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Giant submarine collapse of a carbonate platform at the Turonian–Coniacian transition: The Ayabacas Formation, southern Peru

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ABSTRACT

The Ayabacas Formation of southern Peru is an impressive unit formed by the giant submarine collapse of the mid-Cretaceous carbonate platform of the western Peru back-arc basin (WPBAB), near the Turonian–Coniacian transition (∼90–89 Ma). It extends along the southwestern edge of the Cordillera Oriental and throughout the Altiplano and Cordillera Occidental over $>80\,000\,\text{km}^2$ in map view, and represents a volume of displaced sediments of $>10\,000\,\text{km}^3$. The collapse occurred down the basin slope, i.e. toward the SW. Six zones are characterised on the basis of deformational facies, and a seventh corresponds to the northeastern 'stable' area (Zone 0). Zones 1–3 display increasing fragmentation from NE to SW, and are composed of limestone rafts and sheets embedded in a matrix of mainly red, partly calcareous and locally sandy, mudstones to siltstones. In contrast, in Zones 4 and 5 the unit consists only of displaced and stacked limestone masses forming a 'sedimentary thrust and fold system', with sizes increasing to the southwest. In Zone 6, the upper part of the limestone succession consists of rafts and sheets stacked over the regularly bedded lower part. The triggering of this extremely large mass wasting clearly ensued from slope creation, oversteepening and seismicity produced by extensional tectonic activity, as demonstrated by the observation of synsedimentary normal faults and related thickness variations. Other factors, such as pore pressure increases or lithification contrasts probably facilitated sliding. The key role of tectonics is strengthened by the specific relationships between the basin and collapse histories and two major fault systems that cross the study area. The Ayabacas collapse occurred at a turning point in the Central Andean evolution. Before the event, the back-arc basin had been essentially marine and deepened to the west, with little volcanic activity taking place at the arc. After the event, the back-arc was occupied by continental to near-continental environments, and was bounded to the southwest by a massive volcanic arc shedding debris and tuffs into the basin.

INTRODUCTION

Mass-wasting processes are recognised as a major mechanism of sediment redistribution over continental margins, but how they are triggered is incompletely understood. Most giant submarine landslides have been described from the Recent on the basis of bathymetric and geophysical data (e.g. Collot *et al.*, 2001; Huvenne *et al.*, 2002; Haflidason *et al.*, 2004, 2005; Frey-Martínez *et al.*, 2005, 2006) but ancient examples of such phenomena are scarce (Martinsen & Bakken, 1990; Steen & Andresen, 1997; Payros *et al.*, 1999; Graziano, 2001; Floquet & Hennuy, 2003; Lucente & Pini, 2003; Vernhet *et al.*, 2006; Spörli & Rowland, 2007) and their anatomy has been rarely described at scales >100 km.

This paper deals with the Ayabacas Formation of southern Peru, an interesting rock unit that has received a puzzling variety of interpretations. Here, we confirm one of these by demonstrating that the unit was formed by the giant submarine collapse, at the Turonian-Coniacian transition, of a carbonate platform that had developed in the Andean back-arc basin during the Albian-Turonian interval. The unit mostly consists of millimetric to kilometric size limestone fragments and can therefore be described as a limestone megabreccia (*sensu* Spence & Tucker, 1997). In the northeastern half of the study area, these fragments are enclosed in reddish siltstones and mudstones reworked from the underlying stratigraphic unit, and rock fragments from older units also occur; only limestones are involved in the southwestern half.

The Ayabacas Formation forms a single mass-wasting body, which displays noteworthy internal facies variations. It irregularly crops out over $>60\,000\,\text{km}^2$ and is inferred to extend over more than $80\,000\,\text{km}^2$. Its thickness varies

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from 0 to ≥ 500 m, and its volume is estimated to be $> 10\,000$ km^3 ($> 10^{13}$ m^3). Although it is formed by a number of coalescent landslides, these can be clearly distinguished only in some cases. No undisturbed strata divide the Ayabacas Formation into subordinate sliding units. The Ayabacas collapse is ≥ 500 km in width and > 100 m in average thickness, and when compared with the published dimensions of mass-wasting bodies it plots at the far end of Lucente & Pini's (2003) compilation diagram. The Ayabacas thus appears as the most extensive ancient submarine mass-wasting body currently known, and one of the thickest. Its extension and thickness are of the same magnitude as the largest and thickest recent bodies described to date, e.g. the Storegga Slide (Haflidason *et al.*, 2004, 2005), the Bjørnøyrenna Slide (Vorren & Laberg, 2001), the Cape Fear Slide (Popenoe *et al.*, 1993), the Saharan Debris Flow (Gee *et al.*, 1999), the Israel Slump Complexes (Frey-Martínez *et al.*, 2005) or the Orotava-Icod-Tino Avalanche (Wynn *et al.*, 2000). Here, we focus on the age and anatomy of the Ayabacas Formation, and on the cause(s) of the collapse.

Absolute stratigraphic ages mentioned in this paper are taken from Hardenbol *et al.*'s (1998) chart unless specified otherwise. We use the abbreviation Ma (*mega-annum*) for a point in time, and Myr (millions of years) for a duration of time.

THE AYABACAS FORMATION IN ITS GEOLOGICAL SETTING

Location of the study area and basin architecture

The study area extends in southern Peru, along the southwestern rim of the Cordillera Oriental and throughout the Altiplano and Cordillera Occidental, including the Arequipa area (Figs 1 and 2). The number and extension of Ayabacas Formation outcrops decrease markedly toward the west-southwest due to an increasing cover of Neogene volcanic rocks and other deposits. No mid-Cretaceous limestone unit has been mapped so far immediately west and south of the study area.

The study area includes a few important Andean-age structural systems that have also controlled a number of depositional characteristics of the pre-orogenic accumulations, such as facies and thicknesses (Sempere, 1995; Sempere *et al.*, 2002a, b, 2004b, c; Pino *et al.*, 2004). In particular, Mesozoic subsidence has constantly been lower, and depositional environments shallower, northeast of the Urcos-Ayaviri-Copacabana-Coniri fault system (abbreviated as SFUACC in Spanish; Fig. 1), a major lithospheric boundary (Carlier *et al.*, 2005) that has behaved as a mainly sinistral fault system during the Andean orogeny (Sempere *et al.*, 2002b, 2004b; Sempere & Jacay, 2006, 2007). The Cusco-Lagunillas-Laraqueri-Abaroa structural corridor (abbreviated as CECLLA in Spanish; Fig. 1) is a broad structural system which separates two domains that behaved very distinctly during the Cenozoic and at least the Jurassic, more subsidence and a much deeper depositional environment being recorded west of the CECLLA (Sempere *et al.*, 2002b, 2004b). We provide evidence below that the SFUACC and CECLLA fault systems played a significant role during the Ayabacas collapse as they separate domains characterised by different facies distribution, subsidence, and depositional processes.

The Ayabacas Formation and underlying units were deposited in the southern region of the western Peru back-arc basin (WPBAB), which was active in the Jurassic and Cretaceous (Jaillard *et al.*, 1995). This basin had developed in an extensional tectonic context and deepened overall to the west. Subsidence was greatly enhanced in the mid-Cretaceous, starting in the Early Albian, as a consequence of the western WPBAB evolution toward a state of marginal basin in central Peru, due to considerable lithospheric thinning there (Casma sub-basin; Atherton & Webb, 1989; Atherton, 1990; Jaillard, 1994; and references therein). Myers (1974) proposed that the accumulation of > 2 km of eastward-tapering carbonates and marls during the Early Albian-Turonian interval ($\sim$109–89 Ma) east of the Casma sub-basin implied significant subsidence, which must have been facilitated by the ongoing lithospheric thinning. The edge of the continental domain, along which the Albian-Turonian carbonate platform developed, thus technically behaved as a kind of passive margin in relation to the much deeper Casma sub-basin to the west. To the south ($\sim$13–15°S), 1–2 km of calc-alkaline basalts and basaltic andesites interbedded with locally bituminous Albian marine strata were deposited in the southern extension of the WPBAB, which was narrowing in a southeastward direction (Atherton & Aguirre, 1992; Jaillard, 1994). A 'passive margin' setting similar to that in central Peru can thus be proposed for the carbonate platform in southern Peru, although lithospheric thinning was much less intense in this region.

Stratigraphy of southern Peru

The Mesozoic stratigraphy of southern Peru is summarised in Fig. 3 (see supplementary documentation online for details). Before the Ayabacas collapse, the Mesozoic units of southern Peru were deposited in a largely marine basin, with continental to shallow-marine facies in the northeast, and deeper water facies in the southwest and west. In contrast, the units younger than the Ayabacas Formation were deposited in an almost exclusively continental basin that was bounded to the southwest by topographic highs, apparently volcanic in nature. In particular, the Arcurquina Formation (and equivalent deposits) mostly consists of marine limestones, whereas the Lower Vilquechico Formation (and equivalents) is dominated by abundant red mudstones that testify to a continental or near-continental environment (Jaillard, 1995). In the Central Andean domain, away from the coast, true marine deposits are extremely rare afterwards. The Ayabacas Formation was thus deposited at the time when

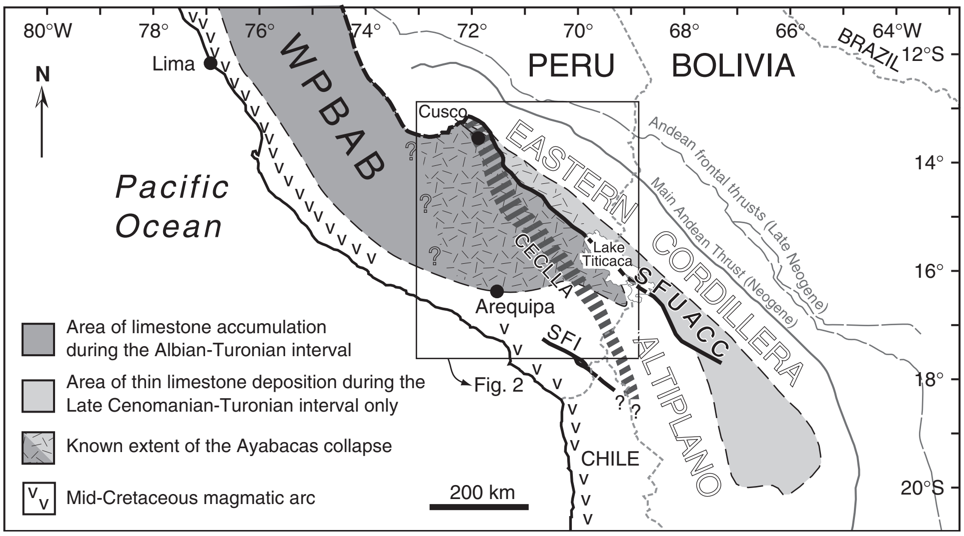

Fig. 1. Map of southern Peru and adjacent regions with elements relevant for Albian to Turonian times. Both shaded areas belong to the western Peru back-arc basin (WPBAB) which accumulated mostly limestones during this time interval. The Early and Middle Albian transgression is only recorded in the main basin (darker shading); the Late Cenomanian–Turonian transgression flooded this main basin and also the sub-basin located northeast of the SFUACC system (lighter shading). The Ayabacas collapse (irregular dashes) developed in the northwesternmost segment of this sub-basin, and in the southwestern part of the main basin. A magmatic arc was active along the present-day coastal belt, but, before the Coniacian, the region south of Arequipa was apparently devoid of volcanic activity as only plutons are recorded there. CECCLA, SFUACC: see text; SFI = Incapuquio fault system (Spanish abbreviation). Adapted from Jaillard & Sempere (1991), Jaillard & Arnaud-Vanneau (1993), Jaillard (1994), Sempere (1994), Jaillard *et al.* (1995), Sempere (1995), Sempere *et al.* (2002b, 2004b).

the south Peruvian basin underwent a dramatic and permanent change from marine to continental conditions.

Some units are particularly relevant to the Ayabacas issue:

- The Paleozoic basement is Ordovician to Devonian in age and mainly consists of dark shales intercalated with generally subordinate siltsones and sandstones.
- The Middle Jurassic Muni Formation (red mudstones and subordinate sandstones) grades into the Late Jurassic Huancané Formation s.s. (dominantly quartzose sandstones of fluvio-eolian origin), these two units forming a continental sedimentary system prograding toward the southwest.
- Some deformation affected the southern Peruvian basin at some time in the Early Cretaceous (and, possibly, Late Jurassic), in particular along the SFUACC system (Sempere *et al.*, 2002b, 2004b). This deformation produced local uplifts that led to partial to complete erosion of the Mesozoic succession, locally down to the Paleozoic basement. The resulting erosional surface was subsequently onlapped by the major mid-Cretaceous transgression. In the Arequipa area, this transgression is mainly recorded by the ~250 m-thick Arcurquina Formation. In the Altiplano, the ~100 m-thick transgressive stratigraphic set of late Early to middle Cretaceous age is formed by the Angostura (conglomerates and sandstones, occurring in specific areas), Murco (mainly red mudstones and siltstones) and Arcurquina (marine, regularly bedded, thickening-upward, grey to black, organic-rich micritic limestones; see section 'Age of the Ayabacas formation') formations, and onlaps the mentioned regional unconformity. Contacts between these units are gradational. Interstratified red mudstones and thin, grey to black limestones are typical of the rapid Murco-Arcurquina transition, as in the Arequipa area. In the Cusco area, the continental set formed by the Angostura and Murco formations is represented by the local Maras Formation (Carlotto *et al.*, 1996), which mainly consists of red mudstones and silstones, and evaporite masses (mainly gypsum; halite also occurs).
- The Ayabacas Formation, the object of this paper, consists of an extraordinarily deformed, chaotic unit reworking previous deposits and rocks. Although the Ayabacas and Arcurquina formations dominantly consist of limestones and occupy the same stratigraphic position, overlying the Murco Formation and underlying the Vilquechico Group and equivalent units, they must be formally distinguished since the Arcurquina was deposited in regular beds in a stable carbonate platform, whereas the Ayabacas resulted from the reworking of the Arcurquina and previous units: their deposition was therefore neither contemporaneous nor driven by similar processes. Owing to these markedly different depositional processes, they display distinct characteristics, which are obvious in the field.
- The Vilquechico Group (Late Campanian-Early Paleocene, ~700 m thick) post-dates the Ayabacas Formation and its typical deformation. Its equivalent in the Arequipa area is the $\leq$ 400 m-thick Ashua Formation (Cruz, 2002). A Coniacian ammonite from the Ashua Formation testifies that the Ayabacas-Ashua contact represents an interruption of the stratigraphic record of little time duration, if any. In contrast, the

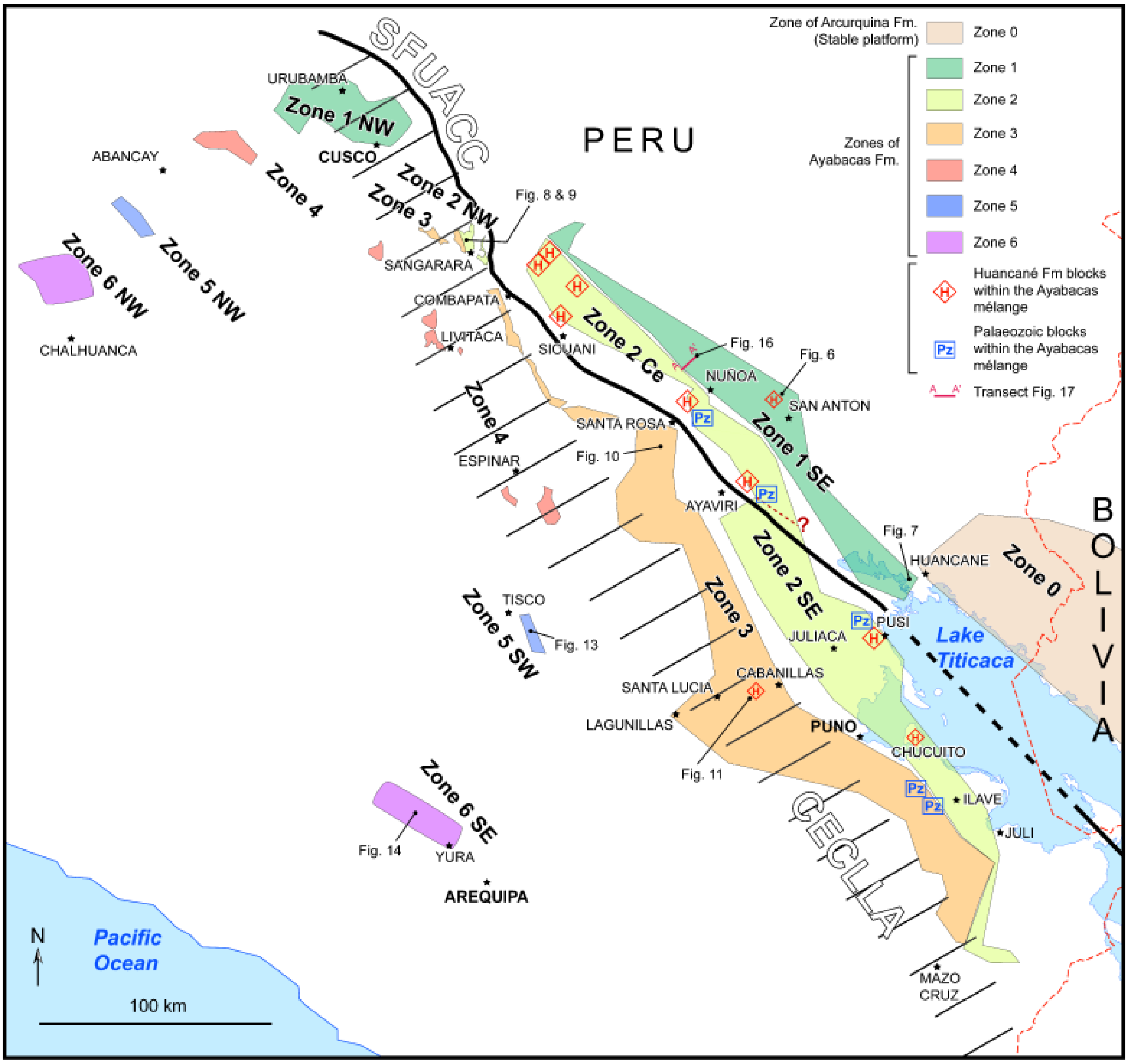

Fig. 2. Distribution of main deformational facies in the Ayabacas Formation, localities cited in text, and location of the SFUACC and CECLLA fault systems. According to deformational facies, outcrops of the Ayabacas Formation are distributed into six zones, numbered 1–6 (see details in the text). Zone 0 is formed by the Arcurquina Formation, i.e. the deposits of the stable carbonate platform. Pz and H indicate sites where massive blocks respectively derived from the Palaeozoic and Huancané Formation occur within the mélange; these sites are located near the SFUACC fault system, or near local normal faults (San Antón and Cabanillas). Note the NW–SE variations in zone width, in particular between northern (Cusco–Abancay–Chalhuanca) and southern (Huancané–Juliaca–Santa Lucía–Lagunillas–Yura) transects; see details in the text.

Ayabacas-Vilquechico contact, more to the north, apparently marks a ~5 Myr-long hiatus, during which some erosion must have occurred (Sempere *et al.*, 2002a, 2004a). However, the preservation of stromatolites at the very top of the Arcurquina Formation, east of Huancané, suggests that this hiatus may have been much shorter at least locally.

Stratigraphic and depositional characteristics of the Ayabacas formation

The Ayabacas Formation typically lacks internal stratification and presents a highly disrupted to chaotic aspect, in marked contrast with the underlying and overlying units. Its thickness is irregular but generally increases from a few metres in the northeasternmost sections, where it can be locally lacking, to ≥ 500 m in the west and southwest.

The Ayabacas mainly consists of mm- to km-size fragments of regularly stratified and/or folded limestones, mostly or entirely reworked from the Arcurquina Formation, and enclosed in a largely red-siltstone 'matrix' reminiscent of the Murco deposits (given their similar facies, presence of fragments of the Sipín limestones and involvement of Muni red siltstones cannot be excluded). Particularly significant is the frequent local occurrence of

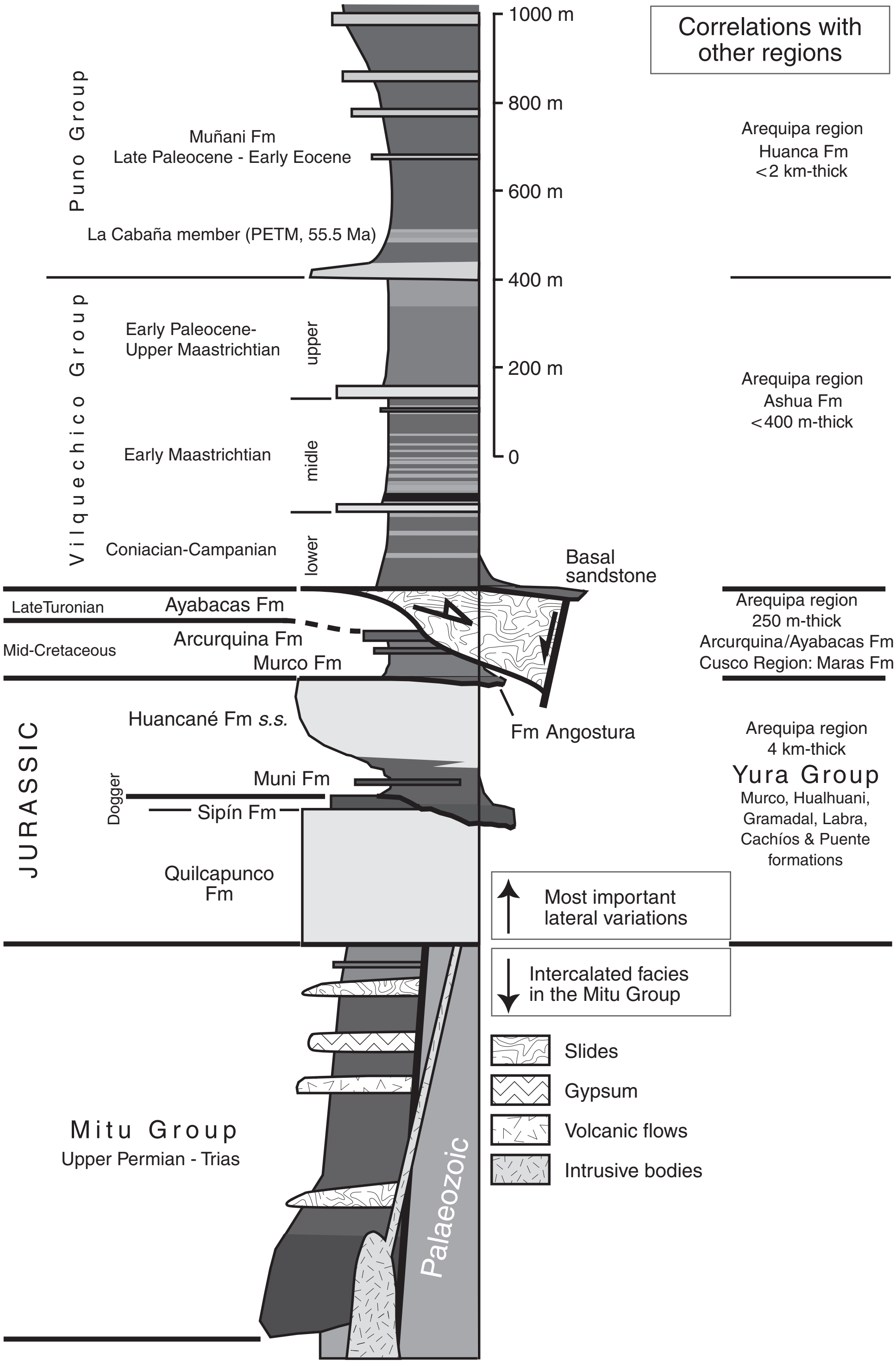

Fig. 3. Generalised Palaeozoic to Paleogene stratigraphic column in the Lake Titicaca region. Correlations with other areas are specified on the right. Thicknesses are approximate and subject to lateral variations. PETM = Paleocene-Eocene Thermal Maximum. Adapted from Sempere *et al.* (2004a).

fluidised sediments and breccias within the 'matrix'. In northeastern areas, lithified blocks of Huancané sandstones and Paleozoic shales are, respectively, commonly and locally observed. In specific areas, cm- to dm-size clasts of typical Mitu volcanic conglomerates are also found.

We underline that no undisturbed marine limestone strata occur either within or at the top of the Ayabacas Formation, which is directly overlain by reddish strata of mainly continental origin.

Age of the Ayabacas formation

A regional synthesis of the available information concerning the units that predate and postdate the Ayabacas Formation indicate that the collapse occurred near the Turonian-Coniacian transition, i.e. at ~90–89 Ma (see supplementary documentation online, and Callot *et al.*, 2007).

The Arcurquina Formation was deposited during two transgressive periods, which are also recorded in the more subsident northern Peruvian part of the WPBAB. The first transgression and highstand lasted from the middle Early to the late Middle Albian (~110–102 Ma; Hardenbol *et al.*, 1998). The Late Albian-Middle Cenomanian interval (~102–95 Ma, ~7 Myr) was characterised by a relative regression. The second transgression was initiated in the latest Middle Cenomanian (~95 Ma) and highstand lasted until the Late Turonian (~90–89 Ma). Only the second transgression reached areas northeast of the SFUACC system, where compacted depositional rates varied between 2.7 and 4.3 m Myr^{-1}, whereas in the Arequipa area they were ~20 m Myr^{-1} for the Early-Middle Albian interval, and ~28 m Myr^{-1} for the Late Cenomanian-Turonian interval. This contrast implies that subsidence was higher by one order of magnitude in the Arequipa area than northeast of the SFUACC, as suggested by the overall deeper and thicker facies in the former. Our chronostratigraphy confirms the recognition of the OAE-2 event in the lower part of the Arcurquina Formation in westernmost Bolivia (Graf, 2002; Graf *et al.*, 2003) and nearby Peru, where it is represented by an organic-rich mudstone layer referred to as the 'Nuñoa-1' level (Fig. 4; and supplementary documentation online).

The Vilquechico Group and Ashua Formation sharply postdate the Ayabacas collapse in the Lake Titicaca and Arequipa regions, respectively. These deposits dominantly consist of red mudstones and span the Coniacian–Paleocene interval (Jaillard *et al.*, 1993; Sigé *et al.*, 2004). A similar stratigraphic contrast is known in northern Peru, where the Turonian limestones are sharply overlain by ~300 m of reddish to brown mudstones and fine sandstones that were deposited in marine to non-marine environments from the Early Coniacian to the Middle Campanian. This noteworthy discontinuity is thought to reflect the onset of aerial erosion in western areas throughout the Central Andes (Jaillard, 1994; Sempere, 1994). As indicated by ammonite faunas in northern Peru, this sharp change from carbonates to reddish mudstones occurred approximately at the Turonian–Coniacian transition. Because the Ayabacas Formation post-dates the termination of the carbonate platform and pre-dates the onset of red mudstone deposition, it coincides with this change. The Ayabacas collapse is thus likely to have also occurred near the Turonian–Coniacian transition (~90–89 Ma).

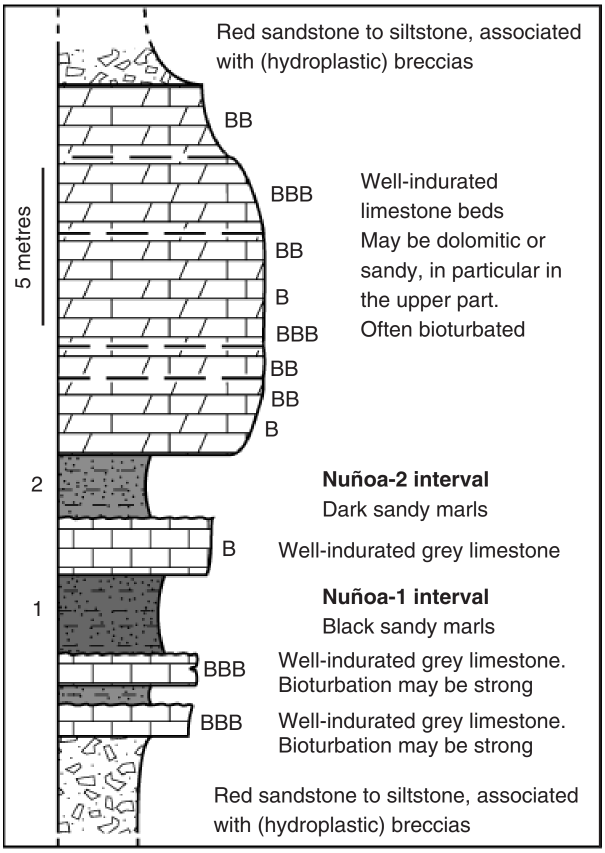

Fig. 4. Standard section of limestone blocks in Zone 1. Stratigraphic sections from San Antón (Pacuta and Coñejuno), Yanaoco, Nuñoa (Antacalla), Larimayo 1 and 2, and Cusco, are shown. Thicknesses are used in Table 1 (see supplementary documentation online). Nuñoa-1 and Nuñoa-2 mudstone levels may include limestone fragments derived from the brecciated base of the overlying limestone bed. Minor lateral facies variations occur: the three beds underlying the Nuñoa-1 interval cannot be distinguished everywhere; the limestone bed between the Nuñoa-1 and Nuñoa-2 intervals is locally missing (e.g. in San Antón).

ONE DISRUPTED UNIT, A VARIETY OF INTERPRETATIONS

Previous descriptions of the Ayabacas Formation, and conflicting interpretations

This intriguing unit was first described as the Ayavacas [*sic*] Formation by Cabrera La Rosa & Petersen (1936) from the outcrops near the namesake village located ~10 km northeast of Juliaca; spelling was later corrected to Ayabacas by Sempere *et al.* (2000) to be in conformity with the official local toponymy. The first studies were mainly limited to the area formed by the Pirín, Ayabacas and Pusi localities, due to the existence of a small oil field. Because Rassmuss (1935) and, more precisely, Cabrera La Rosa & Petersen (1936), authors have wondered about the amazing peculiarities of these deeply disturbed limestones (Heim, 1947; Newell, 1949; Kalafatovich, 1957; Portugal, 1964, 1974; Audebaud & Laubacher, 1969; Chanove *et al.*, 1969; Audebaud, 1970, 1971a, b; Audebaud & Debelmas, 1971; Audebaud *et al.*, 1973; De Jong, 1974; Laubacher, 1978; Green & Wernicke, 1986; Klinck *et al.*, 1986; Ellison *et al.*, 1989; Moore, 1993; Carlotto *et al.*, 1992, 1996; Jaillard, 1994; Sempere *et al.*, 2000; Carlotto, 2002). Newell (1949) eloquently described these peculiarities, highlighting that the unit is intricately folded and faulted, in extreme disorder, in so far that it may form a nondescript mass of red shales and large limestone blocks; complex masses of deformed limestone are locally violently disturbed; beds may form intricate isoclinal to recumbent folds, and locally they '*are oriented in every conceivable position with numerous duplications of the same strata in every hillside*'. Newell (1949) also described fragments of older units involved in the Ayabacas Formation, and emphasised that the formation displays a '*very characteristic*' deformation that contrasts with the underlying and overlying units.

However, although descriptions of the Ayabacas Formation have been generally similar, interpretations have divided between tectonic and gravitational processes, and, among the latter, between subaerial and submarine sliding (discussed below).

Compressional tectonic interpretations, and why they are untenable

The first work concerning the Ayabacas Formation was produced by Rassmuss (1935), who described the limestone unit as a chaotic formation and suggested a tectonic explanation for its disrupted aspect. Heim (1947) and Newell (1949) both observed multiple repetitions of stratified limestone blocks and interpreted them as the result of Andean tectonics. Audebaud (1967) wondered whether early mass sliding might have been partly responsible for the deformation, but considered that the deformation was mainly of tectonic origin (Audebaud & Laubacher, 1969; Audebaud, 1970, 1971a, b; Audebaud & Debelmas, 1971; Audebaud *et al.*, 1973), locally complicated by early karstification (producing the noteworthy breccias mentioned below), gypsum diapirs, and hypovolcanic intrusions (Audebaud, 1971a). In the Pirín area (SW of Pusi), Chanove *et al.* (1969) interpreted the Ayabacas Formation as a piling-up of tectonic nappes.

The observed deformation has however a markedly 'soft' aspect and is hardly compatible with tectonic processes. Tectonic thrusting and folding would have produced typical features, such as slickenslides and striated faults, oriented tectonic breccias, cleavage, and/or pervasive calcite veining. But all of these elements are missing. Away from Andean structures, faults in limestone blocks neither display calcite slickenslides nor are they striated. Limestone blocks are piled up without signs of tectonic thrusting, as noted by Heim (1947) and Portugal (1964, 1974). Limbs of recumbent folds are generally unthinned (Portugal, 1964, 1974), suggesting a low overlying load during folding (Audebaud, 1967). Contrary to what is expected in the case of tectonic phenomena, orientations of folds and faults in the Ayabacas Formation are usually extremely variable at each locality (Fig. 5a).

It is also noteworthy that the grade of deformation in the Ayabacas Formation decreases toward the Eastern Cordillera, i.e. in the direction of increasing Andean deformation. Andean folding and faulting has very generally developed at much larger scales than the Ayabacas deformation. As underlined above, the Ayabacas Formation contrasts greatly with the underlying and overlying units, which have similar bedding attitudes at each locality and have generally been only tilted by Andean deformation at the outcrop scale. Furthermore, in all visited localities, the basal and top contacts of the Ayabacas Formation are evidently stratigraphic, not tectonic.

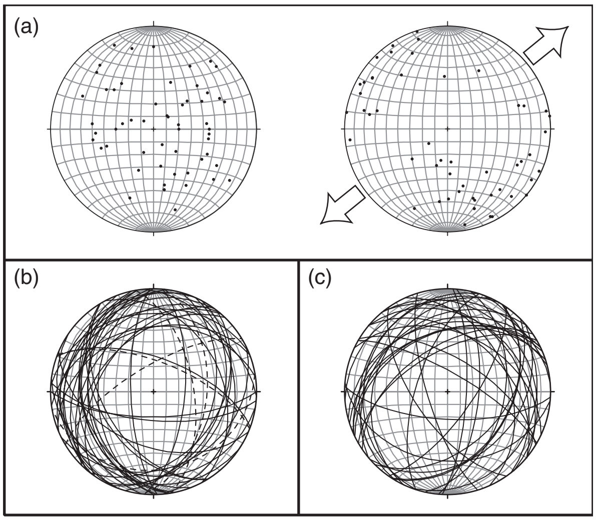

Fig. 5. Schmidt stereonets (lower hemisphere) of data from Zones 2 and 3. (a) Fold axes in rafts ($N = 52$) in the Ilave-Juli (left), corrected (right) for tectonic tilting (using underlying and/or overlying units). Scattering is evident before correction, implying that deformation was not produced by orogenic shortening. A ~NW–SE preferential orientation becomes apparent after correction, suggesting sliding occurred to the NE or SW. (b) Bedding attitudes of rafts (solid lines, $N = 35$) and Huancané blocks (dashed lines, $N = 5$) dispersed in the mélange in the Pusi area, where Chanove *et al.* (1969) interpreted the unit as resulting from the piling up of tectonic nappes. Their random distribution is not compatible with orogenic tectonics. (c) Bedding attitudes of Palaeozoic rafts in the Ayabacas mélange, from a ~3 km^2 area ~15 km south of Chucuito ($N = 34$); their random distribution confirms they are elements in a sedimentary mélange, and not the result of tectonic deformation.

All these observations are compelling evidence against any idea that the Ayabacas deformation results from large-scale Andean tectonic deformation.

Subaerial gravity sliding: also untenable

De Jong (1974) published interesting descriptions of the Ayabacas Formation in the Puno-Juliaca area and rightfully criticised Newell's (1949) and Chanove *et al.*'s (1969) tectonic interpretations. However, he favoured that the unit resulted from subaerial sliding in the mid-Cretaceous, drawing a comparison with the Amargosa Chaos in Death Valley, western USA. Laubacher (1978) discussed the diverse interpretations published at that time, and concluded that both Chanove *et al.*'s (1969) and De Jong's (1974) interpretations were warranted. Klinck *et al.* (1986) and Ellison *et al.* (1989) also favored subaerial gravity sliding, but of Late Neogene age.

Green & Wernicke (1986) and Moore (1993) claimed that the Ayabacas Formation was a continental collapse produced in the Late Miocene by large-magnitude crustal extension, caused by the gravitational spreading of the overthickened Andean crust. They mapped low-angle detachments at the base of the Ayabacas Formation, and estimated that they accomodated 10s of kilometers of extension. They agreed with De Jong's (1974) observations of similarities between the Ayabacas Formation and the Amargosa Chaos.

A subaerial sliding interpretation is precluded, however, by the abundance of plastic, soft-deformation features, hydroplastic breccias and fluidised sediment facies. The fact that the Ayabacas deformation is regionally postdated by Late Cretaceous strata precludes any Neogene process as its cause. Interpretations by Klinck *et al.* (1986), Green & Wernicke (1986), Ellison *et al.* (1989), and Moore (1993) are contradicted by the fact that the base of the Ayabacas Formation is clearly not a tectonic contact, at any locality visited by us.

It is interesting that the Ayabacas could be interpreted as the product of contractional tectonics by some authors and of extensional tectonics by others. In particular, the same area of Pirín (southwest of Pusi) has been mapped as a piling-up of contractional nappes by Chanove *et al.* (1969) and as structured by low-angle normal faults, interpreted to express ≥ 5 km of extension, by Green & Wernicke (1986) and Moore (1993). In addition to the fact that key characteristics have been overlooked, such contrasts in interpretations are intriguing.

Evidence for submarine sliding

Cabrera La Rosa & Petersen (1936) were the first to precisely describe the Ayabacas Formation. In particular, they noted that generation of its typical limestone breccias could not be explained by any tectonic deformation, and proposed instead that submarine sedimentary processes were responsible for their facies and the overall disruption displayed by the unit. Although the notion of submarine mass wasting was largely ignored at that time, these authors reached conclusions close to modern models, understanding that limestone strata had been fragmented before their lithification and that brecciation had occurred 'on the sea bottom', probably due, in their mind, to a tsunami-triggered instability.

Portugal (1964, 1974) was the first to clearly identify, in the Puno-Santa Lucia area, that the Ayabacas Formation was the result of submarine mass wasting, toward the southwest, necessarily on a slope, and that sliding had possibly been facilitated by the underlying red mudstones; among other features, he emphasised that the chaotic distribution of limestone blocks was evidence that they had moved independently from one another, and that deformation preserved unthinned limbs and produced no cleavage.

In the Cusco area, Carlotto *et al.* (1992, 1996) re-interpreted the intriguing disruption displayed by Kalafatovich's (1957) Yuncaypata Formation as a result of synsedimentary deformation, and identified this unit as the local expression of the Ayabacas Formation. The pecularities and size of this formation in southern Peru were underlined by Sempere *et al.* (2000), who recognised again that the unit, best described as a limestone megabreccia, resulted from submarine sliding.

In the northeastern half of the study area (Zones 1–3 as defined below), the Ayabacas Formation generally has a chaotic appearance (Fig. 5b). The limestones are highly disturbed, folded, disrupted, fragmented and brecciated (e.g. Newell's (1949) description above). When folded, limestone strata yielded plastically, and are deformed without cleavage. Other evidence of soft-deformation includes: slumps, fluidised sediments, hydroplastic breccias, clastic and/or mud dykes. Limestone blocks are often chaotically distributed, and have clearly moved independently from one another. All these characteristics are strongly indicative of gravitational submarine deformation, especially as shown by 3D seismic images of recent landslides (e.g. Collot *et al.*, 2001; Huvenne *et al.*, 2002; Frey-Martínez *et al.*, 2005, 2006), and confirm the interpretation of the Ayabacas Formation as a giant submarine mass-wasting body.

ORGANISATION OF THE AYABACAS COLLAPSE INTO DEPOSITIONAL ZONES

Distribution of deformation facies characterises depositional zones

Restriction of previous studies to limited areas has obviously hampered accurate and precise interpretations of the intriguing Ayabacas deformation. Here we attempt to understand the collapse as a whole, i.e. over its entire known extension. Such a large-scale vision of the basin consolidates the interpretation of the Ayabacas Formation as the collapse of a major part of the regional Albian-Turonian carbonate platform.

The Arcurquina Formation, which marks the parts of the platform that were not destabilised, mainly occurs in the eastern part of the basin. The Ayabacas Formation characteristically occurs in all localities WSW of this area. Six different zones are characterised on the basis of the deformational facies exhibited by the Ayabacas Formation (Fig. 2), and a seventh corresponds to the northeastern 'stable' area. Facies evolve progressively from Zones 1 to 3, and from Zones 4 to 5. In contrast, sharp facies differences separate Zone 3 from Zone 4, whereas Zone 5 is somewhat distinct from Zone 6 in some aspects.

Zone 0: Northeastern, undisturbed part of the platform

In Peru, the Arcurquina Formation is entirely preserved northeast of Lake Titicaca (Figs 1 and 2), where it is <25 m-thick and overlies the red mudstones and siltstones of the Murco Formation. The Arcurquina Formation displays lagoonal to supratidal facies; bioturbation is often intense in the former. East of Huancané, the very top of the unit exhibits numerous stromatolites which have been buried by the overlying red mudstones (Lower Vilquechico Formation). This unit is neither fragmented nor folded and there is no indication of soft-sediment deformation, testifying to the stability of this part of the basin during the Ayabacas collapse.

Zone 1: Gravitational sliding, folding and thrusting of rafts and sheets

Zone 1 is entirely located northeast of the SFUACC. In this zone, the Ayabacas Formation displays synsedimentary deformation of diverse intensity. It consists of a mélange of limestone blocks and a mainly red, partly calcareous and locally sandy, mudstone to siltstone matrix, sometimes turning to yellow near the limestone masses. The unit is very variable in thickness: locally, the Vilquechico Group directly overlies the Huancané Formation and the Ayabacas and Murco formations are totally absent; in other areas, the Ayabacas Formation consists of a chaos of limestone rafts and folded strata floating in the red matrix, whose thickness can be over several hundreds of metres.

In Zone 1, the unit mainly consists of limestone sheets or rafts 'floating' in the red matrix. These sheets and rafts are generally ≤ 20 m-thick, fairly reflecting the depositional thickness before the collapse when compared with Zone 0, and clearly exhibit the same internal stratigraphy (Fig. 4). Although relatively thin, the sheets display a fair to excellent lateral continuity, ranging from 40 m (raft-type end-member) to over several kilometres (sheet-type end-member, as observed in aerial photography). These limestone rafts can overlap each other and form stacks of two or more elements separated by breccias and red marly siltsones (Fig. 6). Some rafts are strongly folded; folds are generally asymmetric and recumbent, rarely with thinned limbs, and without any cleavage (Portugal, 1964, 1974; Audebaud, 1967; De Jong, 1974; Sempere *et al.*, 2000). Although a large-scale organisation is generally evident in aerial photographs, the folds are chaotically organised at the outcrop scale. Orientation of fold axes is variable, but folds are generally NE- or SW-vergent, indicating that sliding occurred in opposite directions. Along with evidence for synsedimentary normal faulting, this suggests that opposite slopes were locally created by tectonic tilting of the substratum.

The base of the standard stratigraphic section (Fig. 4) of these rafts and sheets consists of two (or sometimes three) 0.5–3 m-thick lithified limestone beds that display incipient hard-grounds at their tops. These limestones are separated by two to three darker and marlier beds (the Nuñoa-1 and Nuñoa-2 intervals, and a lower, similar, ~0,5 m-thick bed; see supplementary documentation online for details) that may include limestone fragments derived from the brecciated base of the overlying limestone; this brecciation apparently developed at the interface between the two lithologies through injection of the unlithified mudstones into the already partly lithified limestones. An 8–14 m-thick set of limestone beds forms the upper part of the section and is often highly bioturbated. Bioturbation affects all beds, with among-block vertical and lateral variations, but ranges from very intense to nearly absent.

Other breccias, generally hydroplastic in origin, are frequently observed at the bases and tops of rafts and sheets (they are particularly well-exposed at Yanaoco, ~8 km WSW of Huancané, with abundant fluidised sediments, and randomly oriented clastic and/or mud dykes). In good outcrops, the matrix that usually separates rafts and sheets

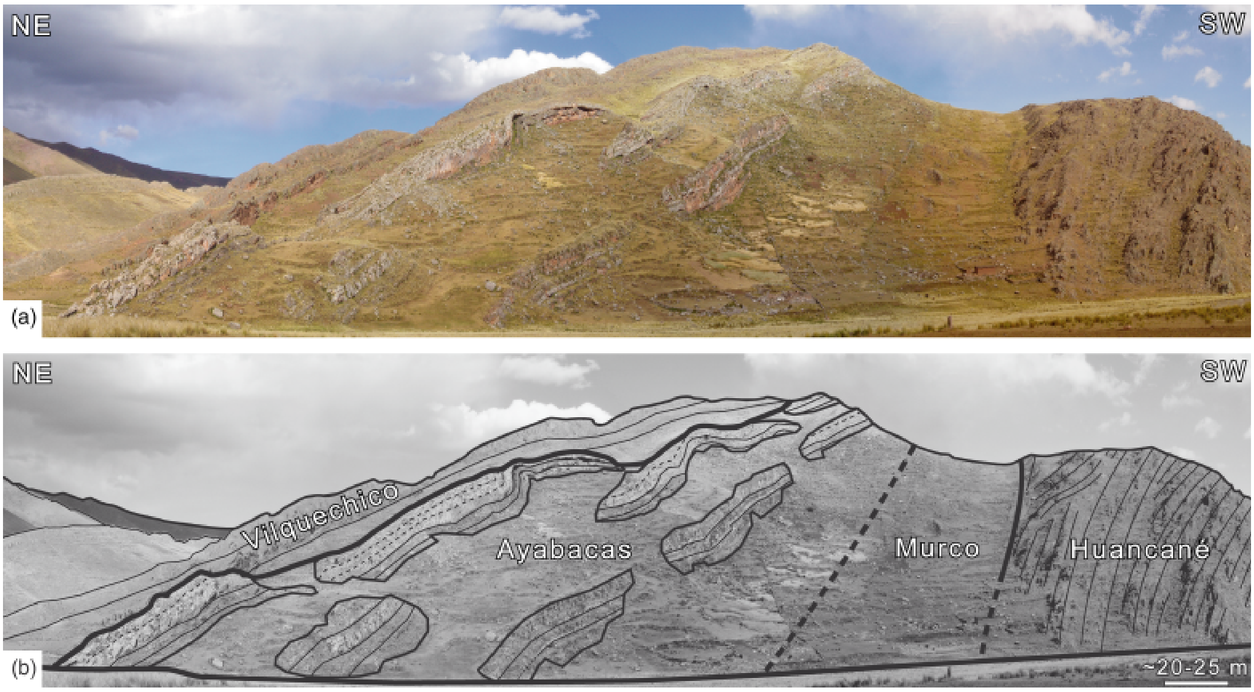

Fig. 6. (a) Deformation typical of Zone 1 near Larimayo (~9 km NNW of San Antón, UTM 0354876–8396892–4081 m, Zone 19L). Limestone rafts (interpretative outline highlighted in (b) 'float' in a matrix of siltstones and hydroplastic breccias and overlap each other with some gentle folding. Stratigraphic sections from each raft (Fig. 4) are identical. The Ayabacas Formation is underlain by the Huancané Formation (SW) and overlain by the Vilquechico Formation (NE), which includes here its basal sandstone member (Fig. 3); both units have been only tilted by Andean tectonics, very unlike the Ayabacas Formation.

appears itself as a breccia of red to locally yellow marly siltstones, and includes clearly fluidised sediments (Fig. 7). Clasts are of mm- to m-size and somewhat heterogeneous in nature, usually from surrounding limestone blocks; reddish and yellowish sandstones are also found. Clastic and mud dykes partly or completely intersect some limestone blocks, and others commonly cut across breccias within the matrix.

Two sub-zones, one limestone-rich and the other limestone-poor, are respectively distinguished in the SE (from Huancané to Sicuani) and NW (Cusco-Urubamba area) parts of Zone 1 (Fig. 2). The NW part of Zone 1 displays a peculiar large-scale facies characterised by sporadic (either isolated or concentrated in limited areas), chaotic limestone blocks dispersed within large stretches covered by the Maras Formation, which is the local equivalent of the Murco Formation and consists of red calcareous siltstones and subordinate gypsum and halite bodies. The presence of evaporites beneath thin carbonate deposits is likely to have favoured sliding, and facilitated larger displacements of limestone sheets, rafts and blocks during the collapse (Vendeville & Cobbold, 1987; Demercian *et al.*, 1993; Spathopoulos, 1996; Brun & Fort, 2004; Gradmann *et al.*, 2005). The sporadic occurrence, and thus rarity, of limestone blocks in this area is explained by their massive removal toward the SW, due to a regional facilitation and enhancement of sliding by the evaporite horizons that underlay the carbonate platform.

Zone 2: Chaotic melange of commonly strongly folded rafts

Zone 2 forms a strip running from the southern (Juli, Ilave) and western (Pusi, Juliaca) shores of Lake Titicaca, to Sangarara through Santa Lucía and Sicuani. Three sub-zones are distinguished, respectiveley in the SE, centre (sub-zone 2Ce), and NW (Fig. 2). Sub-zones 2SE and 2NW are located southwest of the SFUACC system and exhibit very similar facies; in contrast, sub-zone 2Ce is located northeast of the SFUACC and displays somewhat different facies. No sharp boundary separates the adjacent zones 1 and 2; the change in deformational facies is transitional, in particular between Zone 1 in the northeast and sub-zones 2SE and 2NW in the southwest. In the three sub-zones, and in particular in sub-zone 2Ce, the Ayabacas Formation is on the whole thicker than in Zone 1. Its thickness varies generally rapidly, from locally 0 m to > 400 m.

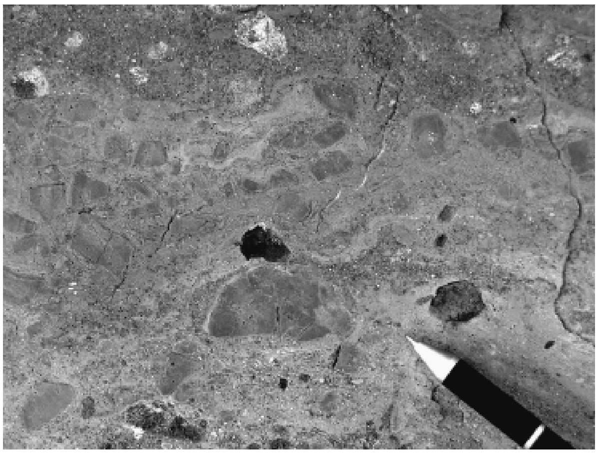

Fig. 7. Fluidised sediments in Zone 1, near Yanaoco (~8 km WSW of Huancané). Real size of the picture is ~14 × 10.5 cm. Note the cm-sized limestone clasts, tilted and floating in a fluidised matrix of marly–sandy sediments.

Limestone rafts are similar to those in Zone 1, but sheets are less common. They are thicker, generally about 20–30 m, suggesting that subsidence had been higher in their source area during initial deposition of the Arcurquina Formation. The limestones are often very bioturbated, in particular at their stratigraphic top. A majority of rafts in sub-zones 2NW and 2SE exhibit a somewhat similar internal stratigraphy, albeit less markedly than in Zone 1. The internal stratigraphy of rafts usually differs from that recorded in Zone 1 in that limestone beds are thicker and more frequently separated by marly interbeds. As in Zone 1, rafts are wrapped in a red calcareous siltstone to mudstone matrix. Hydroplastic breccias are also found, although less commonly than in Zones 1 and 3.

In sub-zones 2SE and 2NW, limestone rafts (and sheets) are more folded and fragmented than in Zone 1 (Figs 8 and 9). However, their lateral continuity remains significant, and is generally over a few hundreds of metres. Sheets appear to have been fragmented into discontinuous successions of rafts that can generally be followed over a few kilometres in aerial photographs (Fig. 8). Outcrops are also locally particularly chaotic and fragmented, notably near Uyuccasa (E of Mazo Cruz) at the southeastern end of the zone, and near Sangarara in the northwestern end of the zone.

Deformational facies in sub-zones 2SE and 2NW closely resemble that in Zone 1. The similitude of facies and the presence of recumbent folds with a majority of ENE and WSW vergences suggest that these sub-zones behaved similarly to Zone 1 during the collapse. We thus assume that a sliding mechanism in two opposite directions was also active in Zone 2, pointing to the creation of local opposite slopes by tectonic tilting of the substratum.

Sub-zone 2Ce, i.e. the part of Zone 2 located northeast of the SFUACC, is characterised by the occurrence of large and massive blocks of older units (Huancané Formation, Palaeozoic rocks) within the Ayabacas mélange, in association with the usual limestone rafts. These blocks are locally abundant, and such concentrations of displaced older units have no known equivalent in any other part of the study area. They are variable in size, but on the whole clearly larger and thicker than limestone rafts in sub-zones 2SE and 2NW, exceeding 100 s of m in length and 10 s of m in thickness. They form rigid rafts that are generally much more massive than the limestone rafts; unlike the limestone rafts, they are not affected by folding, although they locally exhibit incipient bending. They must therefore have been already fully lithified at the time of collapse. Internal cross-stratification in sandstone rafts shows that

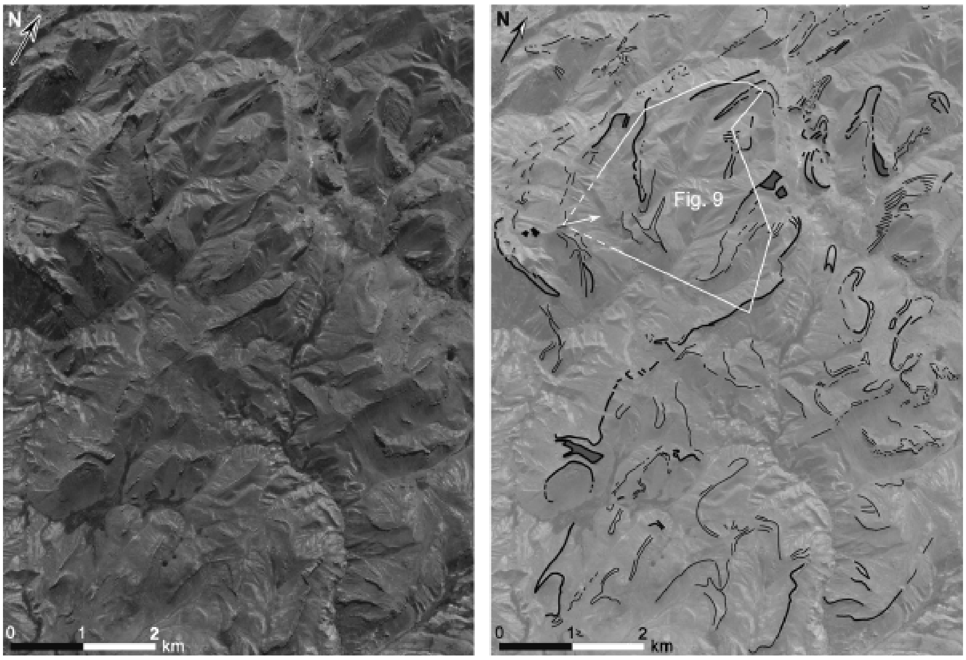

Fig. 8. Aerial photo of Zone 2 typical large-scale facies north of Sangarara, and interpretative outline of its folded rafts. Sheets, although folded and fragmented into rafts, can still be recognised (see text).

some of them are upside down. Their distribution is chaotic to the point that clear orientations appear neither in the field (Fig. 5c) nor in aerial photographs. The only exception is provided, in some of these rafts, by a regularly spaced and regularly oriented fracturation that developed at a ~30–40° angle with the raft sole, revealing the sense of displacement of the rigid mass.

The abundance and huge size of Early Cretaceous-Jurassic and Paleozoic olistolites in sub-zone 2Ce imply that these older units were being exposed to catastrophic erosion, down to the Paleozoic basement, in a nearby area. This could only be achieved by the creation and subsequent collapse of a major fault scarp in the vicinity of sub-zone 2Ce.

Zone 3: Chaotic mélange of more fragmented limestone blocks

Deformational facies in Zone 2 transitionally grade into those in Zone 3, to the point that they are often difficult to distinguish, particularly in the southeast. Here, the Ayabacas Formation generally consists of a mix of limestone blocks, 10–100 s of m in size, enclosed in a matrix of red mudstone and siltstone including a large amount of fluidised sediments and hydroplastic breccias. Good outcrops are found north of Mazo Cruz; south of Ilave and Puno; in the Cabanillas-Santa Lucía-Lagunillas area; south of Santa Rosa, Sicuani and Combapata; and in the Sangarara area. The thickness of the unit is difficult to measure due to the fact that its stratigraphic base and/or top are rarely exposed, and due to the gentle relief in this area. Thickness is however estimated to be approximately 500 m, and appears variable as in other zones.

Maximum stratigraphic thickness of limestone blocks increases in Zone 3 to reach 30–40 m, but blocks can also be ~20–25 m-thick as in Zone 2. However, blocks are much more fragmented, and rarely display significant lateral continuity. At Cabanillas a ~25 cm-thick stromatolitic bed locally duplicated by minor thrusts during the sliding is observed in the lowermost part of the unit, below the main wasting body, indicating that facies deposited in a supratidal environment during the early stage of transgression were here involved in the collapse. Folded blocks are rare, in contrast with Zone 2 (Figs 10 and 11). Although blocks are generally roughly oriented ENE-WSW, some outcrop areas are strongly disorganized (for example SW of Juli-Ilave, as shown by the disparate orientation of the fold axes in Fig. 5a).

Zone 3 is particularly rich in sedimentary breccias, the abundance of which varies in all outcrops. The breccias consist of a mix of red and yellow marly and sandy mudstones to siltstones, locally fluidised, and heterogeneous angular clasts derived from the Murco and Arcurquina formations, and less frequently from the Angostura Formation; all facies known in the Arcurquina Formation are represented; cm- to dm-size rounded clasts of the Triassic Mitu Group occur in breccias 13 km west of Santa Rosa. Limestone clasts are of mm- to m-size, but grade into stratified blocks that can be up to 10–100 s of m in size. Breccia clast shapes often indicate that they were produced by fracturing under an isotropic state of stress (Cosgrove, 1995). Some outcrops reveal that injection of fluidised breccia into a more lithified block locally split the limestone and fragmented it into clasts that were incorporated into the breccia.

The outcrops along the Cabanillas-Santa Lucía road are impressively rich in breccias. They are clearly associated here with a series of normal faults affecting the substratum (including here the Angostura Formation). They exhibit heterogeneous masses mixed with sedimentary breccias, on the whole up to 100 m-thick (but the top does not crop out). These masses are derived from the

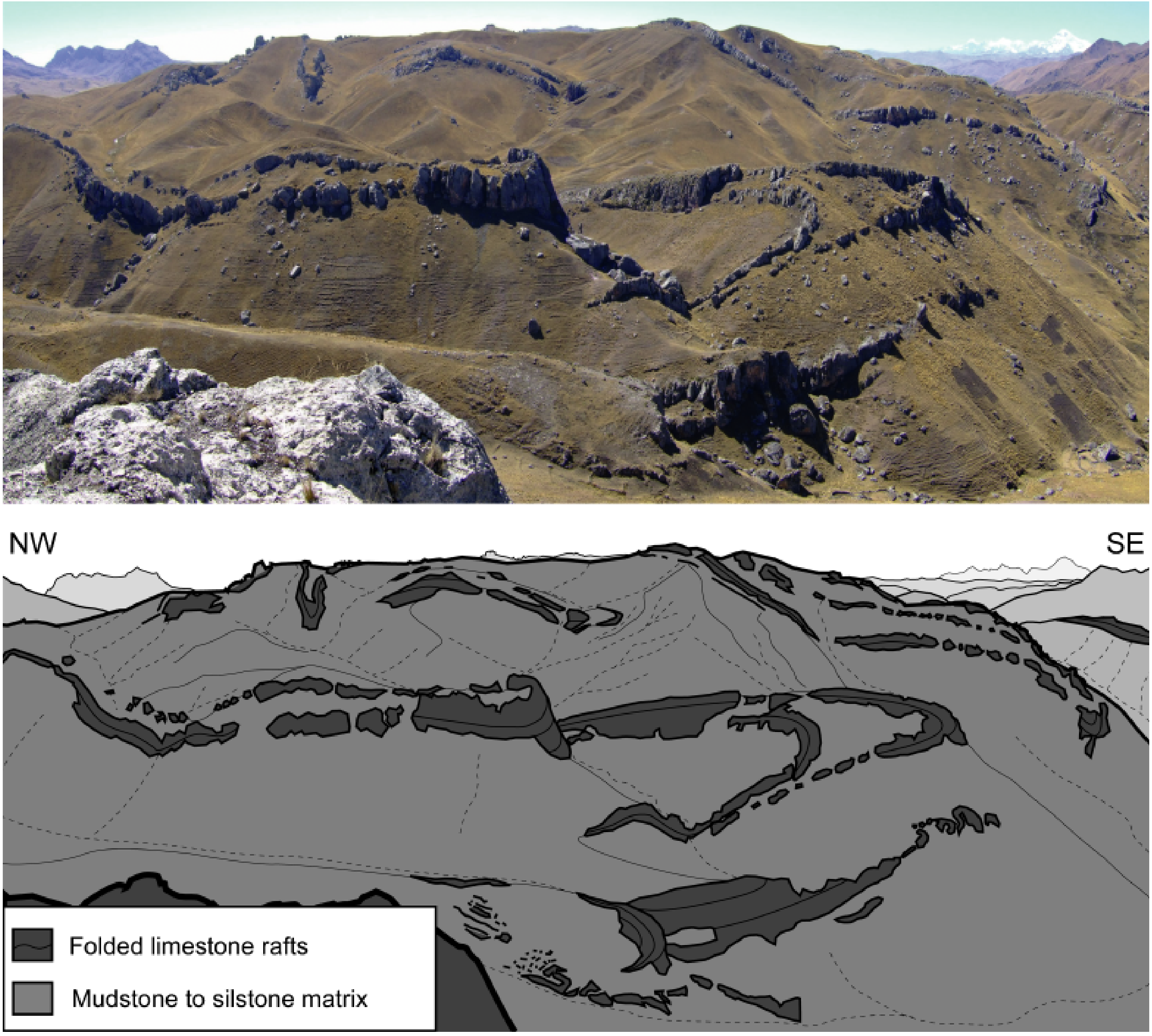

Fig. 9. Field view (looking towards N40) of the Ayabacas Formation in area depicted in Fig. 8 (Zone 2, north of Sangarara, UTM Zone 19L 0215394/8461415, 4377 m elevation). Shaded areas highlight fragmented and plastically folded limestone rafts. This Zone 2 outcrop is somewhat atypical in that the rafts are relatively thin (~20 m).

Arcurquina Formation, and less frequently from the Angostura Formation.

Zone 4: Rafts associated with stratabound breccias

The Ayabacas Formation crops out rather poorly in Zone 4, mainly around Yauri (Espinar) and Livitaca, and, badly, NE of Abancay (Fig. 2). Zone 4 is located ~15–20 km southwest of Zone 3, mainly within the CECLLA structural corridor, and exhibits a number of markedly distinct features. Owing to the gentle relief and to extensive covering by younger rocks, outcrops generally have a limited extent, making difficult to define characteristic deformational facies, as well as a precise measurement of its thickness (estimated to be at least a few 100s of meters).

In marked contrast with Zones 1–3, red mudstones to siltstones are extremely rare in the Ayabacas Formation of Zone 4. The unit almost exclusively consists of < 40 m-thick stacked stratified limestone rafts separated by, and including, limestone breccias (Fig. 12). The only observable features are these stacked rafts, as well as recumbent folds and slumps. Their horizontal dimensions generally vary between 1 and 500 m. At a larger scale, the unit appears less chaotic than in previous zones due to the absence of red mudstones (limestone blocks do not stand out in relief) and because the rafts are more regularly piled up.

At Livitaca, many beds within these rafts consist of breccias. In all of Zone 4, the matrix of these breccias is calcareous, not argillaceous (in contrast with previous zones), and their clasts are almost exclusively composed of limestones (displaying different facies), limestones with calcite veins, and calcite. As usual in the Ayabacas Formation, clast size varies considerably, from < 1 mm to several metres. As in previous zones, their shapes indicate that

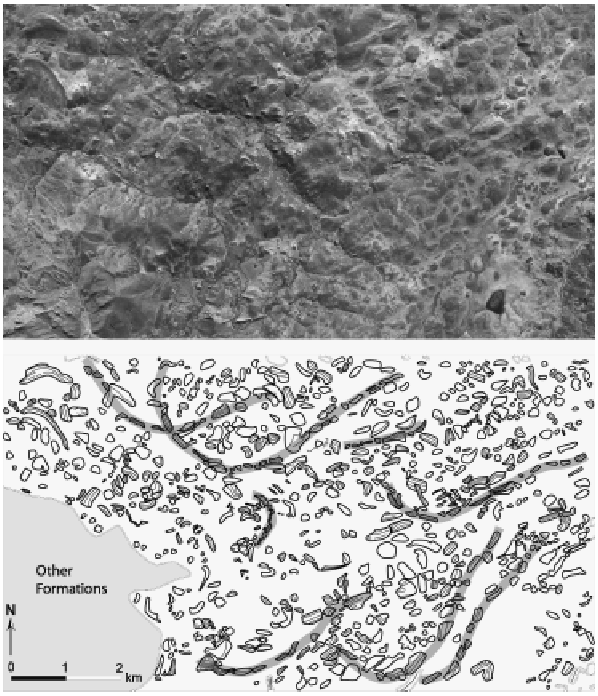

Fig. 10. Aerial photo in Zone 3 SW of Santa Rosa and interpretative outline of rafts and possible slide lobes. Raft thicknesses and fragmentation is higher than in Fig. 8 (Zone 2). There is almost no organisation, although some $\sim$SW-ward slide lobes may be detected (highlighted in light grey). This view markedly resembles Huvenne *et al.*'s (2002) Fig. 3.

they were initially fractured by hydrostatic stress. Some breccias or parts of breccias were clearly fluidised and locally even show fluid motion (e.g. in Fig. 12).

In contrast with Zone 3, the breccias locally include clasts of calcite and of calcite-veined limestones. In some limestone rafts, fluidised-sediment dykes may cut calcite veins. These observations demonstrate that calcite veining developed quite early in the diagenesis, before the Ayabacas collapse.

Zone 5: Chaotic mélange of very large rafts and sheets

This zone is defined by two main outcrop areas: SW of Abancay, and around the pass $\sim$14 km SE of Tisco (7 km WSW of the Condoroma dam at Lago del Colca) in the Western Cordillera (Fig. 2). In Zone 5, the Ayabacas Formation consists of a >500 m-thick mélange of km-size stratified limestone masses that amalgamate smaller sheets and rafts. This mélange is particularly impressive near Lago del Colca (Fig. 13). This zone can be described as a 'sedimentary thrust and fold system' (*sensu* Frey-Martínez *et al.*, 2006; see also Lewis, 1971; Varnes, 1978; Martinsen, 1989; Frey-Martínez *et al.*, 2005).

Limestone is nearly the only lithology, as in Zone 4. Limestone masses consist of well-stratified strata, brecciated beds, and/or associations of both; lateral transitions between well-stratified and brecciated beds are commonly observed. Stromatolitic beds 0.1–1 m in thickness are observed in association with brecciated beds, again indicating that facies deposited in a supratidal environment were involved in the collapse as far as Zone 5. The masses reach 2–4 km in length and <1 km in width, but their internal characteristics are not uniform over large distances; smaller bodies, $\sim$100 m in size, are also found. Stratigraphic thickness of the masses generally exceeds several 10 s of m and can reach 100 m. The well-stratified masses are gently to strongly folded. Folds can affect the entire mass or only some rafts within it. Some portions of the masses are undeformed, implying that they were more lithified and rigid at the time of collapse. Despite bedding continuity, variations in folding geometry and in the degree of brecciation are generally observed within each mass.

The masses appear to have moved somewhat independently during the collapse. The larger however display a dominant NNW-SSE orientation in map view (e.g. Fig. 13), which suggests that they slid toward the WSW or ENE. A km-size mass forms a WSW-vergent recumbent fold, indicating motion in this direction. In agreement with the data from other zones, a general motion of masses toward the WSW is deduced in Zone 5. Collecting more data is made impossible by the paucity of outcrops in this zone.

Zone 6: Burial of autochthonous limestones by stacking of rafts and sheets, and gravitational folding

Zone 6 crops out in two relatively small areas: northwest of Yura in the Arequipa region, and north of Chalhuanca in the NW region. In both areas, the limestone succession is thick and generally devoid of mudstone intercalations, and apparently includes both the Arcurquina and Ayabacas formations.

Most observations were obtained in the Yura area, where outcrops are better. Here the lower part of this succession is $\geq$ 130 m-thick and displays regular beds of even thickness. The $\leq$ 135 m-thick upper part exhibits signs of destabilisation, with a somewhat increasing-upward degree of deformation; this deformation, however, is minor over the first $\sim$100 m as strata appear essentially regular, and this part of the succession is regarded as the upper Arcurquina Fomation in order to keep the stratigraphic nomenclature simple. In contrast, the $\sim$25–40 m-thick topmost part of this upper succession includes rafts, piled-up slides, slumps, and commonly display boudinage structures, and is therefore described as the local Ayabacas Formation.

In the Arequipa area, the deformation is furthermore marked by large, >500 m-wide, asymmetrical to overturned WSW-vergent anticlines and related synclines (Fig. 14), which fold the entire limestone succession but neither the Jurassic-Early Cretaceous substratum nor younger strata. These folds formed shortly after termination of limestone deposition, i.e. at the time of the Ayabacas collapse, and, because they do not 'root' into underlying units, they must have been similarly produced by gravitational deformation. Furthermore, in this folded

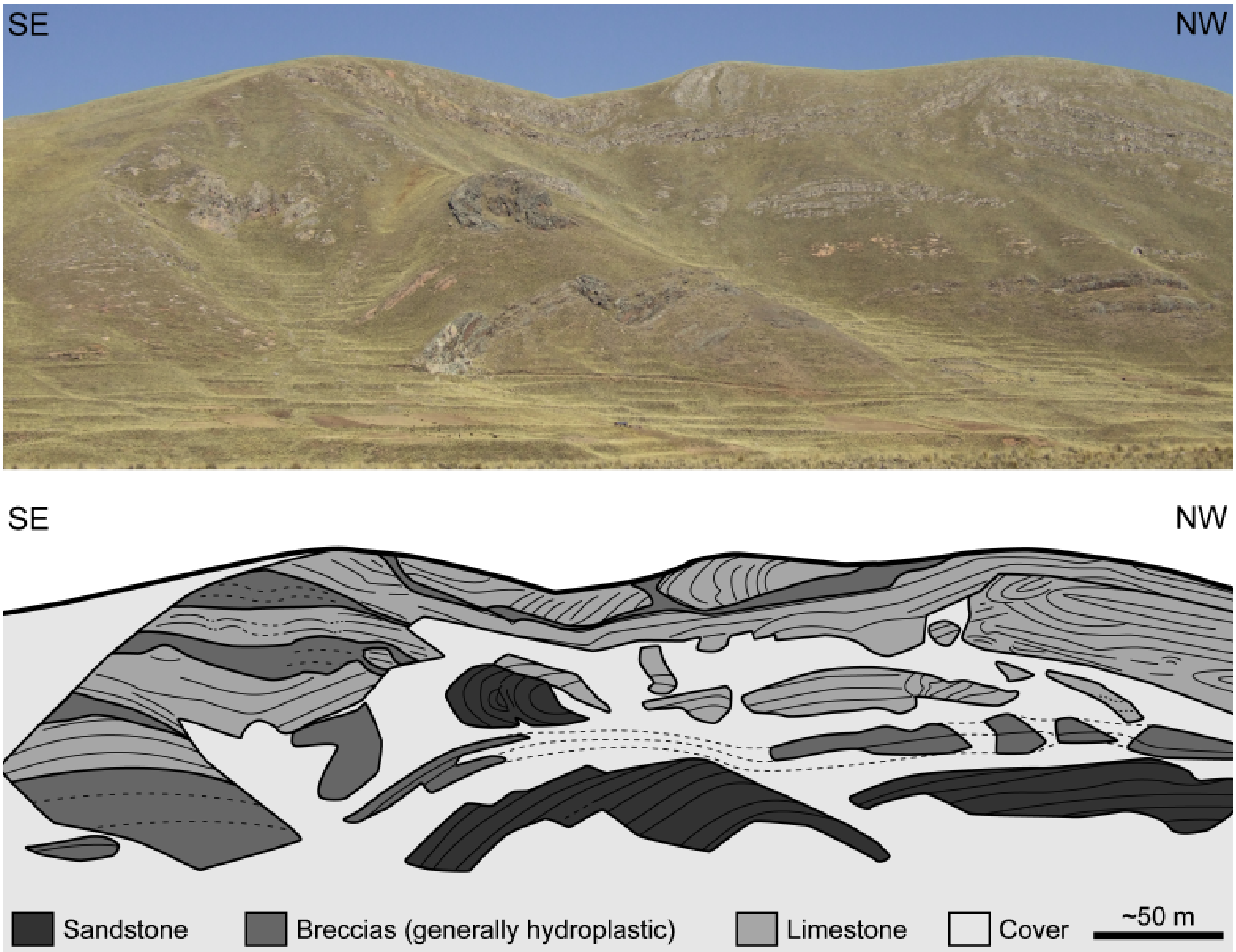

Fig. 11. Field view of the Ayabacas Formation in Zone 3, south of the Cabanillas-Santa Lucía road (UTM Zone 19L 0343000/8267000, 4000 m elevation), and interpretative outline. The unit consists of a mixture of limestone rafts (light grey) and a few lithified sandstone-conglomerate blocks derived from the Angostura Formation (dark grey; see Fig. 3) within a matrix mainly composed of hydroplastic breccias and fluidised marly siltstones (medium grey). It is likely that syndepositional normal faults, as those known elsewhere in this area (see text), were responsible for exposing the Angostura Formation at scarps and causing blocks to slide.

section northwest of Yura, the upper stratigraphic sets that consist of 'cobbly marls' are thicker (up to ~15, ~30, and ~40 m-thick, respectively, for beds 30, 33 and 35) in the synclinal depressions, and much thinner (~1 m, ~0.5 m, and ~1 m, respectively) in the anticlinal crests (Fig. 14), whereas the underlying and immediately overlying limestone beds do not show any variation in thickness. Thickness variations across the folds are clearly restricted to the 'cobbly marl' lithology, which appears as a mix of plastically crushed, smooth-shaped fragments of limestone beds in a marly matrix (Fig. 15); many limestone 'cobbles' exhibit flattening parallel to the bedding plane and stretching perpendicular to the anticlinal axis. These observations strongly suggest that the 'cobbly marl' beds were relatively unlithified at the time of deformation and that during folding they underwent a dominantly plastic flow that redistributed their mass gravitationally, producing thickening in the synclinal axes from thinning in the anticlinal axes, in marked contrast with the limestone beds, which were folded concentrically because they were already lithified at that time. It is also noteworthy that the upper ~25–40 m of the Ayabacas Formation are made up by plastically deformed limestone beds and rafts (Fig. 14c), that testify that these were partially unlithified at the time of deformation, in contrast with the underlying limestones. As lithification is delayed in marls relative to limestones (cementation of carbonates is much faster than that of argillaceous sediments; Müller, 1967; Bathurst, 1971; Bryant *et al.*, 1974), the simplest interpretation is that folding developed at a time when the most recent limestones, over the upper 25 m, and marls, down to a depth of ~135 m, were only partly lithified.

The limbs of these gravitational folds are locally affected by normal and reverse synsedimentary faults that cut bedding over 10 s of cm to a few m. These faults generally agree with a downslope movement along the fold limbs (i.e. ENE-vergent reverse fault and WSW-vergent normal fault in the short limbs; WSW-vergent inverse fault and ENE-vergent normal fault in the long limbs). NNW- and ENE-trending minor synsedimentary normal faults have also been locally observed by Jaillard (1994) in the upper part of the limestone succession.

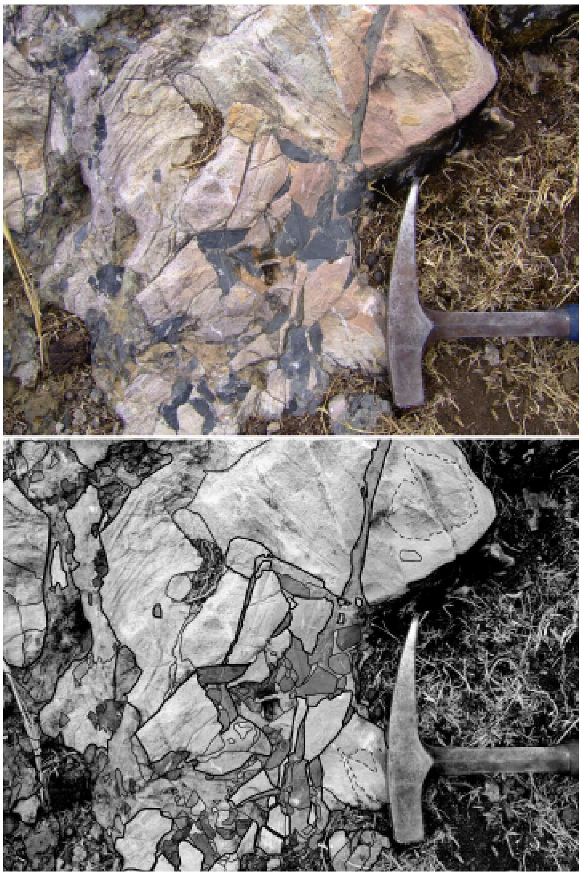

Fig. 12. Detail of a brecciated limestone bed in Zone 4. All clasts and the matrix are calcareous. The fluidised sediment (e.g. the little clastic dyke top-left of the hammer, and the matrix) locally displays fluid motion. Calcite veins are limited to some clasts and thus veining developed before the breccia formation. Size of the hammer head is ~17 cm.

We favor that gravitational folding of the Albian-Cenomanian limestone succession slowly developed during the Ayabacas collapse but that the emerging anticlines did not yield catastrophically, except for the upper few 10 s of m which developed more typical Ayabacas deformational facies. It is likely that the same process led to varying degrees of disruption in other areas, whereas it was 'frozen' in the Yura area. The recumbent folds and stratified masses observed at Lago del Colca (~100 km NNE of Yura; Zone 5) probably represent more evolved states initially produced by similar gravitational folding, but in this case reaching mass thrusting and km-scale disruption.

SYNSEDIMENTARY NORMAL FAULTING AND BLOCK TILTING

In areas where the Ayabacas Formation is thick and the underlying and/or overlying strata do not crop out, it is not always possible to securely separate deformation due to the collapse from the possible local effects of Andean tectonics. A few excellent outcrops in Zones 1 and 3, however, provide evidence that the Ayabacas collapse was accompanied by block faulting and tilting of the underlying rocks.

Syn-collapse normal faulting

A geological cross-section ~15 km northeast of Nuñoa (Zone 1) shows several normal faults affecting the Ayabacas substratum. The Antacalla outcrop is particularly significant (Fig. 16): a W-dipping normal fault offsets the Huancané Formation more than 100 m, is accompanied by a marked thickness variation of the Ayabacas Formation (from <1 m in the footwall to >100 m in the hangingwall), and is post-dated by the basal sandstone beds of the Vilquechico Group and younger units. East of the fault, a NE-vergent recumbent fold occurs in the Ayabacas mélange and is interpreted to have been produced by sliding on the tilted surface of the local substratum.

Near Cabanillas (Zone 3), the pre-Ayabacas substratum has been shaped into tilted blocks by a number of normal faults oriented ~N130–N180 that affect the Angostura Formation and below. These faults are post-dated by hydroplastic breccias within the Ayabacas Formation; however, these breccias do exhibit some gentle plastic deformation above the faults, but no fracturing, indicating they were emplaced during faulting.

Asymmetrical thickness variations as a signature of normal faulting

In Zone 1, the thickness of the Ayabacas Formation generally increases gradually from a minimum near a fault to a maximum near the next fault. On the contrary, it varies sharply across such faults, regardless of whether these are post-dated by the Vilquechico Group or not. Because of the evidence of synsedimentary normal faulting in this Zone, our interpretation is that these characteristic asymmetrical thickness variations were produced by block faulting and tilting, the minimum thicknesses corresponding to the elevated part of a tilted block, i.e. on the footwall of the fault, whereas the maximum thickness was accumulated at the foot of the normal faults (Fig. 17b).

In Zone 1 (e.g. near San Antón – Coñejuno), sharp boundaries between a thick and a thin Ayabacas often coincide with ~NNW-trending reverse faults that dip strongly to the ENE or WSW. It is noteworthy that a thick Ayabacas systematically occurs in the hangingwalls, and a thin Ayabacas in the footwalls, pointing to a link between sedimentary accumulation and the existence of these faults; such geometries, however, are contrary to what would be expected in the case of synsedimentary reverse faults, and instead strongly suggest that the observed reverse faults developed as Andean-age reactivations of former normal faults dipping the same way, in agreement with the observation of non-inverted normal faults in the same zone (Fig. 17).

Extensional faulting and tilting of the substratum was synchronous with sliding

At least Zones 1 and 3 thus provide evidence that the substratum of the Ayabacas Formation was normal-faulted and tilted (some faults in Zone 1 undergoing inversion during the Andean orogeny; e.g. Fig. 17). Normal faults were

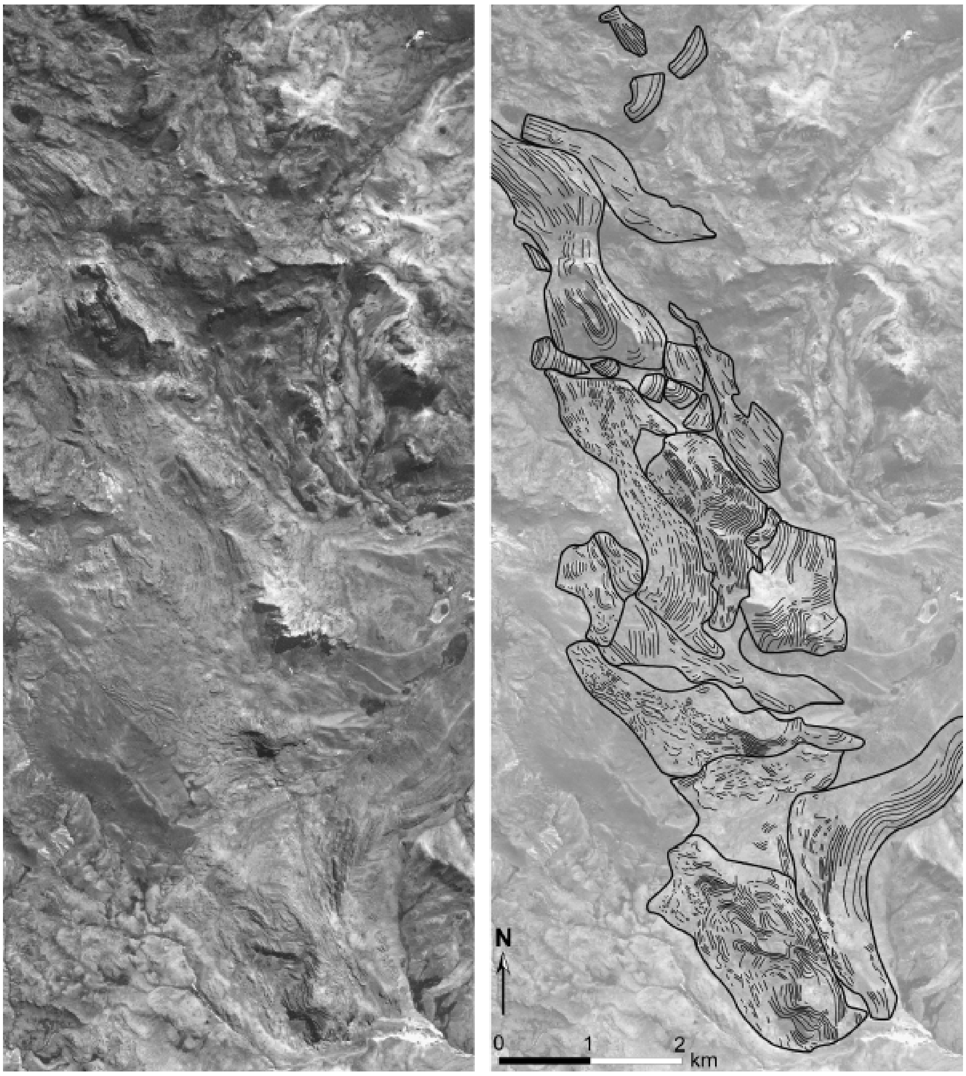

Fig 13. Aerial photo of the road pass ~14 km SE of Tisco (Zone 5), and interpretative outline. The outcrop consists of km-size limestone masses, some of them forming recumbent folds (with ~WSW trend). The masses are not homogenous, consisting of a mixture of sheets and rafts that include well-stratified and brecciated beds in lateral transition (see section 'Zone 5: Chaotic mélange of very large rafts and sheets' in text).

generally NW-trending and associated with down-to-the-NE tilting of substratum blocks, making gravity sliding of mudstones and limestones of the Murco and Arcurquina formations possible both NE-ward above the tilted surface and SW-ward along the fault scarps (Fig. 17). Evidence also exists that both normal faults and sliding were post-dated by the Vilquechico Formation (e.g. Fig. 16). In Zone 2, no clear evidence of normal faulting and tilting has been found so far, but this may be due to a lack of favourable outcrops. A similar association of normal faults, tilted blocks, and large-scale sliding has been described offshore New Zealand by Collot *et al.* (2001).

Measurements of fold axes and vergences are commonly considered to provide indications on sliding directions when they are sufficiently numerous and distributed over a sufficiently large area (Lajoie, 1972; Woodcock, 1979; Strachan & Alsop, 2006). Gravitational folds in the Ayabacas limestones are commonly distributed into outcrop sets displaying opposite NE and SW trends, indicating that at a large scale slides developed in these two main directions. Furthermore, observations are highly suggestive that NE-ward sliding developed at smaller scales and SW-ward sliding at larger scales. The first are interpreted to result from local tilting of the pre-Ayabacas surface down to the NE in association with SW-dipping faults, whereas the second are likely to represent sliding toward the greater basin in agreement with the more regional slopes generated by these faults. Based on the vergence of overturned folds, Portugal (1964, 1974) recognised in Zone 3 that sliding motion was dominantly toward the SW. The other synsedimentary structures (clastic dykes, palaeodirectional indications in the breccias) observed in the study area generally agree with the reconstructed NE and SW directions of sliding.

Block faulting and tilting of the substratum during the Ayabacas collapse is in agreement with the fact that the western Peru back-arc basin (WPBAB) developed in a dominantly extensional context until at least the end of the Turonian (see above). Northeast of the SFUACC, some normal faults underwent inversion when Andean-age shortening developed in the Eastern Cordillera (similar to faults described by Bond & McClay, 1995). Normal faults were not inverted in the Cabanillas area, i.e. southwest of the SFUACC where Andean shortening has been weak or absent (Sempere & Jacay, 2006, 2007).

Catastrophic erosion along fault scarps

Large blocks of lithified sandstones derived from the Angostura and/or Huancané formations, and others from older units, down to the Palaeozoic basement, occasionally occur chaotically in areas of high thickness [at various places in Zone 2 (see Fig. 2)]. These blocks are up to 100s of m in length and width, and up to several 10s of m in stratigraphic thickness. The occurrence of such large blocks implies that the pre-Ayabacas units were exposed to catastrophic erosion. We suggest that this was made possible by creation of significant fault scarps. These particular facies rich in older blocks are therefore interpreted to have accumulated at the foot of such scarps, from which they were removed catastrophically. Huancané blocks 10–100 m in size are indeed observed in association with the small synsedimentary normal faults in zones 1SE (near San Antón) and 3 [near Cabanillas (e.g. Fig. 11)]. However, the localities where the largest blocks are observed closely follow the SFUACC fault system (Fig. 2), strongly suggesting that this major, old, subvertical structure (Carlier *et al.*, 2005) came to form a significant scarp during the Ayabacas collapse. Normal faulting being documented in Zones 1SE and 3 in association with the collapse, it is likely that the SFUACC scarp was also created by normal fauting. Taking into account the stratigraphic thicknesses known in the area, and the caveat that the Paleozoic basement had been locally uplifted in the Early Cretaceous, this fault scarp is estimated to have been at some time at least ~100 m high, in order to enable catastrophic erosion of basement blocks. It is likely that this scarp was created by accumulated offsets along the SFUACC.

In contrast with Zone 2, where blocks derived from the Huancané Formation commonly occur, Huancané clasts of only cm–dm size are observed in Zone 3 and only at some localities; this implies that some Huancané blocks underwent pervasive desintegration during collapse of the SFUACC scarp and acquired an impetus sufficient to transport large fragments several km away from this scarp. Near Santa Rosa and Cabanillas, clasts of volcanic conglomerates typical of the Mitu Group are observed, likewise suggesting that the Mitu Group had been exhumed in some fault scarp located in the local upslope area.

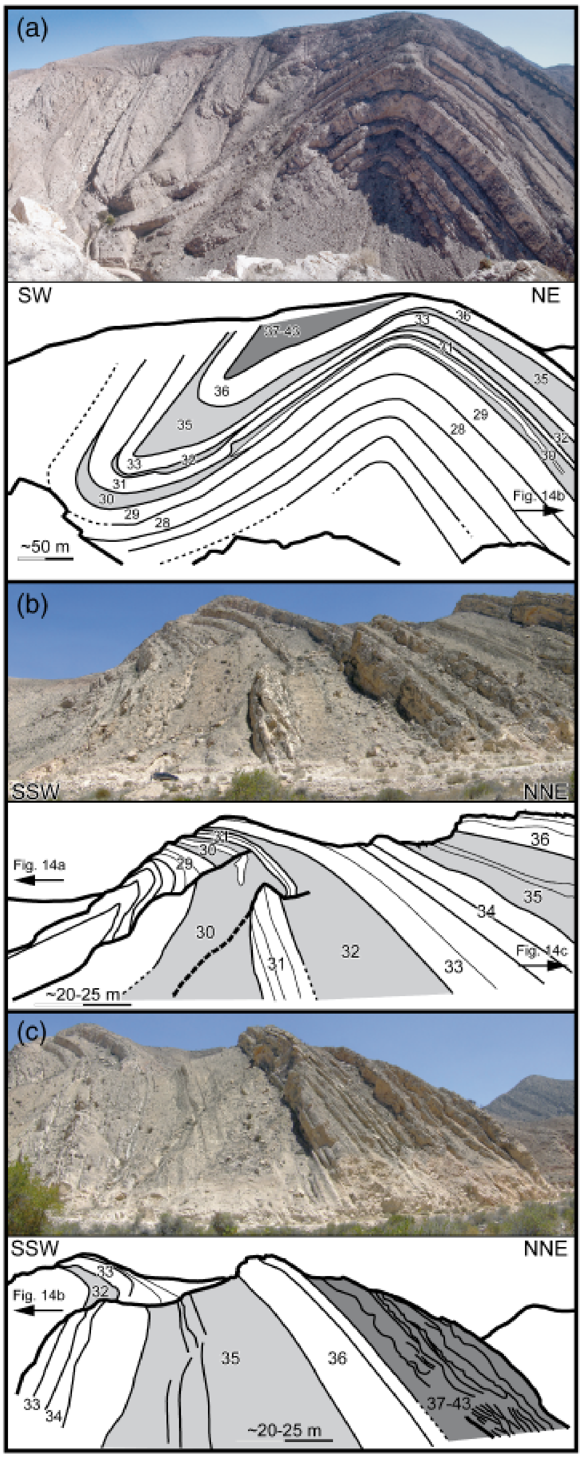

Fig 14. Photographs and interpretative outlines of the same asymmetrical fold 20 km NW of Yura (Zone 6), taken from different points of view from SW to NE (a to c). Bed numbers are those used by Benavides-Cáceres (1962). Vergence is to the WSW (underlying and overlying units evidence that Andean deformation has tilted the local section down to the NE). The 'cobbly marl' beds (no. 30, 32 and 35, in grey in the line drawings; see also Fig. 15) are clearly thicker in the synclinal depressions and much thinner in the anticlinal crests. Older beds (29 and below) do not display such thickness variations, whereas limestone beds 31, 33 and 36 are hardly affected. Beds 29 and below are typical of the Arcurquina Formation; although they display minor deformation, beds 30–36 are sufficiently regular to be also assigned to the Arcurquina Formation. In contrast, deformation in the topmost part of the succession (beds 37–43 in dark grey) is much more pronounced, due to sliding of unlithified marls and limestone rafts and slumps, typical of the Ayabacas Formation.

DISCUSSION

Anatomy of the Ayabacas mass-wasting body

Deformational facies vary across the six zones recognised in the basin, depending on the involved lithologies and pre-collapse thicknesses and lithification states. Across Zones 1–3, from NE to SW, strata deposited in the mid-Cretaceous carbonate platform were progressively and increasingly fragmented. Thicknesses of the limestone rafts and of the entire collapse increase, respectively, from ~20 to ≤ 40m, and from ~40 to > 300 m. The average shape of the limestone elements evolve from relatively unfolded, ~20 m-thick, km-size sheets in Zone 1, to folded sheets fragmented into rafts in Zone 2 and more fragmented, chaotically arranged rafts in Zone 3. Mid-Cretaceous deposits were removed, locally completely, from areas where slides originated, as in the uplifted parts of tilted blocks (e.g. Fig. 16). In contrast, relatively thick Ayabacas deposits accumulated in downwarped areas (as already suggested by Portugal, 1964, 1974) such as those in the hangingwalls of normal faults. Zones 1–3 thus exhibit a characteristic downslope fragmentation of the collapsed material.

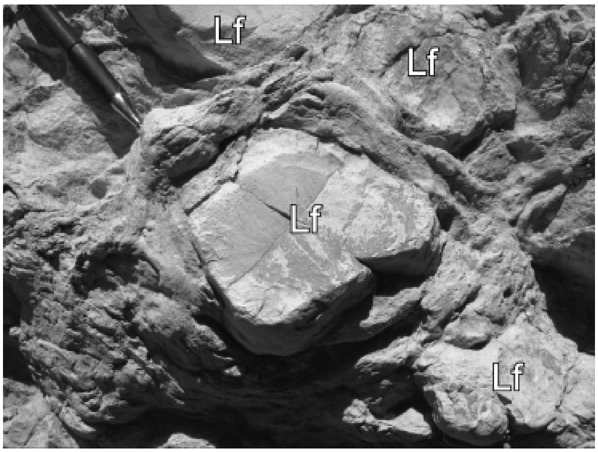

Fig. 15. Illustration of the 'cobbly marl' lithology, characterised by smooth-shaped limestone fragments (Lf) surrounded by a marly matrix. The visible part of the pen is ~4 cm.

In contrast with Zones 1–3, the average size and continuity of limestone masses increase from Zones 4–6. In Zones 4 and 5, the Ayabacas deposits are thick (commonly > 500 m) and result from the stacking of limestone rafts and sheets, whose average size increases from east to west, as in a 'sedimentary thrust and fold system' (*sensu* Frey-Martínez *et al*., 2006). In Zone 6, the upper part of the limestone succession consists of stacked rafts and sheets characteristic of the Ayabacas Formation, whereas the lower part consists of the regularly bedded Arcurquina Formation. Thus, no sliding occurred during at least the first part of the depositional interval, dismissing the hypothesis that the carbonate platform would have been repeatedly affected by mass-wasting processes, and instead confirms that the Ayabacas collapse represents a unique event that occurred at the end of the platform history. In the Yura area, gravitational folds represent a 'frozen stage' of the 'sedimentary thrust and fold systems' observed in Zone 5, complete sliding having probably been hampered by the high viscosity imposed by a more advanced state of lithification. More generally, it seems reasonable to propose that lithification progressed at a quicker pace in the western areas, because these lay deeper in the Arcurquina basin and were reached earlier by the transgressions. Higher viscosity and cohesiveness in the west are likely to have prevented the local Arcurquina limestones from being involved in the Ayabacas collapse. We therefore expect the Ayabacas-related structures to die out into the WPBAB west of the study area.

The deformational facies and anatomy of the Ayabacas body furthermore refute an origin by compressional tectonics. The organisation of the collapse into six deformational facies zones, plus one undisturbed zone in the northeast, closely parallels the architecture of the mid-Cretaceous marine basin but is clearly unrelated to the Andean-age deformation distribution and styles, in particular in the northeast. It is revealing that the Ayabacas disruption is maximum in Zone 3, where Andean shortening

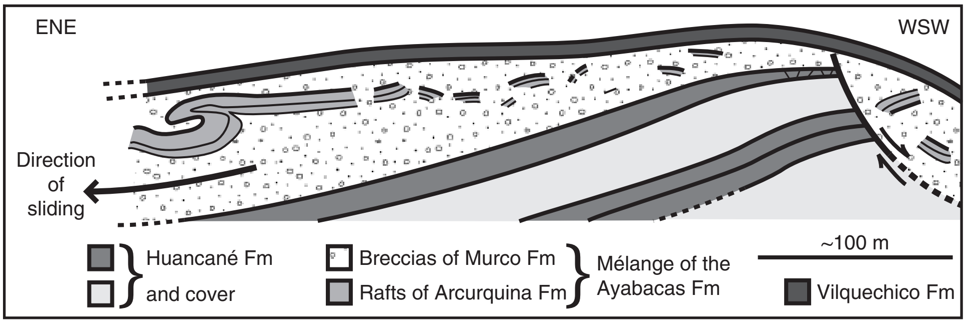

Fig. 16. Line drawing of the Antacalla outcrop (UTM Zone 19L: 0317728/8405150, 4120 m elevation; see also Sempere *et al*. 2000). The normal fault affects both the Huancané and Ayabacas formations, but is post-dated by the sandstone basal member of the Vilquechico Formation (see Fig. 3). The attitude of the Vilquechico Fm nevertheless appears gently controlled by the existence of the buried fault scarp. The Ayabacas is thick in the hanging-wall. In the footwall, the Huancané Formation is tilted down to the NE and its top is fractured close to the fault (black lines). Limestone blocks occur SW of the fault, but are absent just NE of it and progressively appear NE-wards, where one of them displays soft, NE-vergent folding, indicating that sliding occurred in this direction.

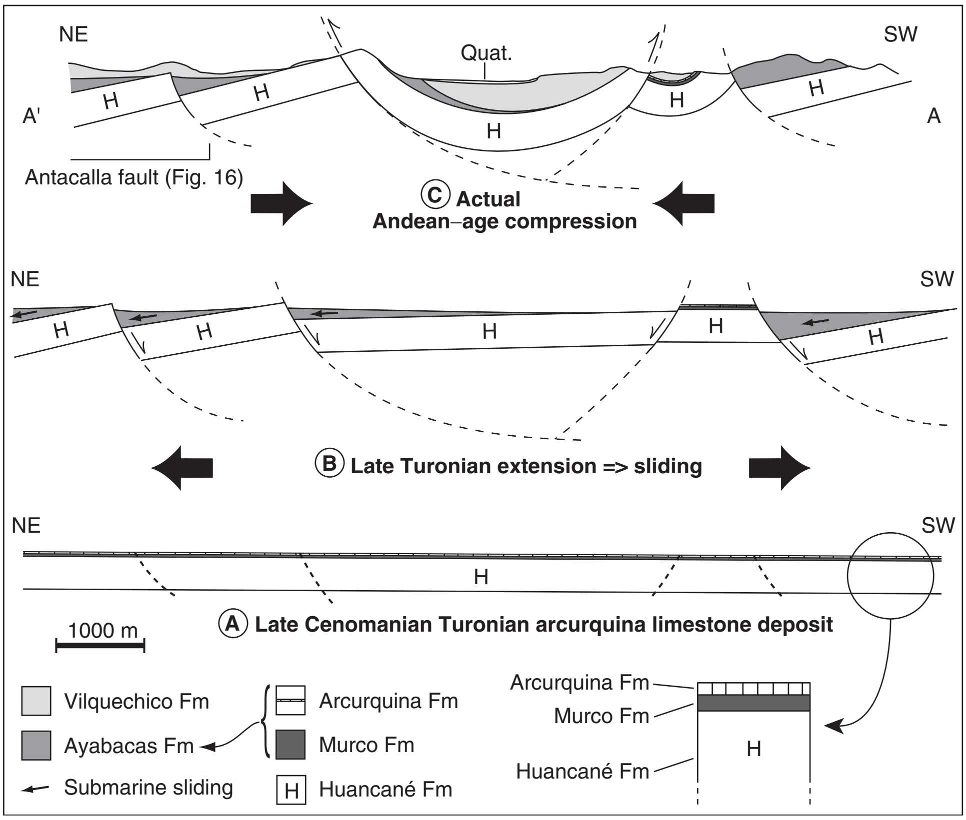

Fig. 17. Present (C) and reconstructed (B, A) sections near Nuñoa (Zone 1). (a) Deposition of the Arcurquina limestones during the Late Cenomanian-Turonian tectonic quiescence. (b) Intense extensional tectonics at the Turonian-Coniacian transition (~90–89 Ma); the pre-Ayabacas substratum is shaped into tilted blocks by ~NW-trending normal faults; the Arcurquina and Murco formations collapse on the created, oversteepening slopes to form the Ayabacas Formation, which is very thin or absent in the origination areas of the slides and very thick (up to > 100 s of m) in the hanging-wall of the normal faults. (c) During the Andean-age shortening of the Eastern Cordillera, some normal faults undergo inversion; others, as the Antacalla fault (Fig. 16), do not, making clear that the normal faulting and Ayabacas deformation are post-dated by the Vilquechico Formation.

was weak or absent (Sempere & Jacay, 2006, 2007), whereas it is minimum in Zone 1 to non-existent in Zone 0, i.e. close to the Eastern Cordillera where Andean shortening was maximum.

What triggered the Ayabacas collapse?

Submarine slides are widely viewed to result from a variety of short-term triggering mechanisms such as oversteepening of the depositional surface, increase in pore pressure, seismic loading, storm-wave loading, rapid sediment accumulation and under-consolidation, gas charging, gas hydrate dissociation, low tides, seepage, diapirism, glacial loading and volcanic island processes (Locat & Lee, 2002; Mienert *et al.*, 2002; Sultan *et al.*, 2004). Factors such as slope angle, mass-movement history and unloading, may be insufficient to initiate failures but can favour them, and therefore constitute long-term, 'slow' triggers. Sea-level changes have also been proposed as a potentially favourable factor for slope failure (Spence & Tucker, 1997).

Increase in pore pressure and differences in lithification rate (Nichols, 1995; Spence & Tucker, 1997; Mourgues & Cobbold, 2003; Vendeville & Gaullier, 2003) were indeed likely to be present at the time of the Ayabacas collapse, and to have facilitated sliding, but they quite probably existed also during the entire deposition of the Arcurquina limestones and yet no sliding is recorded before the Ayabacas event: therefore they cannot be invoked as a triggering factor for the collapse. At the end of the Early-Middle Albian transgression, sediment characteristics in the western part of the basin (Arequipa region) must have been similar to those that later preceded the Ayabacas collapse more to the northeast: the water-laden Murco siltstones and sandstones were underlying partly lithified Arcurquina limestones, probably generating some excess pore pressure, but, although this potential sliding sole was present throughout the deposition of the carbonate platform, sliding did not occur in any part of the basin until the Ayabacas event.

Absence of slides interstratified in the Arcurquina Formation, where this unit is preserved (Zones 6 and 0), dismisses relative sea-level fall or rise as triggering factors because neither the Early Albian and Late Cenomanian transgressions, nor the Late Albian regression, had any noticeable effect on the stability of the southern Peruvian carbonate platform. The Ayabacas event, however, apparently occurred during a marked global regression that was abruptly initiated in the late Middle Turonian (~91 Ma) and slowly terminated near the Turonian-Coniacian boundary (~89 Ma) (Hardenbol *et al.*, 1998). However, a triggering role of this ~91 Ma sharp sea-level fall appears unlikely because its age apparently disagrees with the ammonite record from northern Peru, which documents that carbonate sedimentation continued into the Late Turonian (Jaillard, 1990, 1994), and with our own chronostratigraphic model (see above and supplementary documentation online). Furthermore, the global sea-level was dominantly high again during the Senonian, whereas the Ayabacas collapse was immediately followed by nearly exclusively continental sedimentation in the southern Peruvian basin. The collapse in fact coincided with other, non-eustatic, geological phenomena in southern Peru, an intriguing observation that should provide valuable insights into this triggering mechanism.

One main clue lies in the striking association of the Ayabacas collapse with extensional tectonic activity, as demonstrated by synsedimentary normal faults and related thickness variations. As documented in outcrops, normal faulting produced tilting of the substratum as well as scarps, and thus created seismicity and slopes on which sliding of the Arcurquina and earlier strata was enabled. The nearly constant thickness and standard internal stratigraphy of the limestone rafts and/or sheets within each zone (as observed in Zones 1–3, and therefore also inferred to be true in Zones 4–6) suggest that the bottom of the basin had been remarkably flat before the Ayabacas collapse, confirming that slopes had to be created in order to make the mass-wasting process possible. In the Late Albian–Early Cenomanian limestone succession of northern Peru, slumps, breccias, and large clastic dykes, likewise occur in association with synsedimentary normal faulting (Jaillard, 1994). Such associations between extensional tectonics and sedimentary sliding in the WPBAB, at different times, strongly suggest that the triggering of mass wasting in this carbonate platform ensued from slope creation and seismicity produced by extensional tectonic activity, and that other factors, such as pore pressure increases or lithification contrasts, only facilitated sliding.

The relationship between regional extensional tectonic activity and the Ayabacas collapse is strengthened by the occurrence of some peculiar features in the vicinity of the two major fault systems that cross the study area (SFUACC, CECLLA; Figs 1 and 2). During the Cenozoic and in particular the Central Andean orogeny, these two ancient fault systems have had significant tectonic activity, and have been the loci of considerable magma emplacement, revealing that they represent major crustal to lithospheric heterogeneities (Sempere *et al.*, 2002b, 2004b; Carlier *et al.*, 2005, for the SFUACC). Although synsedimentary normal faults and related thickness variations were observed in Zones 1 and 3, thanks to outcrops providing spectacular exposures, there is evidence that the SFUACC and CECLLA were activated during the Ayabacas collapse.

The SFUACC had had some syndepositional activity during the mid-Cretaceous carbonate sedimentation (Arcurquina depositional interval) as it formed the northeastern boundary of the depositional area during the Early and Middle Albian transgression and highstand. This barrier was overflowed by the Late Cenomanian-Turonian trangression and highstand, but subsidence and water depth apparently remained much lower northeast of the SFUACC. During the Ayabacas collapse, older rock units, down to the Paleozoic, were exposed along $\geq$ 100 m-high, southwest-facing scarps formed by the SFUACC activity; giant blocks of these lithified units were catastrophically removed as these scarps collapsed and slid down to the southwest, and their fragments were transported away in the same general direction. The occurrence of large blocks along the northeast fringe of the SFUACC (Fig. 2) documents that some of them underwent little transport and remained stuck in the slope. It is likely that the smaller normal faulting documented in Zone 1, i.e. a few km northeast of the SFUACC, developed in relation to major normal faulting along the SFUACC. Occurrence of blocks of Paleozoic shales southwest of this fault system (i.e. in its downwarped side) reflects that the Paleozoic basement had been locally uplifted in the Early Cretaceous, rather than implying that its cumulated vertical offset was $>$400 m during the Ayabacas collapse, which seems unlikely. Given the relative shortness of the event, even a 100 m throw is by itself suggestive of a considerable tectonic upheaval in the region.

Activity of the CECLLA system during the Ayabacas collapse is inferred from the sharp facies differences between Zones 3 and 4, which are respectively located east of, and within, this broad fault system. Whereas in Zones 1–3 the mass-wasting body abundantly involved red siltstones derived from the Murco Formation, it only reworked Arcurquina limestones in Zones 4–6, where the Murco Formation was not involved in the collapse. This contrast indicates that, from the CECLLA system to the west, the Murco Formation was located below the sole of the collapse, whereas it lay well above it east of the CECLLA. This geometry suggests that the domain within and west of the CECLLA was structurally downwarped when the collapse was initiated, and it is likely that this resulted from normal faulting along and within this broad fault system. Respective estimated thicknesses of the involved units suggest that vertical offsets within the CECLLA must have been $<$100 m, as they did not form scarps where pre-Arcurquina units could be exposed (unlike what occurred along the SFUACC system), but sufficient enough to downwarp the pre-Arcurquina units to a position where they could be preserved from involvement into the collapse. This was possibly due to the broad, diffuse character of the CECLLA structural system (Fig. 1).

Facies zones distinguished in the Ayabacas Formation vary laterally in map view. The northern Cusco-Abancay-Chalhuanca transect is 120 km-long, clearly shorter than the 200 km-long southern Huancané-Juliaca-Santa Lucía-Lagunillas-Yura transect (Fig. 2), a difference that cannot be explained by a higher Andean-age shortening in the north but rather reflects the different position of these transects relative to the SFUACC and CECLLA. Furthermore, this asymmetry is matched by differences in the deformational facies of the Ayabacas collapse. Southern deposits are limestone-rich along a ~100 km-long transect across Zones 1–3 and their matrix consists exclusively of mudstones to siltstones. From there the width of the set formed by these three zones progressively decreases northwards, down to ~30 km in the Cusco-Urubamba area, which was mapped as a whole as Zone 1NW because facies typical of Zones 2 and 3 could not be recognised; here the Ayabacas Formation presents an atypical limestone-poor facies, its abundant matrix includes voluminous gypsum masses, but its limestone rafts exhibit pre-collapse stratigraphic thickness and facies similar to those in Zone 1SE.

This northern area is likely to have behaved in a particular manner because the SFUACC coalesces with the CECLLA in this area (Figs 1 and 2), suggesting that more pronounced scarps and cumulated relief were created here during the event, enhancing the regional slope and significantly favouring collapse of the local platform. Limestone rafts and sheets disintegrated downslope and were massively transported toward the southwest, explaining the limestone-poor facies observed in this area, which would have resulted from a differential transport of the denser limestone blocks in this direction. The thick stacking of exclusively limestone sheets observed in Zones 4–6 in the same transect is in agreement with this idea. Sliding would have been furthermore facilitated by the abundance of gypsum and halite in the Maras (= Murco) Formation, which provided a weaker sole for the collapse.

The Ayabacas event of southern Peru correlates well with the also extensional Vilcapujio event inferred in central Bolivia (Sempere, 1994) on the basis of (1) rapid thickness variations limited to the Coniacian? Aroifilla Formation (interpreted to result from synsedimentary normal faulting) and (2) local partial to total erosion of the Bolivian equivalent of the Arcurquina Formation (which otherwise testifies to a tectonically quiescent Cenomanian-Turonian period). Extensional tectonics thus appear to have abruptly developed near the Turonian-Coniacian transition over a large Central Andean region, at least from central Bolivia to southern Peru. The duration of this extensional deformation is poorly constrained in Peru, but the case of the Bolivian Aroifilla Formation suggests it possibly lasted some Myr.

CONCLUSION

The mid-Cretaceous carbonate platform of southern Peru was brutally disrupted and terminated by a giant collapse at about the Turonian-Coniacian transition (~90–89 Ma). The resulting mass-wasting body was very large, $> 80\,000\,\mathrm{km}^2$ in map view and $> 10\,000\,\mathrm{km}^3$ in volume. It now forms the Ayabacas Formation, which is organised into six deformational zones from NE to SW. The observed directions of sliding and of material disintegration are consistent and indicate that the platform regionally collapsed toward the southwest, i.e. down the general slope of the pre-Senonian basin. Consistently, most part of the shallow and little subsident sub-basin located northeast of the SFUACC system was not affected by the collapse and remained stable.

The Ayabacas Formation unequivocally appears to be the result of a major submarine mass redistribution, which was triggered by significant slope creation and subsequent oversteepening abruptly forced at that time by extensional tectonic activity. The key role of tectonics in triggering mass movement has often been underlined (e.g. Spence & Tucker, 1997; Payros *et al.*, 1999; Graziano, 2001; Mienert *et al.*, 2002; Floquet & Hennuy, 2003; Canals *et al.*, 2004). Seismicity may have been significant, in particular in the vicinity of the two major fault systems (SFUACC and CECLLA) where large lithified blocks from underlying units were involved in the collapse. Increase in pore pressure and differences in lithification rates facilitated the slides but cannot be considered as the main triggering factor.

The Ayabacas Formation records the only sedimentary collapse that disrupted the mid-Cretaceous marine succession of southern Peru. It thus represents a unique and peculiar event in the history of the regional Andean margin and back-arc. Although it is likely that the collapse resulted from several sliding episodes, the Ayabacas Formation is neither intercalated with, nor post-dated by, limestone strata similar to those involved in it. The collapse was submarine and yet abruptly terminated the carbonate platform evolution. It must therefore have taken place during a limited time span, and can technically be considered as one event.

It seems highly meaningful that the Ayabacas event occurred at a turning point in the Central Andean evolution, namely when the south Peruvian back-arc basin underwent a dramatic and permanent change from marine to continental conditions. Before the event, this basin had been essentially marine since the Early Jurassic and deepened to the west. After the event, the back-arc was bounded to the southwest by topographic highs, apparently volcanic in nature, and occupied by continental to near-continental environments. This regional association of extraordinary events, including a significant reactivation of arc volcanism, is likely to shed considerable light on the regional Andean evolution and will be dealt with elsewhere.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Table of abbreviations used in the paper.

Appendix S1. Detailed documentation about the stratigraphy of southern Peru and the data and discussion relative to the age of the Ayabacas collapse.

This material is available as part of the online article from: http://www.blackwell-synergy.com/doi/abs/10.1111/j.1365-2117.2008.00358.x

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