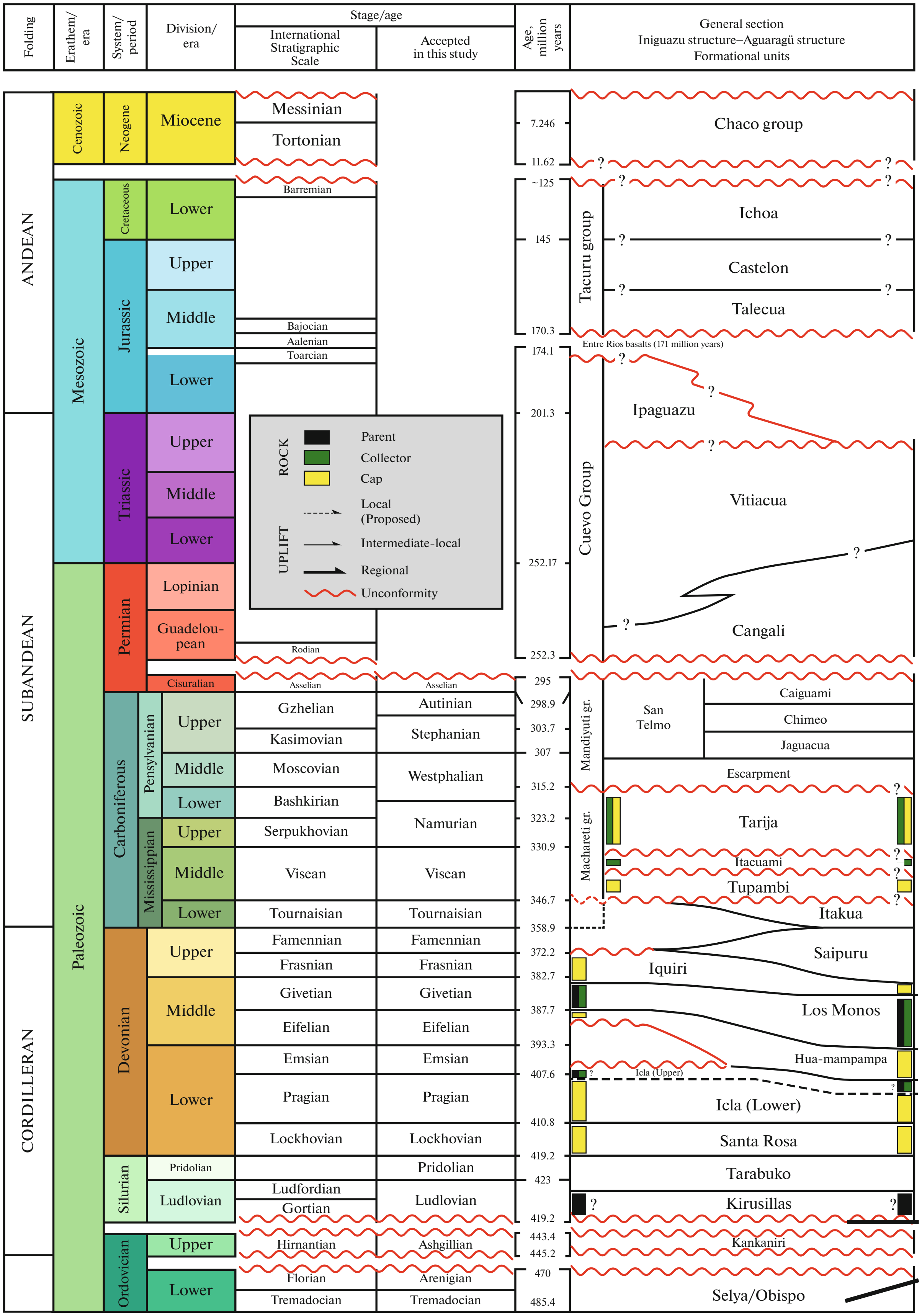


Fig. 2. General stratigraphic scale for the Subandino Sur region.

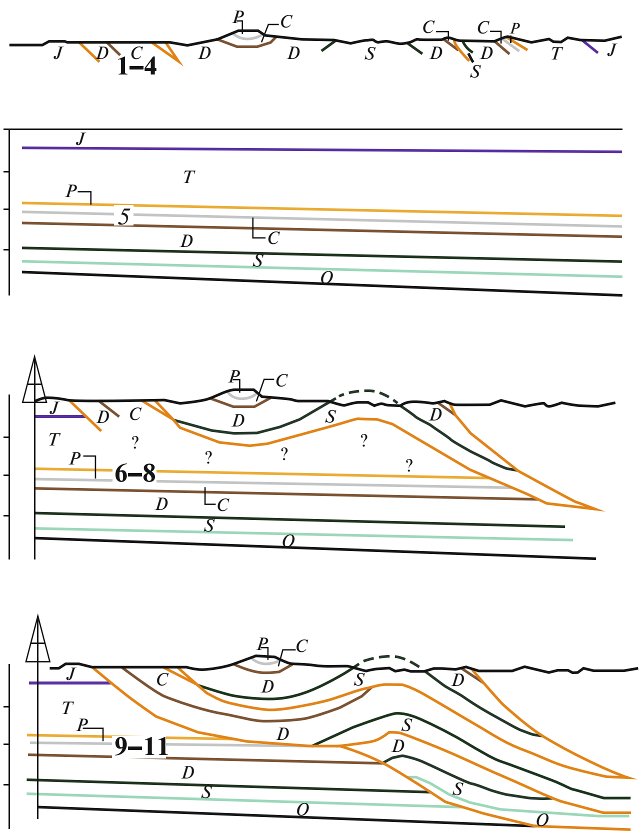


Fig. 3. Sequence of the reconstruction of the structural model, steps 1–11. According to (Woodward et al., 1985) with changes.

“Flexural slip” algorithm. This algorithm (Fig. 4a) is based on the selection of an area with a minimum displacement, followed by the unfolding of all beds relative to the selected template layer (its role is usually played by the layer with the maximum length). When using the flexural slip algorithm, the length (surface area) of the template layer in the unfolding direction is preserved, the capacities (volumes) of all beds along the normal line are preserved, and the lengths of the beds (surface areas) in which the geometry corresponds to the template layer are preserved.

Fault Parallel Flow Algorithm. The fault parallel flow algorithm (Fig. 4b) is based on the principle of dispersed laminar movement of matter over the fault ramp. In this algorithm, the fault plane is divided into separate domains in accordance with the inclination angle of the fault plane. The rocks of the hanging wall moved along the calculated lines parallel to the fault plane. It is the fault parallel flow algorithm that is optimal for performing palinspastic reconstructions of the Subandino Sur zone, since it best describes the movement of the hanging wall along the fault in fold-and-thrust belts and can be used for faults with complex geometry.

The fault parallel flow algorithm is based on the following basic principles. The lying wall is not subject to deformation and displacement processes; the length of the bed (the surface area of the bed) is preserved in the direction of tectonic transport; the length of the bed and the surface area of the bed are preserved when the choice of the displacement angle is correct. The implementation of reconstructions is verified by solving the inverse problem: constructing a direct compression model along the reconstructed profile using the fault bend fold algorithm.

Trishear algorithm. The trishear algorithm was used to reconstruct the structures formed in the triangular zone of plastic deformations (Fig. 4c), which begins at the end of the fault.

The trishear algorithm deforms beds in one (or several) triangular zones of plastic deformation. The thrust value in these zones varies from a certain specified value in the upper part of the zone to zero in lower part of the zone; the direction of the thrust changes from the direction parallel to the fault dip in the upper part of the zone to the direction parallel to the base of the zone in the lower part of the zone. Outside the trishear zone, the beds in the hanging wall are deformed according to the fault parallel flow algorithm.

MODELING RESULTS AND DISCUSSION

Construction of a Kinematic Model of the Aguaragüe Structure

Figure 5 shows a seismic section through the Aguaragüe structure, located in the frontal part of the Subandino fold-and-thrust belt, with a superimposed structural interpretation applied. This profile served as a basis for constructing the kinematic model of the formation of the Subandino thrust-fold belt structures, developed by the authors. The following geological features should be noted:

— the presence of regional detachment at the base of Silurian deposits;

— a significant increase in the thickness of the Los Monos Formation in the cores of the anticlines;

— asymmetrical dipping of anticline limbs;

— displacement of anticline locks to the west with increasing depth; and

— increase in the degree of compression to the west.

Modeling the beds of the lower and upper structural layers assumes the concentric pattern of deformations, and the main problem here is the correct description of the deformation mechanism within the Los Monos Formation. According to drilling data, an increase in the formation thickness of up to 3000 m is observed in the anticline cores. The deposits of the formation are represented mainly by dense clays and argillites. The use of a simple geometric model (exam-

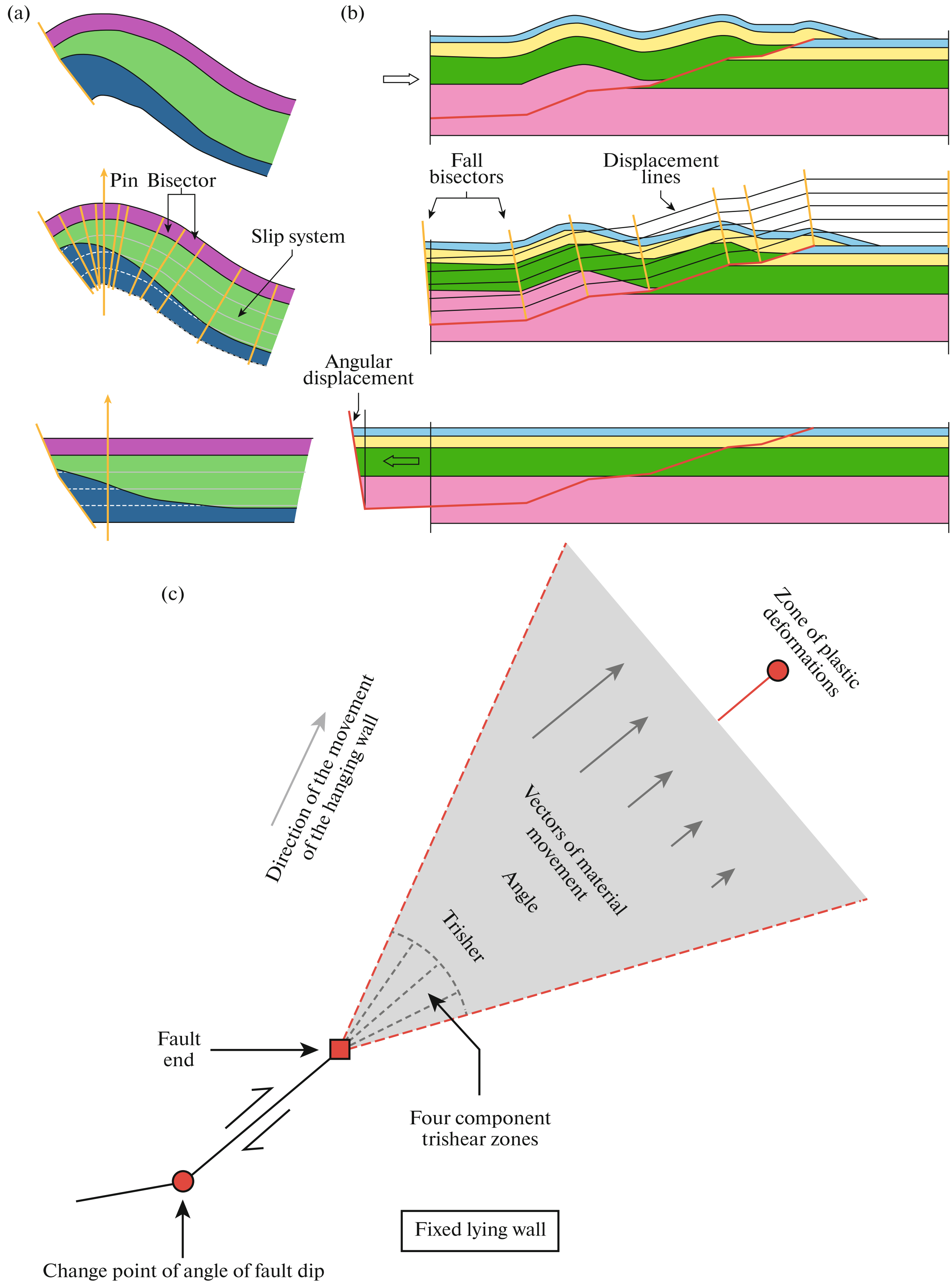


Fig. 4. Algorithms used in the kinematic reconstruction: (a) flexural slip, (b) fault parallel flow, (c) trishear (http://www.mve.com/).

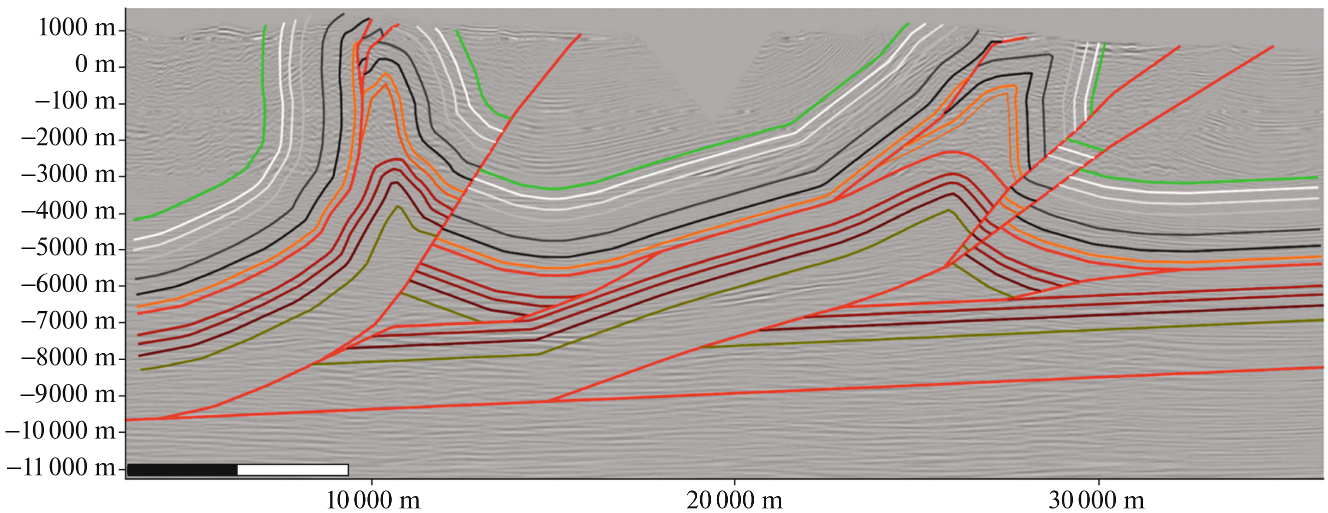


Fig. 5. Fragment of the seismic profile through the Aguaragüe structure.

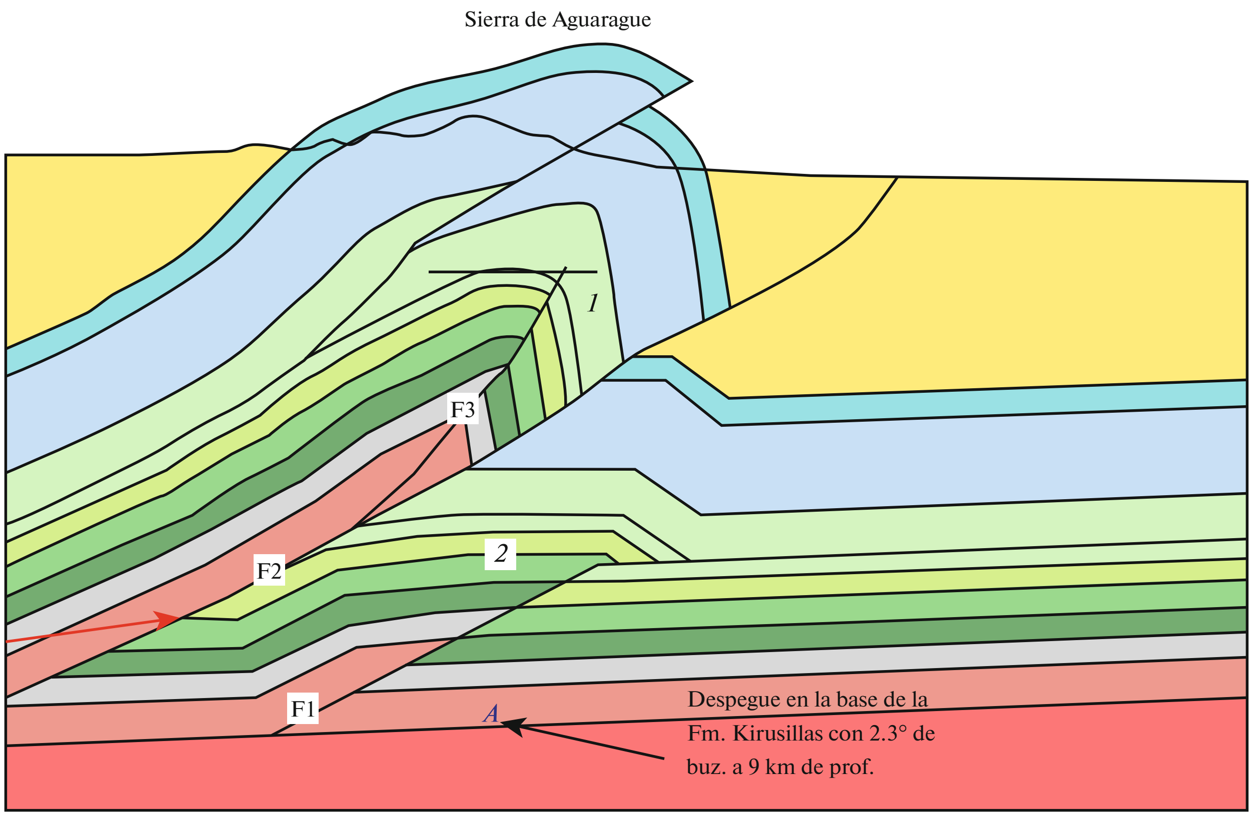


Fig. 6. Structural model of the Aguaragüe fold (Ramirez and Nunez, 2009).

ple in Fig. 6) cannot fully reliably describe the structural plan of the anticline.

The pattern of deformations within the Los Monos Formation was describe using the model of “antiform clustering duplexes,” which made it possible to explain the increase in the thicknesses of the Los Monos Formation in the cores of the anticlines and the asymmetry of the dip angles of the fold limbs.

Below are the results of constructing the kinematic model of the formation of frontal folds of the Subandino belt (e.g., San Antonio, Aguaragüe, and Madrejones). The model of the formation of near-fault anticlines in the frontal parts of thrust belts assumes the

Fig. 7. Kinematic model of the evolution of the structural plan of the anticline. Deformation stages: (a) earlier than 4 million years ago, (b) 4 million years ago, (c)–(f) 3.5–1.5 million years ago, (g)–(h) 1.5–0 million years ago, (i) current state.

relationship between the structure of beds at depth and on surface. As a result of modeling, the following stages of the evolution of the structural plan were identified.

Pre-deformation state: earlier than 4 million years ago (Fig. 7a). Sedimentary layers have gently inclined bedding; displacement along faults and thrust-fold deformations are absent. Red lines show the supposed surfaces of faults, along which further displacement will occur.

First stage: 4 million years ago (Fig. 7b). Within the Silurian deposits, deformations in the form of the

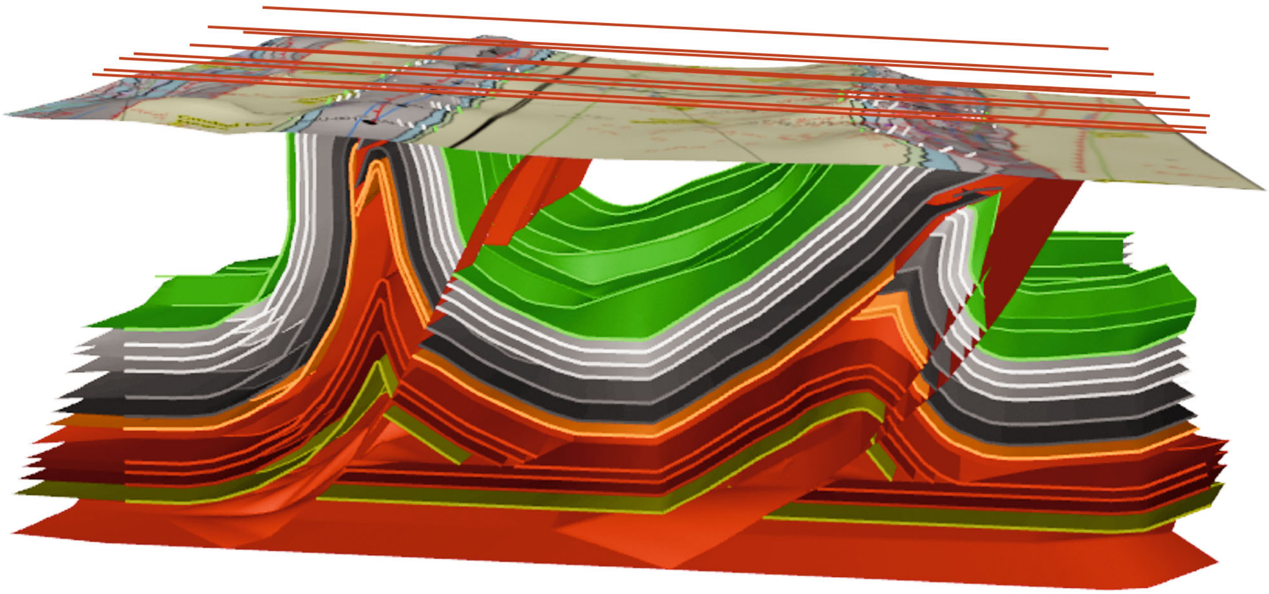


Fig. 8. External view of the three-dimensional structural model of the San Antonio and Aguaragüe folds.

gradual formation of a reverse fold, genetically associated with the formation of ramp "1," begin to be observed. As the fault propagates upward along the section, deformations cover the overlying deposits.

The second stage is dated to 3.5–1.5 million years ago (Figs. 7c–7f). With development of deformations, ramp "1" reaches the deposits of the Los Monos Formation and changes into flat "1a." At this point, the surface of passive thrusts "2" and "3" is formed inside the Los Monos Formation. As the rocks of the lower structural layer are thrust, duplexes "4" and "5" of antiform clustering are formed within the Los Monos Formation, which leads to a significant local increase in the thickness of the formation, observed in some wells. It should be noted that the conceptual model is characterized by a certain degree of simplification and generalization, while the number of individual duplexes will be higher in the real structural environment and the relationships between faults and mechanisms of compensation of horizontal displacement will be somewhat more complex.

The third stage is dated to 1.5–0 million years ago (Figs. 7g–7h). The effect of ongoing compression processes involves steeply dipping faults "6" and "7." These faults are the last to form and complete the formation of the structural plan of the anticline.

Throughout the history of the formation of the anticline, its apical part is gradually eroded. Figure 7i shows the current structure of the anticline; the dotted line shows the reconstructed eroded deposits.

Based on the prepared conceptual kinematic model of the formation of the Aguaragüe fold, taking into account regional geology data, drilling results, and field studies, we performed a structural interpretation of seismic exploration materials and created a balanced three-dimensional model of the structure of the Aguaragüe and San Antonio anticlines (Fig. 8).

Kinematic Reconstruction of the Regional Profile

Based on the conceptual geological model, we performed a kinematic reconstruction using the regional profile (Fig. 9) and the three-dimensional model (Fig. 10).

The formation of the current structural plan of the Subandino thrust-fold belt began during the progradation of the thrust front from the Andean folded structure. The onset of deformations is dated to the Middle–Late Miocene between 12.4 and 8.5 million years ago (Fig. 9b). Between 8 and 6.7 million years, the deformation front falls on the Mandiyuti thrust and the structures of the western province (Suraro, Mandiyuti, Huacaya, Iniguazu, Bermejo, etc.) are formed during this period (Fig. 9b). Deformations spread to the eastern province about 6 million years ago (Figs. 9c, 9d). Until 5.9 million years, the deformation front covers the La Vertiente structure. The San Antonio, Aguaragüe, and Agua Salada structures are successively formed between 5.5 and 2 million years (Fig. 9d). In the Pliocene (4.5 million years), the strong compressional impulse, which covered the entire region, led to the formation of the Mandeyapecua structure (Figs. 9f–9g). Compression deformations are currently observed in the Suaruro, Aguaragüe, and Mandeyapecua structures.

The data obtained from regional 2D and 3D palinspatic reconstructions were used in basin modeling to refine the model of thermal history and the history of hydrocarbon generation in the study region. A visual

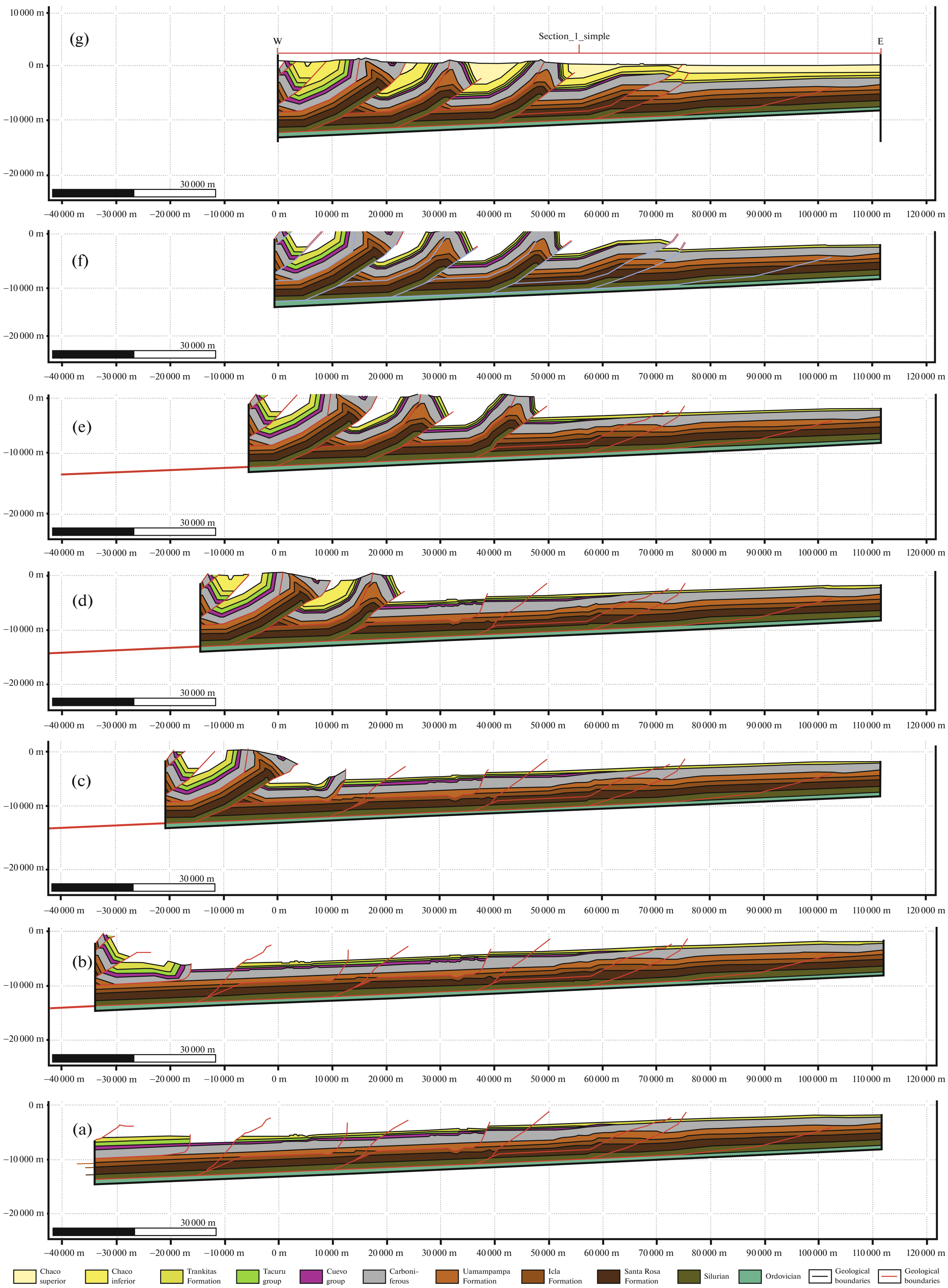


Fig. 9. Kinematic reconstruction by the regional profile. The stages of deformation ((a)–(g)) are described in the text of the article. The location of the profile is shown in Fig. 1.

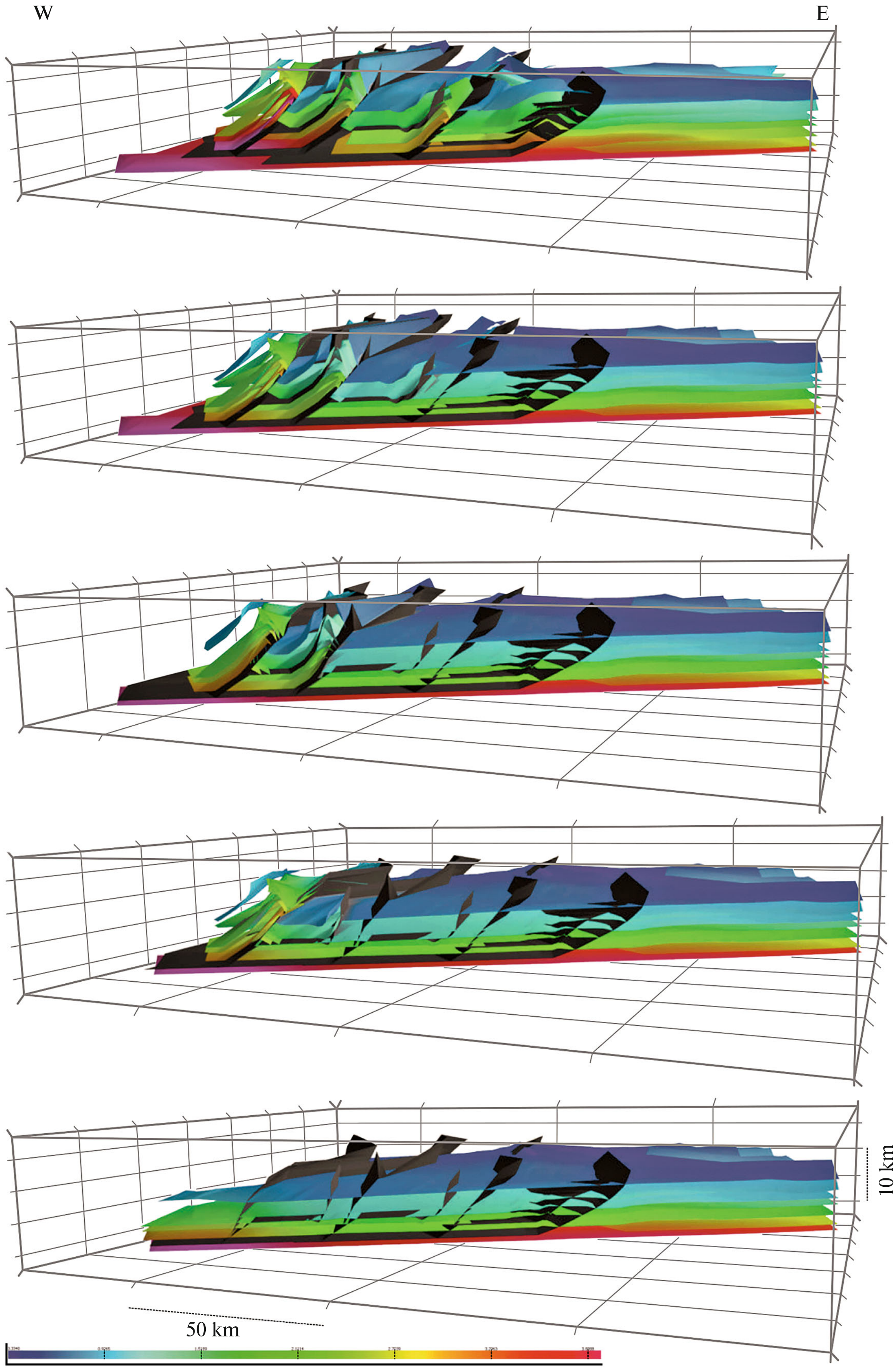


Fig. 10. Kinematic reconstruction of the regional 3D model. The modeling area is shown in Fig. 1. The color indicates the vitrinite reflectance index.

result of the research is a three-dimensional model of reconstructing the evolution of the structural plan of the southern part of the Subandino zone (Fig. 10). Its results were used to calculate a classical basin model of hydrocarbon system development. In the three-dimensional reconstruction, the degree of maturity of organic matter is highlighted in color, which is expressed in the vitrinite reflectance index at the time preceding the onset of active tectonic deformations (about 12 million years).

CONCLUSIONS

(1) Deformations in the Subandino Sur thrust-fold belt began about 12 million years ago and gradually moved from west to east.

(2) The formation of the Aguarague anticline began about 4 million years ago and occurred in three stages, each of which is characterized by its own structural paragenesis.

(3) The deformation processes in the cores of the fault anticlines of the frontal part of the Subandino belt are complex in nature, which cannot be fully described by a single geometric model, and represent a combination of brittle and plastic deformations. In the authors' opinion, the closest to reality model is the model of antiform clustering duplexes, since this model best links together the data of seismic exploration, drilling, and field geological surveys.

(4) The results of the kinematic reconstructions can be used for basin modeling.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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