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Evidence for major shortening on the eastern edge of the Bolivian Altiplano: the Calazaya nappe

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ABSTRACT

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For the first time, evidence is presented of major shortening on the eastern edge of the Altiplano, in Bolivia. A tectonic nappe showing at least 40 km of horizontal displacement towards the east is revealed at the Altiplano–Cordillera Oriental transition (20°S). Analysis of the differences in stratigraphy, sedimentology and structure between allochthonous and autochthonous units confirms the 40 km of overthrust. A geometric analysis of the thrust structures has been made to interpret the three-dimensional geometry of the nappe, and a deformation sequence is suggested.

The nappe emplacement is related to the eastward transport of a large allochthonous domain during the Late Oligocene–Early Miocene. The sole thrust of this allocthtonous domain is located in a stratigraphic unit whose three-dimensional basin geometry controlled the deformation.

The existence of the Calazaya nappe allows us to explain the exceptional thickness of the Altiplano (55–70 km) as mainly resulting from the Neogene shortening that occurred between the Altiplano and the Cordillera Oriental.

Introduction

The Central Andes (Fig. 1), between 10 and 28°S, are characterized by the arcuate shape of the mountain range (the Bolivian orocline), a thick crust (55–70 km), high relief (several summits over 6000 m) and an enigmatic high plateau (the Altiplano) with an average altitude of 3650 m.a.s.l.. It has traditionally been considered that the central part of the Andean Orogeny results mainly of vertical tectonic movements. The crustal thickness has been attributed to the effect of magmatic addition – a fact which is still questioned. Recent work has shown the importance of crustal shortening for the development of the structural pattern of the Eastern Cordillera and the Subandean zone in Bolivia (Roeder, 1985; Sheffels 1988, 1990; Baby et al., 1989), as well as in Argentina (Allmendiger et al., 1983). Crustal shortening tectonics also played an important role in the structural development of the Altiplano (Baby et al., 1990; Sempere et al., 1990a) and tangential movements associated with significant crustal shortening have been demonstrated at the contact between the Altiplano and the Cordillera Oriental (Sempere et al., 1991).

At about 20°S (Fig. 1) this area shows an unusual structural complexity. Field mapping and satellite imagery analysis demonstrate the presence of some tectonic basin-shaped klippes in this area, overlying a previously deformed domain (Fig. 2). The klippes give evidence for a major

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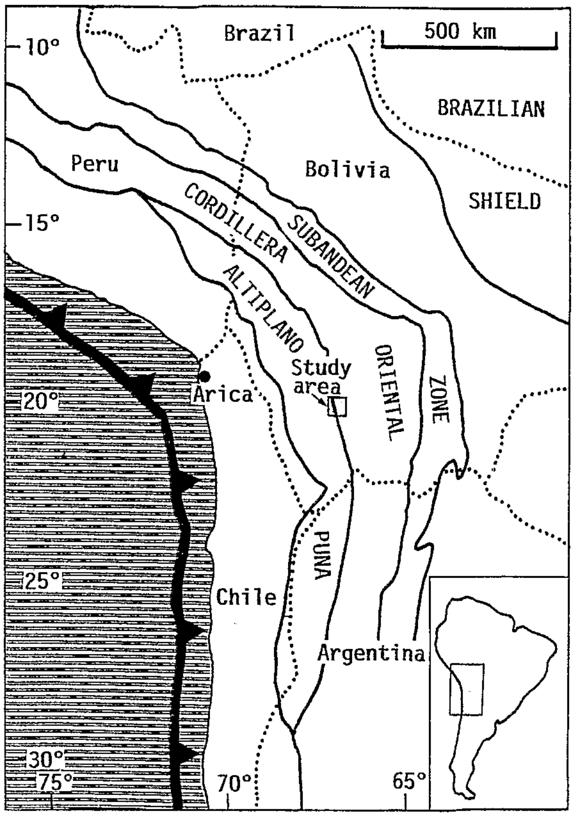

Fig. 1. Location of study area within Bolivia, relative to morphologic units of the central Andes.

subhorizontal thrust (the Calazaya thrust) and make possible the mapping of the present-day front of a tectonic nappe (the Calazaya nappe) whose overthrust towards the east is at least 40 km.

The purpose of this paper is (1) to present the Calazaya nappe data which confirm the existence of a major shortening below the eastern Altiplano and the Cordillera Oriental and (2) to interpret its peculiar three-dimensional geometry and define its regional significance with regard to the Andean orogenesis.

Comparative study of allochthonous and autochthonous units

Stratigraphy and sedimentology

Stratigraphically, the outcropping units are practically the same in the two tectonic domains. However, they exhibit several differences in facies and thicknesses (Fig. 3). The stratigraphic vertical offset between these two domains is about 2 km.

The undifferentiated Ordovician strata (pre-Ashgillian sandstones and shales) crop out in the autochthon and are unconformably overlain by the Tokochi Formation (upper Caradoc?) defined by Sempere et al. (1991). The Tokochi Formation indicates a rapid deepening preceding the Ashgillian–Silurian basin development which becomes deeper to the west of the Calazaya thrust. It consists of 50–200-m-thick black shales with organic matter and pyrite, characterized by an ash-colour due to weathering. The Cancañiri Formation, which lies above the Tokochi Formation, is the oldest unit (Ashgillian) present in the two tectonic domains. In the study area, the Cancañiri Formation consists of glacial-marine diamictites with a pelitic matrix, white quartz and altered sandstone pluricentimetric clasts, and stratified metric sandstone blocks up to 1 m in size. These diamictites are non-stratified with a thickness of about 1500 m in the autochthon where facies are more proximal than in the allochthon; in the southeastern outcrops of the Cancañiri Formation, the diamictite matrix becomes sandy and the size and abundance of olistoliths increase. The diamictites are overlain by the Llallagua Formation (Early Silurian), which consists of sandy turbidites, progressively grading in to the more pelitic Uncia Formation (Middle Silurian). The Llallagua Formation, several hundreds of metres thick in the allochthon, is only tens of metres thick in the autochthon in the few areas where it has not been removed before the deposition of Mesozoic strata. Late-Silurian and sometimes Early Devonian units crop out below the Mesozoic unconformity to the west of the study area.

The oldest Mesozoic unit is the Ravelo Formation which consists of fluvio-eolian sandstones considered to be Jurassic in age (Oller and Sempere, 1990). In the autochthon as well as in the allochthon, the Ravelo Formation crops out only in limited areas where it is unconformably overlain by the conglomerates and sandstones of the Condo Formation of Kimeridgian–Berriasian age (Jaillard and Sempere, 1989). ENE–WSW-striking normal faults affecting the Ravelo Formation

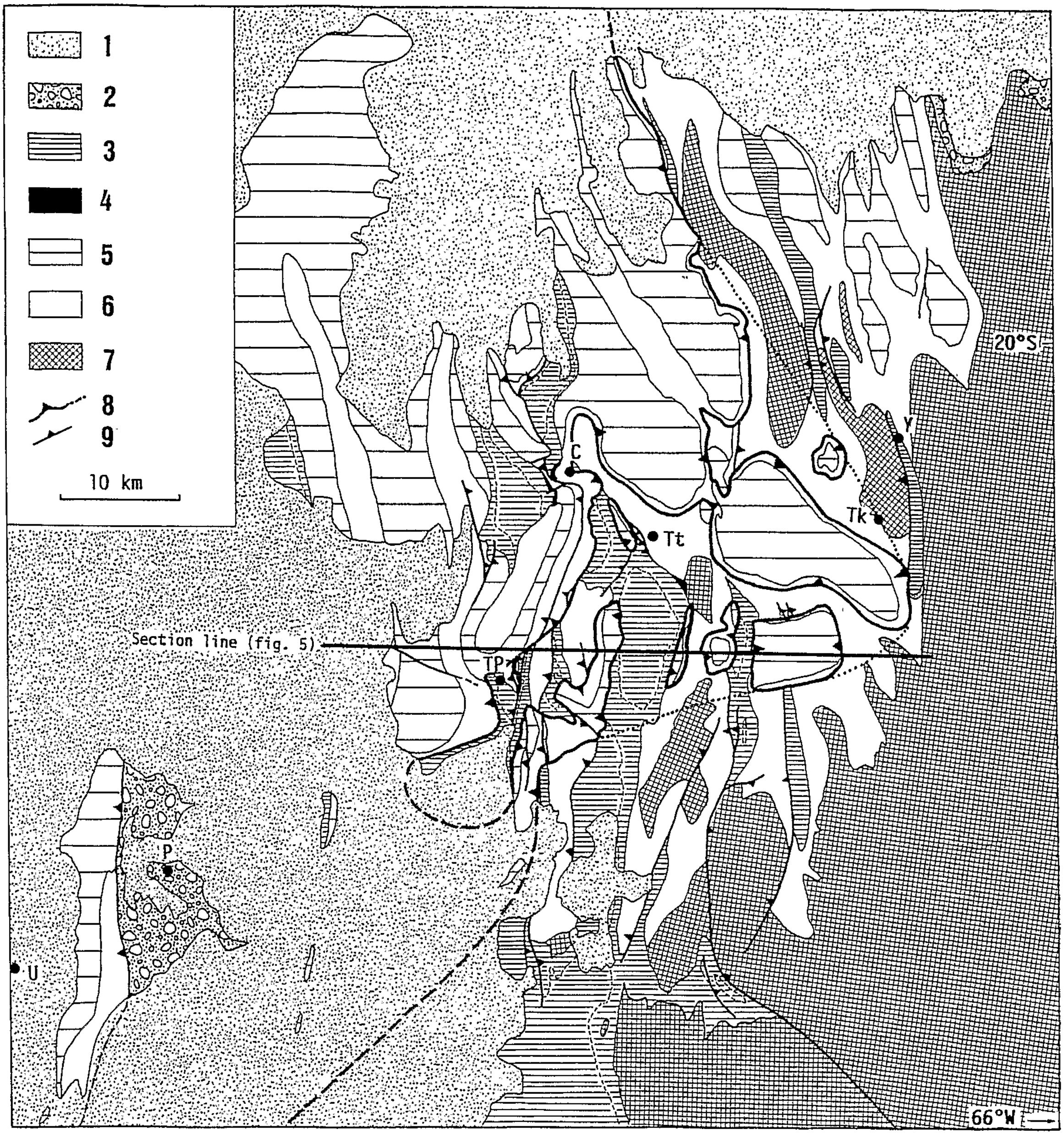

Fig. 2. Geologic map of the Calazaya area (location in Fig. 1 and Fig. 14). From Sempere et al., 1991. Sources of data: Geobol, 1/100.000 sheets "Uyuni" and "Ubina", 1966; J. Oller, YPFB, unpublished geological map, 1973; ORSTOM-YPFB field mapping, 1988–89; Spot and Landsat satellite imagery. *1* = Middle Miocene and youngers rocks; *2* = Late Oligocene-Early Miocene; *3* = Kimmeridgian–Eocene; *4* = Jurassic; *5* = Silurian; *6* = Ashgillian; *7* = Ordovician; *8* = Calazaya thrust; *9* = Other thrusts. *C* = Calazaya; P = Pulacayo; *Tk* = Tokochi; *TP* = Tojra Palca; *Tt* = Ticatica; *U* = Uyuni; *Y* = Yura. The dashed line within the Kimmeridgian–Eocene is a guide level of Late-Campanian age.

and the first few metres of the Condo Formation show that the Ravelo Formation is preserved in half-grabens. The Condo Formation is the thickest (several tens of metres) and consists of conglomerates in these half-grabens, and progressively seals the ENE–WSW normal faults. This shows that an extensional tectonic event occurred during the deposition of the Condo Formation. Near the Turonian–Coniacian boundary, a similar but less spectacular phenomenon is observed:

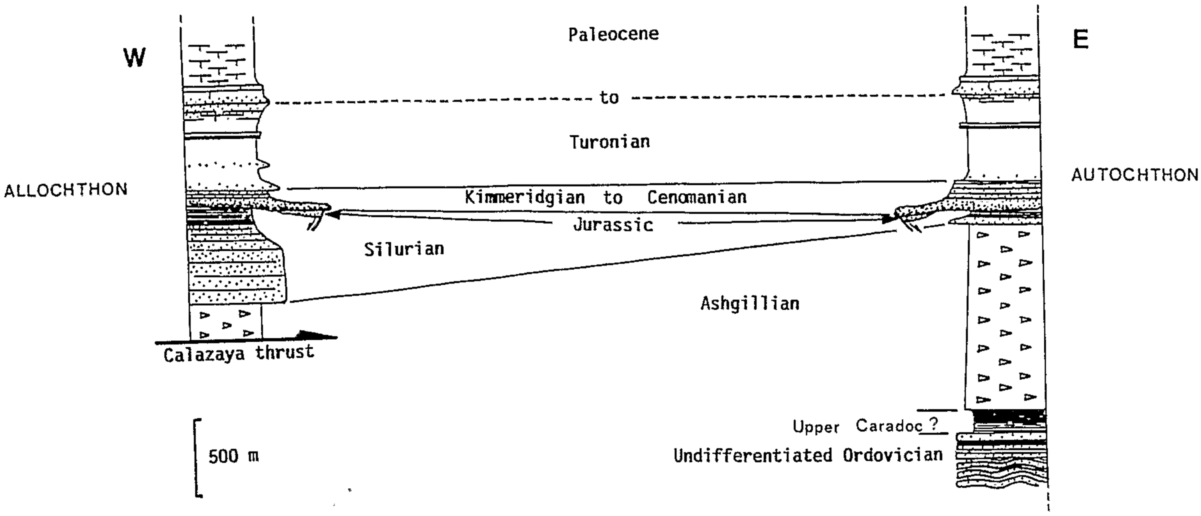

Fig. 3. Schematic stratigraphies of the allochthon and autochthon (from Sempere et al., 1991). See text.

the base of the Aroifilia Formation (Coniacian red mudstones and sandstones) unconformably overlies either the Early Cretaceous or the Paleozoic.

The later deposits, which mostly consist of red mudstones and sandstones (Coniacian to Paleocene), are similar in the autochthon and the allochthon.

TECTONIC EVENTS		AGES	AUTOCHTHON	ALLOCHTHON
Compressive deformation "Ocloyic"	1	Llandeilian-Caradocian	x	
?	2	Post-Silurian Ante-Jurassic	x	x
Extensional deformation "Araucan"	3	Kimmeridgian-Berriasian	x	x
Extensional deformation "Vilcapujio"	4	Turonian – Coniacian	?	x
E-W trending compressive deformation	5	Post-Cretaceous ante-late Oligocene	x	
N-S trending left-lateral transcurrent deformation	6	Late Oligocene	x	
Calazaya nappe development	7	Post-late Oligocene	x	x

Fig. 4. Chronology of the observed deformations in the studied area.

Structure

Field work and satellite imagery analysis (Laubacher, 1990) allowed us to differenciate at least seven deformation stages (or periods) whose superposition explains the structural complexity of the geologic map (Fig. 2). Four or five of these deformations are present in both tectonic domains and two are observed only within the autochthon (Fig. 4).

The Ordovician, only present in the autochthon, shows a local complex folding which does not affect the Tokochi Formation. This deformation may possibly correspond to the "Ocloyic" deformation defined in the northwest of Argentina (Allmendinger et al., 1983) and is probably Llandeilian–Caradocian in age (Sempere, 1989).

The cartographic unconformity located between the Mesozoic and Paleozoic units (Fig. 2) reveals a deformation which occurred between Silurian and Jurassic times and affected the two tectonic domains. However, the characteristics of this deformation are difficult to define because of the superposition of the five later deformations.

The third observed deformation is the extensional tectonics which occurred during the deposition of the Condo Formation (Kimmeridgian–Berriasian), and which probably can be correlated with the "Araucan" tectonic event (Sempere et al., 1988).

The unconformity at the base of the Aroifilla Formation, often difficult to recognize, is due to the "Vilcapujio" extensional tectonic event (Chavez, 1986; Sempere et al., 1988) which took place near the Turonian–Coniacian boundary. This deformation is observed in the allochthon and might also be present in the autochthon.

The geological map (Fig. 2) shows that the autochthon is essentially deformed by kilometric elongate narrow folds with subvertical axial planes and N–S subhorizontal axes. These folds, which deform Paleozoic and Cretaceous units, appear to be decapitated and overlain by the Calazaya nappe klippes (Fig. 5). Therefore, they are prior to the nappe and also to a N–S-trending left-lateral transcurrent deformation because they are locally deformed by decametric folds with subvertical axes and S-symmetry. This strike-slip deformation affects only the autochthon and, therefore, is previous to the nappe. It is recognized also in the southern Altiplano and is probably Late Oligocene in age (Baby et al., 1990).

Complex thrust structures with dimensions of somes kilometers are observed within the autochthon and are probably associated with the thrust system responsible for the nappe development; they will be described later on.

This study allows us to define a chronology of the observed deformations, which is summarized in Figure 4 where the two tectonic domains are compared.

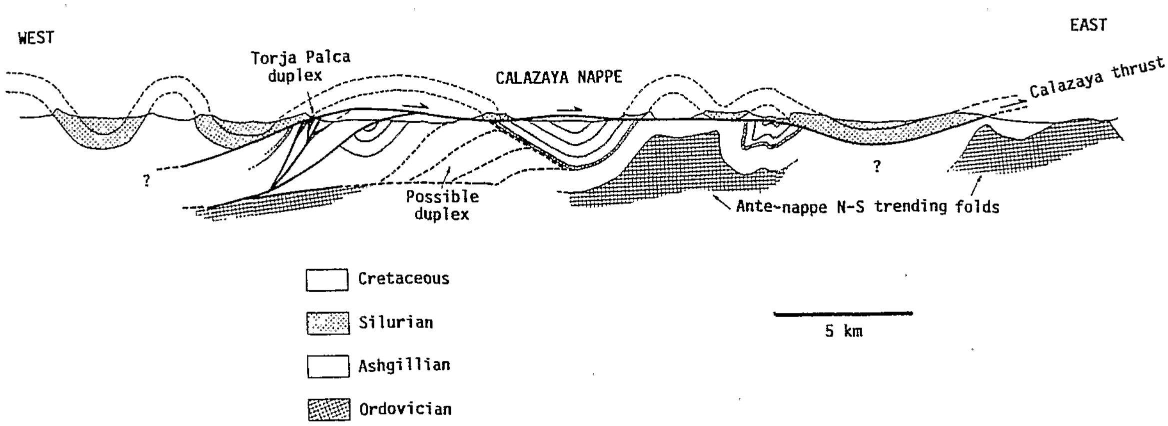

Fig. 5. Structural cross-section across the Calazaya nappe where the overlap is largest (location in Fig. 2).

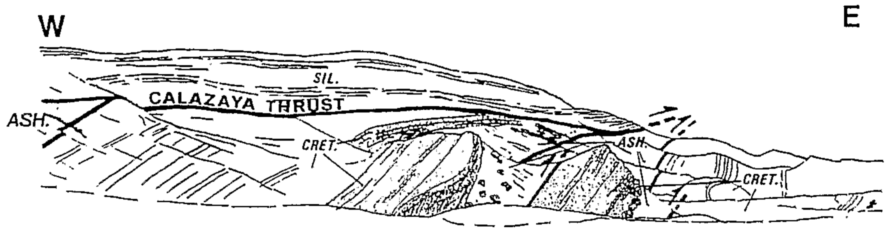

Fig. 6. Field appearance of the Tojra Palca duplex (location in Fig. 2). *ASH.* = Ashgillian diamictites; *SIL.* = Silurian sandstones; *CRET.* = Cretaceous sandstones and pelites.

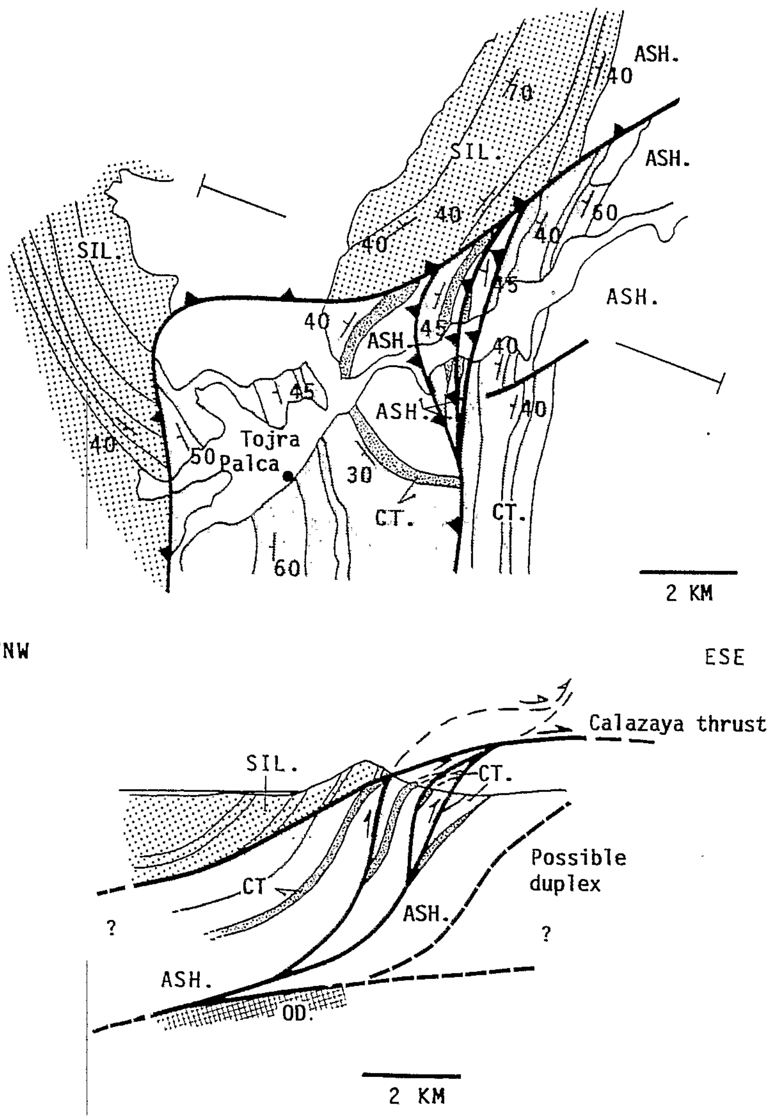

Fig. 7. Structure of the Tojra Palca duplex (location in Fig. 2). *OD.* = Ordovician; *ASH.* = Ashgillian; *SIL.* = Silurian; *CT.* = Cretaceous.

Geometric analysis of the thrust structures

In order to analyse the geometry of the contact between the allochthonous and autochthonous units, we have constructed a structural E–W-oriented cross-section (Fig. 5) across the Calazaya nappe where the overlap is largest (Fig. 2). This cross-section shows that the Calazaya thrust cuts not only most of the structures in the autochthonous units but also those of the allochthonous.

The allochthon is formed by a succession of anticlines with Ashgillian diamictites cores and synclines with Silurian sandstone cores, truncated at their base by the Calazaya thrust (Fig. 5). The anticlines are partially or completely eroded whereas the synclines are preserved. These synclines form the basin-shaped klippes which appear westward of the nappe front (Fig. 2). This suggests that the Calazaya nappe corresponds to a set of domes and basins transported by the Calazaya thrust. Surprisingly, these dome and basin structures are only observed in the allochthon but do not appear either in the west of the root zone of the nappe or in the autochthon. For this reason, we suspect that the formation of these domes and basins, although truncated by the Calazaya thrust, may be contemporaneous with the nappe development.

In the autochthon, the principal structures truncated by the Calazaya thrust are the kilometric N–S-trending folds (Fig. 5). However, the complex thrust structures outcropping near the root zone of the nappe also seem to be decapited by the Calazaya thrust. This indicates an "out of sequence" propagation of the thrust structures associated with the nappe development. One of these complex structures is well exposed in the western part of the cross-section in Fig. 5. This structure, located in Tojra Palca (Fig. 6), repeats the upper part of the Ashgillian diamictites and the distinctive basal sandstones of the Cretaceous. These repetitions disappear to the north below the Calazaya thrust. The detailed study of the Tojra Palca structure (Fig. 7) shows that it corresponds to a duplex made up of two horses. Its floor thrust is located in the Ashgillian diamictites and its roof is truncated by the Calazaya thrust. More to the east at Ticatica (Fig. 6), the same type of duplex is clearly exposed at the surface (Fig. 8). It is made up of two horses similar to Tojra Palca and situated at the front of two thrust sheets consisting of diamictites overlain by Cretaceous sandstones and pelites, partly

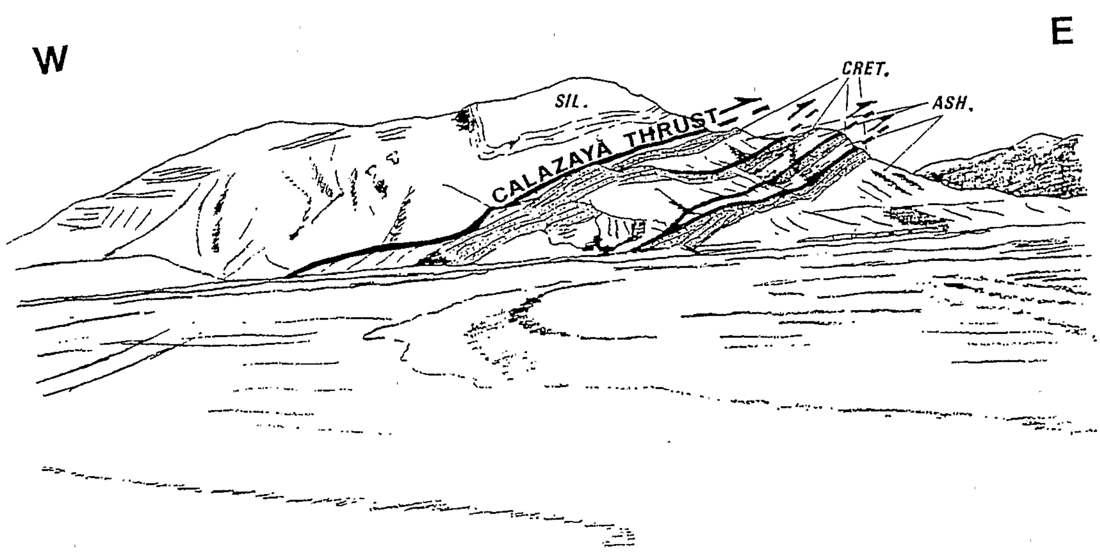

Fig. 8. Field appearance of the Ticatica duplex (location in Fig. 2). *ASH.* = Ashgillian diamictites; *SIL.* = Silurian sandstones; *CT.* = Cretaceous sandstones and pelites.

hidden by the Ticatica klippe (Fig. 9). The cross-section clearly shows that this small thrust system has been cut by the Calazaya thrust. The Ticatica klippe, consisting of diamictites and Silurian sandstones, corresponds to the S-W limb of one of the domes transported within the Calazaya nappe.

Duplexes repeating the distinctive sandstones of the base of the Cretaceous are clearly exposed at the surface (Figs. 6 and 8), but duplexes consisting only of Ashgillian diamictites are difficult to ascertain. The diamictites are unstratified and thus show no key bed. However, the presence of unusually large thicknesses of diamictites suggests the occurrence of duplexes as at the front of the Tojra Palca duplex (Fig. 7) or the Ticatica duplex (Fig. 9). All of these potential duplexes, with or without the Cretaceous sandstones, produced cul-

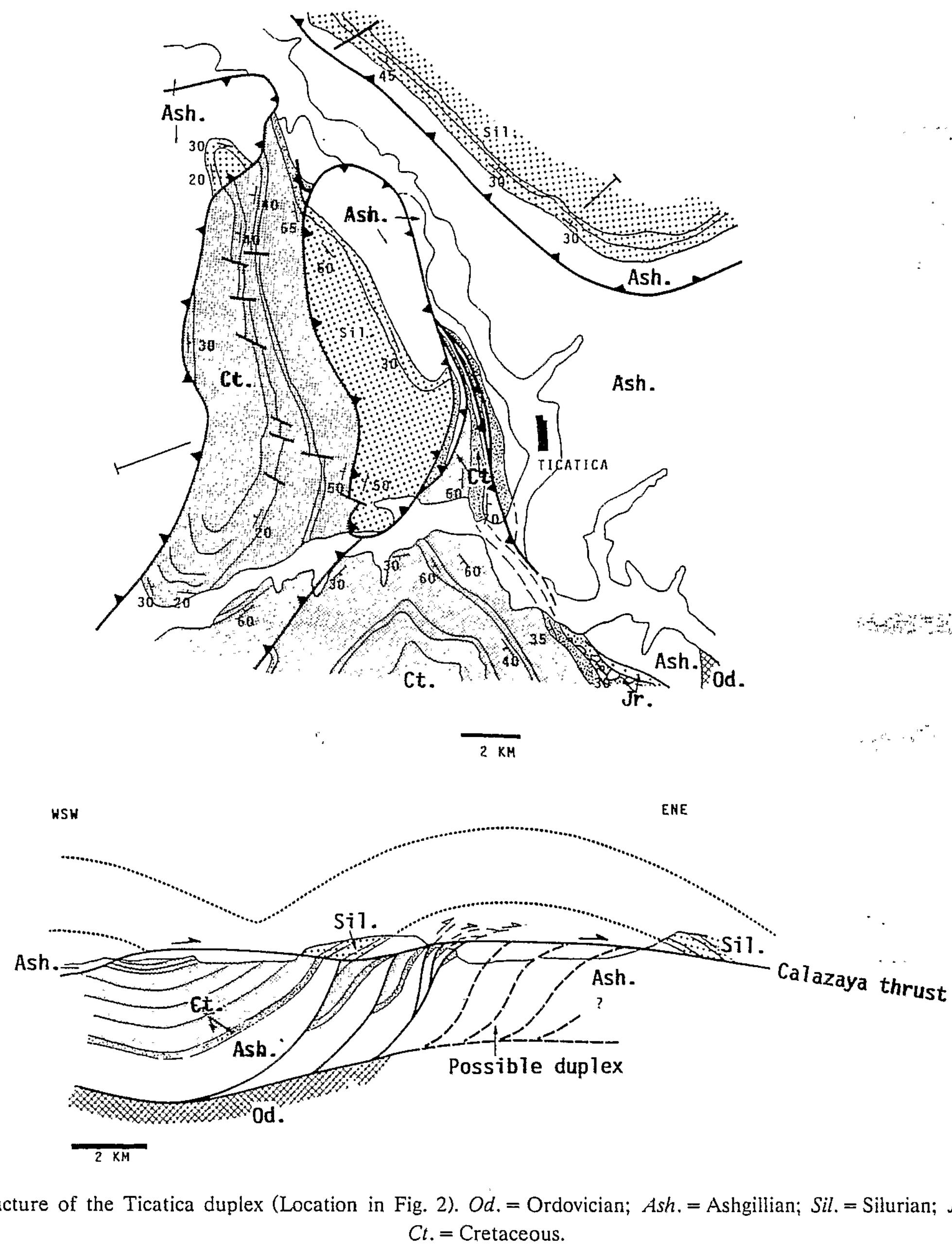

Fig. 9. Structure of the Ticatica duplex (Location in Fig. 2). *Od.* = Ordovician; *Ash.* = Ashgillian; *Sil.* = Silurian; *Jr.* = Jurassic; *Ct.* = Cretaceous.

minations in their cover which are now invisible because they have been decapitated and transported by the Calazaya thrust: these culminations must thus be searched for in the frontal part of the nappe.

Suggested deformation sequence of the Calazaya nappe

Conclusions drawn from the geometric analysis of the thrust structures led us to construct a conceptual evolutive model (Fig. 10), using simple graphical experiments showing the geometric consequences of an "out of sequence" propagation of three identical foreland-sloping duplexes (Mitra classification, 1986) characterized by a shortening "S". In stage 1, the first duplex develops and the displacement "S" is transferred towards the foreland on the upper decollement (A,A′). In stage 2, the second duplex forms just behind the first one; the cover accommodates the shortening by a horizontal forethrust which decapitates the first duplex and transports it for a distance (B,B′) = S on the upper decollement previously used in stage 1. On this horizontal thrust, during its development, a syncline whose amplitude is only dependent on the displacement "S" is forming between the upper parts of the two duplexes. In stage 3, the displacement "S" of the third duplex is transferred towards the foreland in the same way; the second duplex is decapitated and its upper part, as well as that of the first duplex, is transported for a distance (C,C′) = S on the upper decollement. A second broad syncline like the first one is forming between the upper parts of the second and the third duplexes. The final stage thus shows an important subhorizontal thrust separating an allochthonous domain structured into two anticlines and two synclines from an autochthonous domain constituted only by a series of decapitated horses. This allochthon, which is comparable to the Calazaya nappe, seems to have its root at point C, suggesting an overlap and thus an apparent offset (C,A′) = (C,A) + (A,A′). But stages 1 and 4 show that the real offset is only (A,A′) = 3 S, i.e., the total shortening in the three duplexes. (C,A) corresponds only to the length of the series of truncated horses.

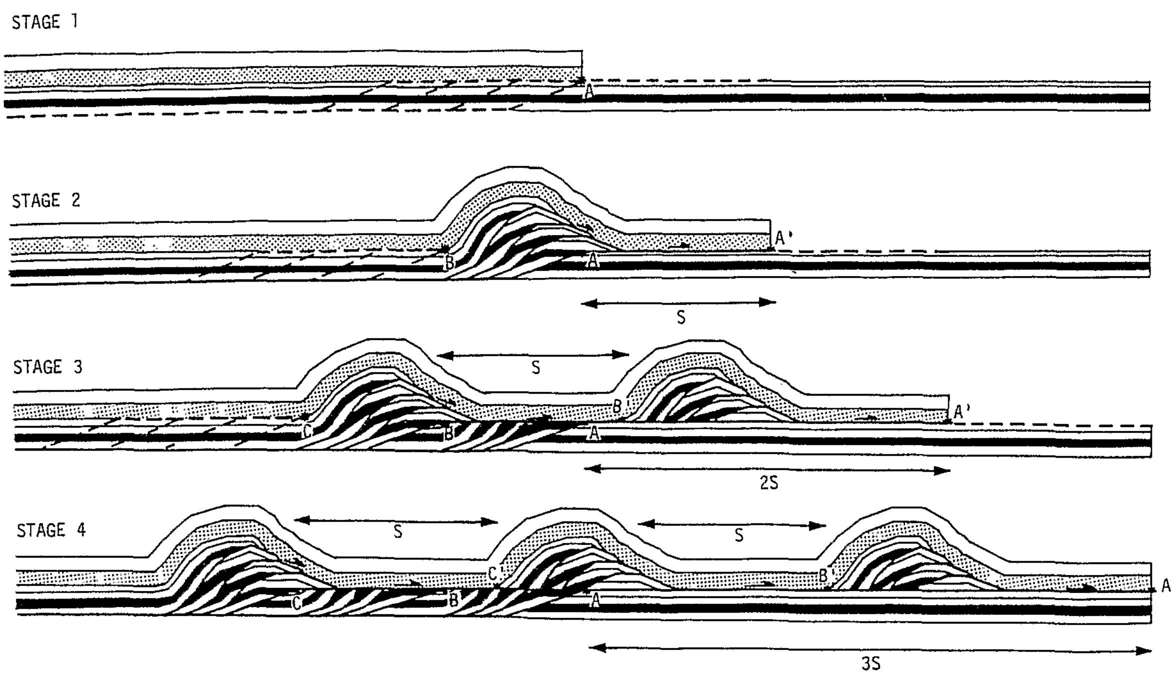

Fig. 10. Geometric consequences of an "out of sequence" propagation of three identical foreland-sloping duplexes (Mitra classification, 1986) characterized by a shortening "S".

The anticlines and synclines of this type of nappe can correspond to domes and basins. Duplex structures such as foreland-sloping duplexes can cause important culminations, and excellent examples are known where contoured duplex thicknesses show a series of domes and basins (see Boyer and Elliott, 1982). In order to illustrate this phenomenon geometrically and, thus, explain the Calazaya nappe structure, a block diagram is presented (Fig. 11). It shows an "out of sequence" propagation of foreland-sloping duplexes which develop in an incompetent unit like the Ashgillian diamictites, with a cover consisting of a competent unit like the lowermost Silurian sandstones. Figure 11A represents the Calazaya nappe in its deformed state. The last-formed duplex is situated in the rear part, while the other ones are decapitated and their upper parts transported forward, as in the evolutive model of Figure 10. At the surface, the cover is deformed into unfaulted domes and basins produced by the development of the duplexes. The domes have disappeared owing to erosion (Fig. 11B), and large surface areas of incompetent units are observable (like diamictites) where, sometimes, the decapitated horses of the autochthon and the transported horses of the allochthon are mixed-up. In the frontal part, above the horizontal thrust, only the synclinal basins are preserved, forming klippes like those of the Calazaya nappe.

From these conceptual models of evolution (Figs. 10, 11A, 11B) explaining the structuration of the Calazaya nappe and its corresponding autochthonous units, we suggest a schematic deformation sequence (Fig. 12) for the structural geometry of the cross-section of Figure 5.

The initial stage of Figure 12 is characterized by the km-sized elongate narrow N–S-trending folds locally deformed by the N–S-trending left-lateral transcurrent deformation prior to the nappe formation. From east to west, the Cretaceous sandstones unconformably and successively overlie the Ashgillian diamictites and the Silurian sandstones. In stage 2, the first foreland-sloping duplex (a) develops; its floor thrust corresponds to the base of the Ashgillian diamictites and its

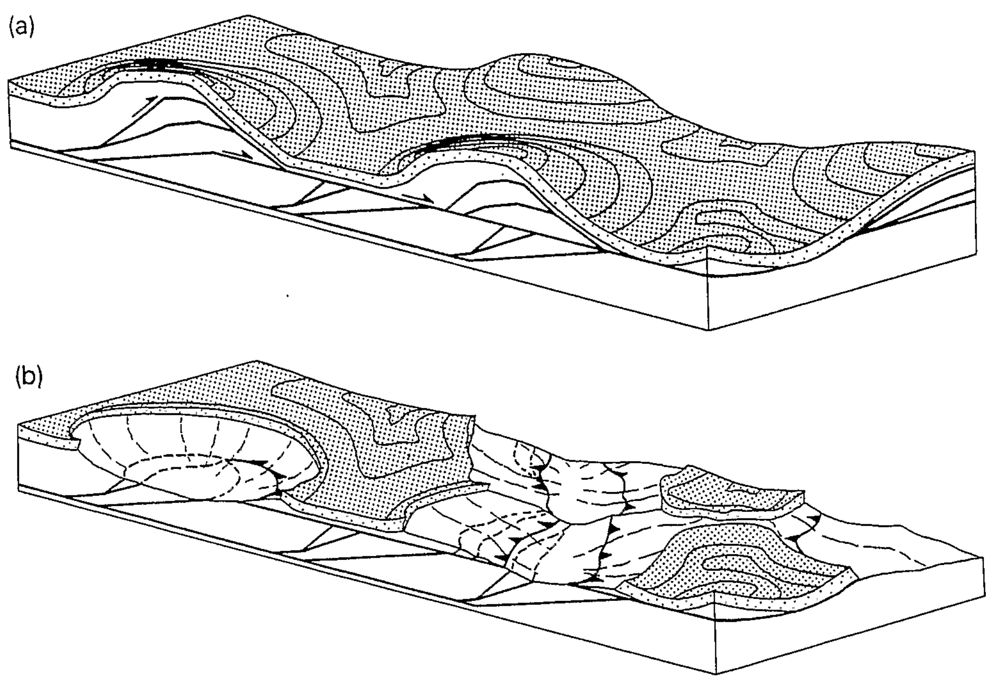

Fig. 11. (A) Block diagram showing an "out of sequence" propagation of foreland-sloping duplexes which develop in an incompetent formation like the Ashgillian diamictites, with a cover consisting of a competent formation like lowermost Silurian sandstones. (B) Block diagram of Fig. 11A after the erosion of domes.

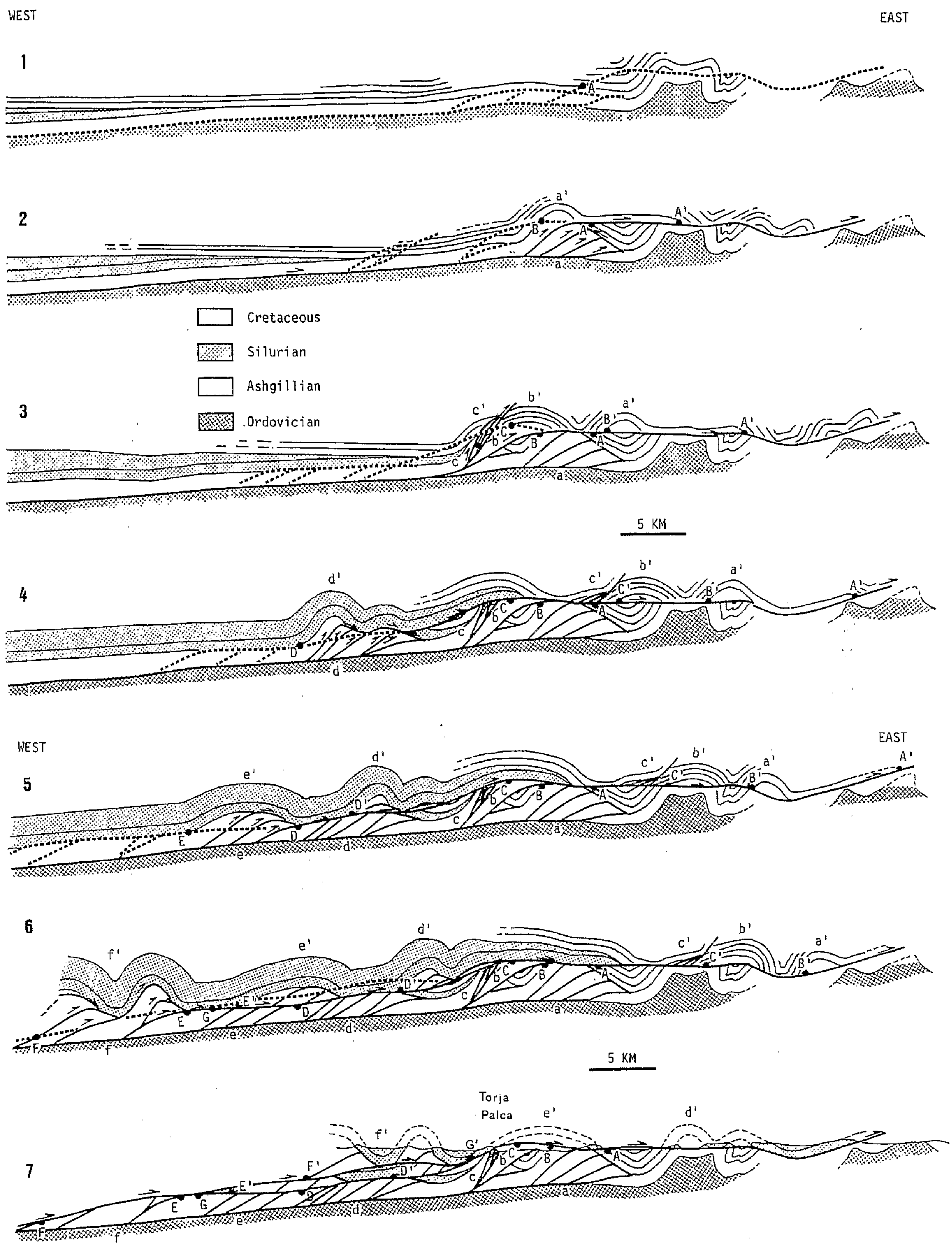

Fig. 12. Schematic sequence of deformation, based on the cross-section in Fig. 5.

roof thrust is located at the Asghillian diamictite–Cretaceous sandstone interface. The shortening in this duplex is accommodated by a subhorizontal forethrust (Calazaya thrust) which decapitates the previous large N–S-trending folds. In stage 3, the first foreland sloping duplex (a) is decapitated by an out of sequence thrust (b) which prolongs the Calazaya thrust backwards. Further towards the west, the Tojra Palca duplex (c), where the Cretaceous sandstones are involved in the horses, develops independently. Stage 4 is characterized by the development of an important foreland-sloping duplex (d) involving the Ashgillian diamictites and whose cover consists here of Silurian sandstones. The shortening in this duplex, producing two culminations (d′) in the Silurian sandstones, is accomodated by a forethrust which decapitates the Tojra Palca duplex (c′) and the ramp anticlines (b′), before transporting them on the Calazaya thrust. Stages 5 and 6 are repetitions of stage 4, where two other foreland-sloping duplexes (e, f) comparable with the earlier one (d), but with different geometries, prolong the Calazaya thrust backwards. At the end of stage 6, the Calazaya nappe overlap is about 50 km (E,A), whereas its offset is about 25.5 km (A,A). In stage 7, there is no more duplex development but an important out of sequence thrust climbs upward through the section from the sole thrust. This major thrust decapitates the culminations (f′) of the westernmost duplex (f) and part of Calazaya nappe (G,G′), before transporting them on the Calazaya thrust. The Calazaya nappe offset increases thus by 18 km; its total displacement is about 41.5 km. At present, the frontal part of the nappe, composed

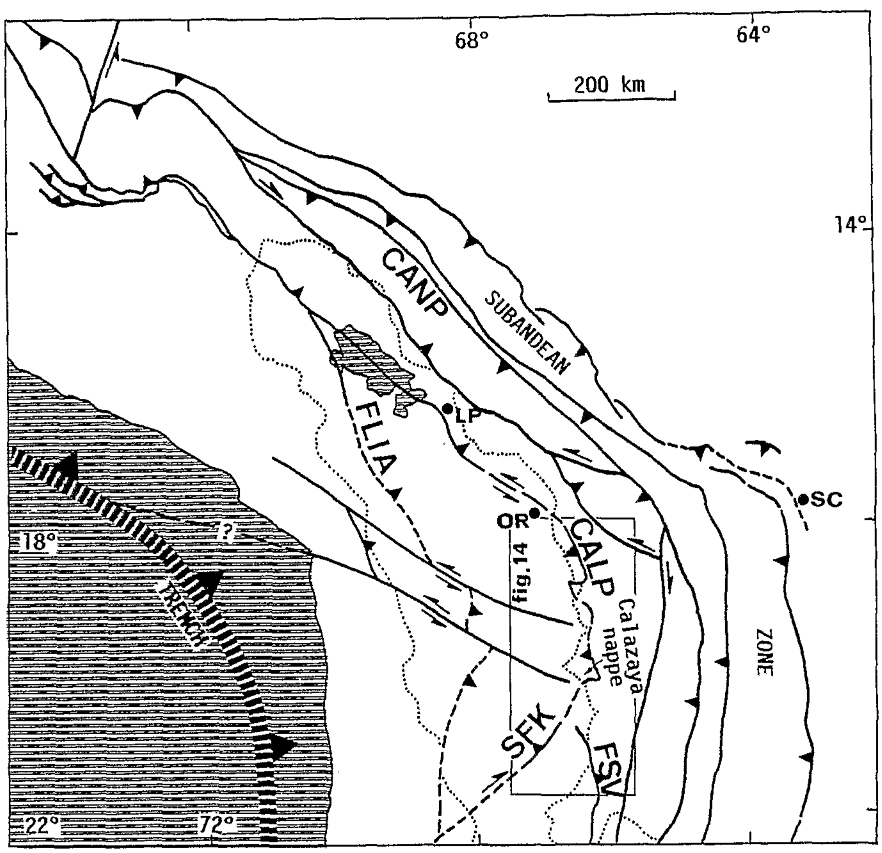

Fig. 13. Position of the Calazaya nappe within the Bolivian orocline (from Sempere et al., 1991). Fine dotted line: boundary of the present-day endoreic Altiplano basin; framed: location of Fig. 14. *FLIA* = Intra-Andean Boundary Fault; *CANP* = Main Andean Thrust; *CALP* = Main Altiplanic Thrust; *SFK* = Khenayani Fault System; *FSV* = San Vicente Fault; *LP* = La Paz; *SC* = Santa Crus; *OR* = Oruro.

of Cretaceous sandstones and shale culminations, has been eroded, and the root zone essentially made up of diamictite horses is not outcropping. Only the reconstruction of the different stages of evolution has allowed us to define them.

Regional significance and paleogeographic control

At the scale of the Bolivian orocline (Fig. 13), the Calazaya nappe occurs at the junction of the east-verging Main Altiplanic Thrust (Cabalgamiento Altiplánico Principal = CALP) with the Khenayani Fault System (Sistema de la Falla de Khenayani = SFK) (Sempere et al., 1991). The Calazaya thrust shows thus that the CALP-SFK system is characterized by an eastward displacement of up to 41.5 km (see Fig. 12) in its central part.

The presence of this major east-verging thrust system allowed us to search for its correlative foreland deposits. Two sedimentary basins filled by fluviatile red-bed deposits of Late Oligocene–Early Miocene age extend along the CALP-SFK system (Fig. 14): the western part of the Lipez Basin corresponds to the SFK-foreland basin (Baby et al., 1990) and the Bolivar-Mondragon Basin to the CALP-foreland basin (Sempere et al., 1986). Several piggyback basins, such as the Pulacayo Basin, appear to have developed at the same time in the western part of the Calazaya thrust and the SFK (Figs. 2 and 14). Thus, the CALP-SFK system is active in Late Oligocene–Early Miocene time (Sempere et al., 1989; 1991; Baby et al., 1990).

On the southern Altiplano (Fig. 14), it has been demonstrated that the geometry of the Khenayani Fault System (SFK), whose sole thrust is also located at the base of the Ashgillian diamictites, was controlled by the geometry of the eastern margin of the Ashgillian-Silurian basin (Baby et al., 1990). This paleogeographic control seems to continue to the north, where the geometry of the Calazaya nappe could reflect the geometry of the continuation of this paleomargin (Sempere et al., 1991). This is confirmed by the presence of proximal Ashgillian facies in the autochthon whereas, in the western part of the Calazaya nappe, the facies of the same formation are thicker and representative of a deeper depositional environment. Thus, the three-dimensional geometry of the Ashgillian diamictites, where the sole thrust of the SFK and Calazaya duplexes is located, seems to have controlled the geometry of a large part of the CALP-SFK system.

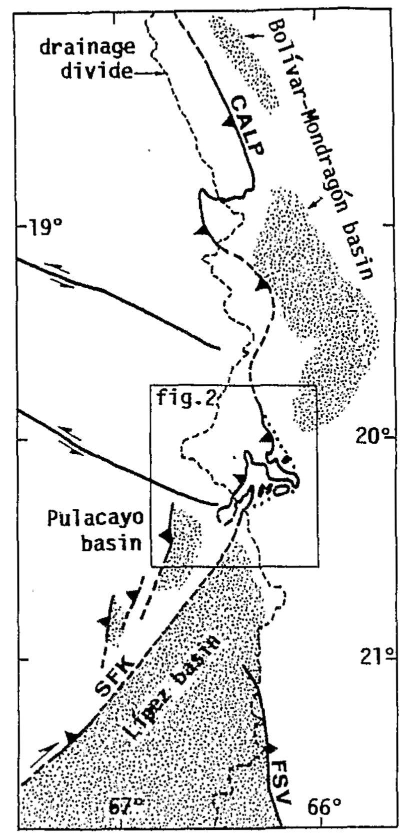

Fig. 14. Structural setting of the Calazaya area (framed). (Location in Fig. 13). Dotted areas: Late Oligocene–Early Miocene foreland basins of the CALP-SFK system, and minor piggyback basins. *CALP* = Main Altiplanic Thrust; *SFK* = Khenayani Fault System; *FSV* = San Vicente Fault.

Discussion and conclusion

The eastward displacement of the Calazaya nappe is mainly due to the accomodation of the shortening in a series of foreland-sloping duplexes, successively decapitated by the Calazaya thrust and now located in the roof zone of the Calazaya nappe (see Fig. 12). Thus, the Calazaya thrust is characterized by a displacement of about

41.5 km of which 23.5 km results from the accommodation of shortening in these duplexes. Without a detailed study of the nappe and the duplexes and without applying an addition of the shortening in the nappe and duplexes would give an unrealistically large estimate of shortening. The overlap of this type of nappe can also be misleading: as we have seen in stage 6 of Figure 12, the overlap can be more important than the offset because the basal overthrust of the nappe has a foreward displacement but is progagating backwards at the same time.

The Calazaya nappe can be considered as the illustration and definition of a new type of thrust system, which confirms the importance of duplexes in fold-thrust belts, as already emphasized by many authors during the past ten years (Suppe, 1980; Price, 1981; Jones, 1982; Boyer and Elliott, 1982; Mitra, 1986; Morley, 1986; Banks and Warburton, 1986; Kulander and Dean, 1986; Dunne and Ferril, 1988).

The Calazaya nappe occurs at the junction of the east-verging Main Altiplanic Thrust (CALP) with the Khenayani Fault System (SFK) (Fig. 3). It is here that this fault and thrust system is the most developped, with a shortening of about 42 km in only one structure. The first structure of this kind observed in the Bolivian Andes, the Calazaya nappe may have developed during the Late Oligocene–Early Miocene; the Bolivar–Mondragon and Lipez basins are the foreland basins of the CALP-SFK (Fig. 14). Paleogeographic structure controls the geometry of the nappe as well as its limits, but this nappe is due to a significant shortening of the crust. This shortening, due to the functioning of the CALP-SFK, is coeval with the Late Oligocene–Early Miocene major tectonic crisis defined by Sempere et al. (1990b) in Bolivia. This crustal shortening explains the crustal thickening below the Oriental Cordillera and the Altiplano.

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References

Allmendiger, R.W., Ramos, V.A., Jordan, T.E., Palma, M. and Isacks, B.L., 1983. Paleogeography and Andean structural geometry, northwest Argentina. Tectonics, 2: 1–16.

Baby, P., Hérail, G., Lopez, G.M., Lopez, O., Oller, J., Pareja, J., Sempere, T. and Tufino, D., 1989. Structure de la Zone Subandine de Bolivie: influence de la géométrie des séries sédimentaires antéorogéniques sur la propagation des chevauchements. C.R. Acad. Sci. Paris, 309 (Sér. II): 1717–1722.

Baby, P., Sempere, T., Oller, J., Barrios, L., Hérail., G. and Marocco, R., 1990. Un bassin en compression d'âge oligo-miocène dans le Sud de l'Altiplano bolivien. C.R. Acad. Sci. Paris, 311 (Sér. II): 341–347.

Banks, C.J., and Warburton, J., 1986. "Passive roof" duplex geometry in the frontal structures of the Kirthar and Sulaiman mountains belts, Pakistan. J. Struct. Geol., 8: 229–237.

Boyer, S.E. and Elliott, D., 1982. Thrust systems. Bull. Am. Assoc. Pet. Geol., 66: 1196–1230.

Chavez, H., 1986. Interpretación geodinámica de las formaciones sedimentarias y estructuras tectónicas de la zona de Challapata. Tesis UMSA, La Paz, unpub. 190 pp.

Dunne, W.M. and Ferril, D.A., 1988. Blind thrust systems. Geology, 16: 33–36.

Isacks, B.L., 1988. Uplift of the central Andes plateau and bending of the Bolivian orocline. J. Geophys. Res., 93: 3211–3231.

Jaillard, E. and Sempere, T., 1989. Cretaceous sequence stratigraphy of Peru and Bolivia. Simp. Cret. Amer. Lat., Buenos Aires, pp. A1–27.

Jones, P.B., 1982. Oil and gas beneath east-dipping underthrust faults in the Alberta Foothills, Canada. In: R.B. Powers (Editor), Geologic Studies of the Cordilleran thrust belt. Denver, Rocky Mountain Association of Geologists, pp. 61–74.

Kulander, B.R. and Dean, S.L., 1986. Structure and tectonics of central and southern appalachian Valley and Ridge and Great Valley provinces, West Virginia and Virginia. Bull. Am. Assoc. Pet. Geol., 70: 1674–1684.

Laubacher, G., 1990. Mise en évidence de structures tangentielles andines dans le sud de la Bolivie (Région de Tica Tica, departamento de Potosi) par SPOT. Symposium International "Geodynamique Andine", Grenoble-France; ORSTOM Ed. Col. Colloques et Séminaires, pp. 159–162.

Mitra, S., 1986. Duplex structures and imbricate thrust systems: Geometry, structural position, and hydrocarbon potential: Bull. Am. Assoc. Pet. Geol., 70: 1087–1112.

Morley, C.K., 1986. A classification of thrust fronts. Bull. Am. Assoc. Pet. Geol., 70: 12–25.

Oller, J. and Sempere, T., 1990. A fluvio-eolian sequence of probable Middle Triassic–Jurassic age in both Andean and Subandean Bolivia. Symposium International "Géodynamique andine", Grenoble, France. ORSTOM ed. Col. Colloques et Séminaires, pp. 237–240.

Price, R.A., 1981. The Cordilleran foreland thrust and fold belt in the southern Canadian Rocky Mountains. In: K.R. McClay and N.J. Price (Editors). Thrust and Nappe Tectonics. Geol. Soc. London, Spec. Publ., 9: 427–448.

Roeder, D., 1988. Andean-age structure of Eastern Cordillera (Province of La Paz, Bolivia). Tectonics, 5: 23–39.

Sempere, T., 1989. Paleozoic evolution of the central Andes (10°–26°S). XXVIII Int. Geol. Cong., Washington, 3: 73.

Sempere, T., Chavez, H. and Perez, M., 1987. VIII Cong. Geol. Boliv., pp. 45–46.

Sempere, T., Oller, J. and Barrios, L., 1988. Los aspectos estructurales y sedimentarios del oroclino boliviano. V Cong. Geol. Chil., 1: A127–A142.

Sempere, T., Hérail, G., Oller, J. and Baby, P., 1989. Geologic structure and tectonic history of the Bolivian orocline. XXVIII Int. Geol. Cong., Washington, 3: 72–73.

Sempere, T., Hérail, G., Oller, J., Baby, P., Barrios, L. and Marocco, R., 1990a. The Altiplano: a province of intermontane foreland basins related to crustal shortening in the Bolivian orocline area. Symposium International "Géodynamique andine", Grenoble, France. ORSTOM, Col. Colloques et Séminaires, pp. 167–170.

Sempere, T., Hérail, G., Oller, J. and Bonhomme M.G., 1990b. Late Oligocene-Early Miocene major tectonic crisis and related basins in Bolivia. Geology, 18: 946–949.

Sempere, T., Baby, P., Oller, J. and Hérail, G., 1991. La nappe de Calazaya: une preuve de raccourcissements majeurs gouvernés par des éléments paléostructuraux dans les Andes boliviennes. C.R. Acad. Sci. Paris, 312, (Sér. II): 77–83.

Sheffels, B.M., 1988. Structural constraints on crustal shortening in the Bolivian Andes. Ph. D., Massachusetts Institute of Technology, Cambridge, 170 pp. (unpubl.).

Sheffels, B.M., 1990. Lower bound on the amount of crustal shortening in the central Bolivian Andes. Geology, 18: 812–815.

Suppe, P., 1980. Imbricated structure of western foothills belt, southcentral Taiwan. Pet. Geol. Taiwan, 17: 1–16.