

## A possible earthquake-triggered mega-boulder slide in a Chilean Mio-Pliocene marine sequence: evidence for rapid uplift and bonebed genesis

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**Abstract:** The type area of the Bahía Inglesa Formation (north–central Chile) is structurally complex as a result of active margin subduction at the Peru–Chile Trench. Inliers of subaerially exposed Mesozoic igneous basement are unconformably overlain by a mid-Miocene to late Pliocene marine siliciclastic sequence, which has become known for its abundance of fossil vertebrates found concentrated in a phosphatite on an omission surface. Mega-boulders derived from one of the largest inliers occur exclusively within this bonebed, which appears to have formed after major localized uplift caused removal of a significant thickness of unconsolidated sediment. The mega-boulders were probably dislodged by a high-magnitude earthquake event that accompanied tilting of the sea floor, and their emplacement was an integral part of the processes involved in genesis of the bonebed.

The western margin of South America is dominated by one of the Earth's most important active convergent plate boundaries, where subduction of the oceanic Nazca Plate at the Peru–Chile Trench (*c.* 8000 m deep) has continued unabated since at least the Late Jurassic (Charrier & Muñoz 1994). This tectonic activity resulted in the uplifting of the Andes, one the largest mountain chains in the world. In Chile important components of the Andean mountain range are the Coastal Cordillera and the Precordillera, which, in northern Chile, rise via a narrow continental shelf and coastal plain to a maximum altitude of 2000 m and 6000 m, respectively (Reutter *et al.* 1986; Rogers 1993). Uplift of the Coastal Cordillera was related to an orogenic phase that began in the Oligocene and intensified in the Pliocene. By the end of the Pliocene both the Coastal Cordillera and the Precordillera were dominant features in northern Chile (Jordan & Gardeweg 1989). Subduction-related tectonism has thus remained an important feature of the area throughout the Cenozoic.

Earthquakes are relatively common today along the northern Chilean coast (Gutiérrez 1999) and clearly must also have occurred throughout the Cenozoic (Delouis *et al.* 1998; Marquardt *et al.* 2004). The intensification of tectonism that led to the first development of major topographic relief in the region in the mid- and late Miocene (Jordan & Gardeweg 1989) would, presumably, have been accompanied by a similar intensification of seismicity. Some record of these palaeoseismic events may be expected in the uplifted mid-Miocene and younger marine siliciclastic sequences found along the coast of northern Chile. Turbidite and tsunami deposits provide some evidence of probable earthquake activity, and have been recognized in sequences to the north (Hartley *et al.* 2001) and south (Paskoff 1991; Le Roux *et al.* 2004).

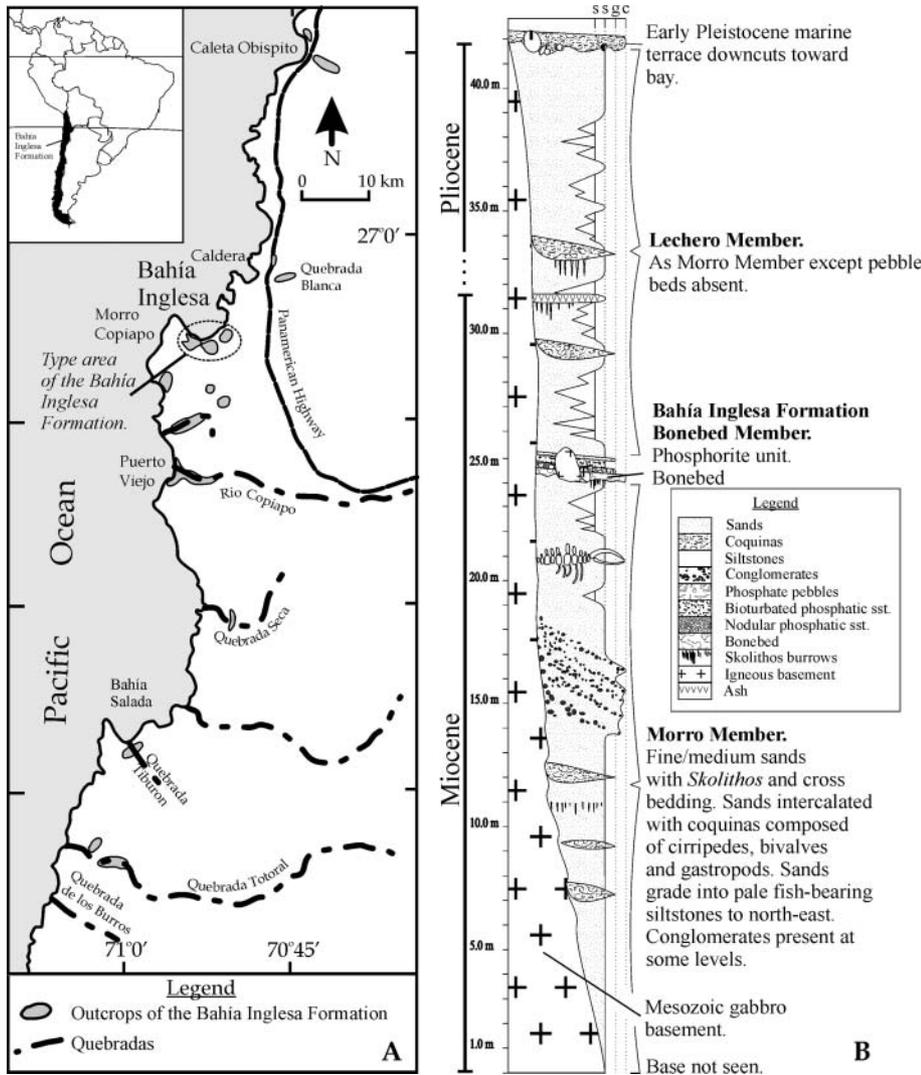
In this paper, the occurrence of mega-boulders on a major, though localized, omission surface within the mid-Miocene to late Pliocene Bahía Inglesa Formation of northern Chile is reported. It is proposed that these boulders provide evidence for palaeoseismicity on a relatively shallow marine shelf. The omission surface on which the boulders rest also forms the base of a relatively thick (up to 0.2 m) bonebed. Bonebeds represent

an important source of palaeontological data (Storrs 1994). In addition, their rarity in stratigraphic sequences indicates that their formation is linked to unusual conditions in the depositional environment, such as periods of major reworking (Martill 1999). As such they are often important as indicators of hiatus horizons such as sequence boundaries (e.g. MacQuaker 1994; MacQuaker *et al.* 1996). Some, such as the one discussed here, may even be commercially important sources of phosphate. Although previous workers have inferred that tectonic processes accounted for the formation of some bonebeds (e.g. Kidwell 1993) the Bahía Inglesa Formation Bonebed is the first to show direct evidence for tectonism associated with its genesis.

### Locality and stratigraphy

The marine Bahía Inglesa Formation (Rojo 1985) comprises more than 42 m of siltstones; claystones; fine to coarse consolidated and unconsolidated arkosic sandstones; bivalve and barnacle coquinas; conglomerates; and commercially important, though thin, phosphorite developments rich in vertebrate remains. The most impressive of these is the Bahía Inglesa Formation Bonebed. An important and extensive exposure of the Bahía Inglesa Formation occurs between S27°02.490" and 20.465", and W70°57.145" and 49.699", some 5 km SW of the small town of Bahía Inglesa, and *c.* 10 km south of the fishing town of Caldera in administrative Region III (Fig. 1a). In this area the formation forms a badlands topography of bluffs and rugged Mesozoic gabbroic and tonalitic igneous inliers in the hinterland to the south and east of Bahía Inglesa bay. The region is arid with excellent exposure. The region can be easily accessed via the Pan American highway and metalled roads to the towns of Caldera and Bahía Inglesa. Several well-used miners' dirt tracks cross the badlands, allowing easy access to key outcrops.

The Bahía Inglesa Formation rests with marked unconformity on the local basement, the contact being seen in many places where the basement projects above the softer sediments. Where seen, the unconformity has an extremely rugged topography and represents a buried terrain of fault bounded grabens and horsts



**Fig. 1.** (a) Location of the type area of the Bahía Inglesa Formation and other key outcrops of the formation (modified after Marchant *et al.* 2000). (b) Simplified stratigraphic column of the Bahía Inglesa Formation.

(Herm 1969; Rojo 1985; Walsh 2001; Marquardt *et al.* 2004). Forearc basins situated between the Coastal Cordillera and the Precordillera have acted as sediment traps since at least the Neogene (Thornburg & Kulm 1987). Clastic input onto the coastal shelf was further reduced by the development of an arid climate that appears to have been a feature of the area since at least the end of the Miocene (Hinojosa & Villagran 1997; Hartley & Chong 2002). Since that time, detrital clastic input from the hinterland has been comparatively low and much of the clastic material deposited in these shallow marine settings was derived from local exposures of the basement (Thornburg & Kulm 1987). Stratigraphic truncation is therefore a feature of the formation.

Invertebrate and vertebrate fossils indicate that the Bahía Inglesa Formation represents a shallow (<100 m) marine to littoral environment (Marquardt *et al.* 2000, 2004; Walsh 2001). Walsh & Suárez (2005) recognized three lithostratigraphic units in the formation: the conglomeratic Morro Member (4–24 m in thickness) forms the base, and the phosphorite-rich Bahía Inglesa Formation Bonebed Member (0.1–5 m in thickness) separates the Morro Member from the overlying fine sandstone and siltstones of the Lechero Member (4–13 m in thickness) (Fig. 1b).

The formation has been dated at between mid-Miocene and late Pliocene on the basis of radiometric data (Marquardt *et al.* 2000; Godoy *et al.* 2003) microfossils (Tsuchi *et al.* 1988; Ibaraki 1995; Marchant *et al.* 2000), molluscan faunas (Herm 1969; Guzmán *et al.* 2000) and vertebrate biostratigraphy (Rojo 1985; Long 1993; Walsh 2001; Walsh & Hume 2001; Suárez *et al.* 2004). The formation is overlain by Pleistocene marine terraces with mono- and polyspecific coquinas, locally reaching several metres in thickness.

### Tectonic setting

The most important structural feature of the forearc close to the study area is the Atacama Fault Zone, which extends for more than 1000 km from La Serena in the south to Iquique in the north (González *et al.* 2003). Activity in the Atacama Fault Zone began in the Mesozoic, simultaneous with the onset of subduction of the Farallon Plate beneath the South American continental plate (Scheuber & González 1999). The subducted plate currently penetrates the mantle at a dip of 22° to the east, with a well-defined Wadati–Benioff zone (Comte *et al.* 2002). The structural style of the Atacama Fault Zone is of north–south–

striking sinistral strike slip and NW-striking splay faults resulting from a largely extensional stress field (González *et al.* 2003).

In the Bahía Inglesa region this extensional regime resulted in the formation of a series of NW–SE-trending grabens representing small (<5 km square) basins into which the Bahía Inglesa Formation was deposited (Godoy *et al.* 2003; Marquardt *et al.* 2004). Today the basement between these grabens is exposed as a series of roughly NE–SW-trending inliers (Fig. 2). The grabens are bounded and controlled by NNW–SSE- and NNE–SSW-striking faults, although a second system of NE–SW-striking faults is also present (Mercado 1978). Because the NNW–SSE and NNE–SSW faults bound the grabens into which the Bahía Inglesa Formation was deposited, they must have been active prior to the mid-Miocene transgression that resulted in the deposition of the succession. At least one of these faults was observed to cut beds of mid- to late Miocene age, but their timing is largely difficult to determine as a result of the unconsolidated nature of much of the formation. Uplift of the most prominent topographic feature of the area, the Morro Copiapó headland (Fig. 2) was controlled by major NNE–SSW and a NNW–SSE fault that cut Pliocene strata (Marquardt *et al.* 2004), and tilting of Pleistocene marine terrace deposits adjacent to the eastern flank of the headland demonstrates that the faults were active in the Pliocene until at least the Pleistocene. Except for the main Morro Copiapó faults (Fig. 2), nearly all faults that cut Pliocene beds in the region belong to the NE–SW system, suggesting that the system became dominant toward the end of the Pliocene (but see Marquardt *et al.* 2004).

Faults of both systems are mostly extensional with steeply dipping fault planes and, with the exception of the main Morro Copiapó faults, observed throws of more than a few metres are rare. The major Morro Copiapó faults are also notable in that they are westward-dipping reverse faults (Marquardt *et al.* 2004). Reverse faults striking NNW–SSE and NE–SW with easterly dips are also encountered in the region. Most of the NE–SW-striking normal faults have a downthrow to the east, and are consistent with those of the Atacama Fault Zone close to 27°S noted by Jordan & Gardeweg (1989).

### Depositional environments of the Morrow and Lechero members

The Morro Member comprises a series of mainly siliciclastic (mostly texturally immature arkosic, coarse to medium sandstones), predominantly massive bedded units with abundant coquinas of marine shallow-water and encrusting molluscs (*Chlamys simsoni*, *Ostrea transitoria*, *O. maxima*, *Anomia atacamensis*, *A. alternans*, *Chorus blainvillei*, *Crepidula* sp.) and cirripedes (*Megabalanus* sp.). Thin ripple lamination was observed in some places, and *Skolithos* facies (*sensu* Bromley & Asgaard 1991) is abundant in some areas. Beds of medium sandstones close to the main inliers grade laterally into thin (normally <1 m thick) siltstone beds close to Morro Copiapó. Channels reaching more than 40 m in width and 12 m depth are common within the member. Where observable these channels trend NW. The largest channels are filled with medium to coarse sands and sometimes exhibit point bar structures, whereas smaller channels (less than 15 m wide and 4 m deep) are mostly filled with imbricated clast supported breccias (clasts up to 0.7 m diameter). Around halfway through the Morrow Member, clast-supported beach conglomerates composed of well-rounded cobbles of locally derived gabbro occur around the inliers.

Based on the sedimentary environment and invertebrate body fossils, the Morro Member is interpreted to have been mainly deposited between storm and fair-weather wave base, the coquina deposits probably representing periods of storm reworking. The abundance of cirripede material in the coquinas probably reflects provenance from the igneous inliers. This and the presence of beach conglomerates around the inliers suggest that they may have been shoals or even emergent islands during deposition. The abundance of fossil penguin and seal remains in the succession in the vicinity of the largest inlier supports this; rocky islands and islets today are a feature of the coast near Bahía Inglesa, and are used by penguins as rookeries and by seals as haul-outs (Walsh & Hume 2001; Walsh & Naish 2002). As suggested by Thornburg & Kulm (1987) for other sites along the northern Chile coast, the abundance of feldspar and textural

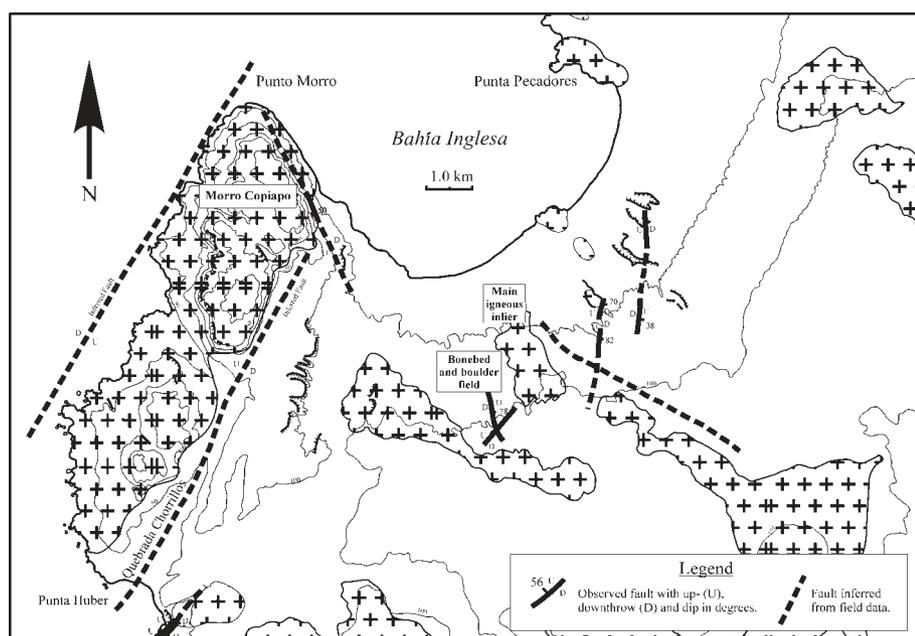


Fig. 2. Simplified geological map of the region showing the main faults observed in the study area. Areas with crosses indicate outcrops at igneous basement rocks; white areas show the distribution of Neogene Pleistocene sediments (including those of the Bahía Inglesa Formation).

immaturity of the sandstone units probably indicate that most of the clastic material was locally derived from the gabbroic inliers, rather than from inland. *Skolithos* facies probably indicate a tendency toward a shifting sand environment (Bromley & Asgaard 1991). Such sand movements would explain the necessary rapid burial of vertebrate skeletons that otherwise would have been disturbed by macro predators. Marquardt *et al.* (2004) interpreted the formation to represent a partially deltaic environment, and the presence of point bar meander deposits is consistent with this view. The more numerous narrow coarsely bedded channels are interpreted to represent rip channels.

Above the Bahía Inglesa Formation Bonebed Member, the Lechero Member comprises a 4–13 m thick succession of laminated and non-laminated claystones and siltstones that grade laterally into fine unconsolidated arkosic sands with occasional clast-supported conglomeratic channel fills (Fig. 1b). These channels are mostly smaller than in the Morro Member (up to 7 m wide and 2 m deep) and contain smaller clasts (largest observed clast 0.2 m diameter). To the east of the main basement inlier the Lechero Member consists of up to 13 m of mostly laminated siltstones that locally contain abundant disarticulated fish remains, rare arthropod claws and occasional shark teeth. The siltstones grade into overlying fine sandstones that contain arthropod claws, and isolated but well-preserved vertebrate fossils including associated skeletons of penguins (*Spheniscus* cf. *chilensis*; *Pygoscelis* sp. nov.) and dolphins (Delphinidae indet.). These sandstones also contain an unworn molluscan fauna including *Turritella cingulata*, *Crassilabrum crassilabrum*, *Eurhomalea lenticularis*, *Tagelus dombeii*, *Ensis macha* and *Mulinia* sp. Arthropods are represented by isolated malacostracan claws and cirripedes (*Balanus* sp.). Trace fossils include locally abundant *Thalassinoides* in the siltstone levels and abundant *Skolithos* in the sandstones. The siltstones of this area also grade into fine sandstones with increasing proximity to the main inlier. West of the main inlier siltstones are only encountered close to the Morro Copiapó headland. The top of the member is truncated by Pleistocene marine terraces.

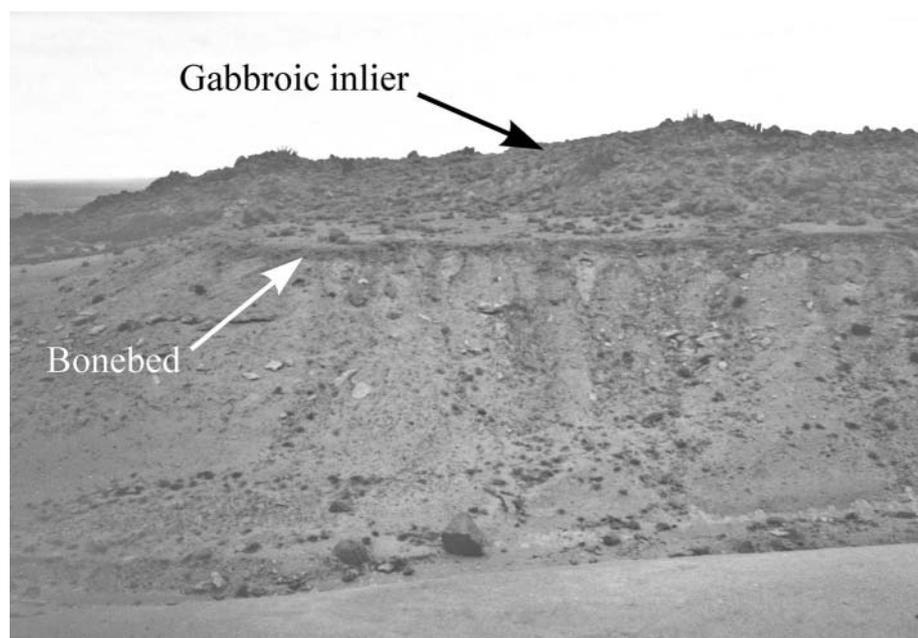
The dominance of siltstone lithologies in the lower Lechero

Member suggests that deposition occurred in a slightly deeper, lower energy environment, with higher energy conditions close to the inlier indicated by deposition of sandstones. Siltstones close to the Morro Copiapó headland occur several kilometres west of the inlier, and are likely to have been deposited in a slightly deeper, more distal setting. The upper Lechero Member is characterized by fine sands that contain a molluscan assemblage indicating a littoral environment no deeper than 10 m. The member is interpreted to represent a shallowing upwards shore-face succession that culminated in emergence and erosion as the marine terraces were formed in the Pleistocene.

### The Bahía Inglesa Formation Bonebed Member

The Bahía Inglesa Formation Bonebed Member is a 0.1–5.0 m thick succession of phosphatite and phosphorite layers (*sensu* Slanski 1986) interbedded with fine unconsolidated sands. The member has an almost continuous outcrop in the south of the region and in several places is seen to overlap the Morro Member onto the basement (Fig. 3). The bonebed is anomalous within the succession as being phosphate-rich with very abundant vertebrate remains. Both the lithic clasts and vertebrate remains are sorted by clast size depending on proximity to the igneous inliers, with larger whale bone fragments being more common closer to the outcrops. This is probably a result of current scour around these features. The vertebrates are virtually all marine organisms, with terrestrial animals being extremely rare (Walsh & Hume 2001; Walsh & Naish 2002; Walsh & Suárez 2005). Cirripede and mollusc steinkerns demonstrate that the bonebed was generated under normal marine salinities.

The phosphatite bonebed occurs with an outcrop area of around 5 km<sup>2</sup> and is developed exclusively between two of the largest inliers (Fig. 2). The base of the bonebed is scoured into the underlying beds with scour depths up to 200 mm. *Skolithos* trace fossils infilled by coarse bonebed matrix are often concentrated at the base of the bonebed. The top is generally covered by a thin veneer of shiny phosphate cement, but is otherwise difficult to observe from above because of overlying strata.



**Fig. 3.** The igneous inlier from which the mega-boulders were derived. The Bahía Inglesa Formation Bonebed (0.2 m in thickness) can be seen at the top of the sediment pile onlapping the inlier and dipping toward the observer at c. 6°.

Viewed laterally the upper surface is sharp and planar. The bonebed framework clasts generally occur as part of rounded laminated phosphatic nodules. Large (i.e. >25 mm diameter) non-biogenic clasts occur only rarely and are mostly composed of well-rounded, locally derived gabbro. A notable exception to this is in the region of the largest basement inlier at 27°08'00.8"S, 070°51'29.8"W, where angular to sub-rounded boulders and mega-boulders (some >6 m diameter) of basement occur within the bonebed (see below). These blocks appear anomalous in that they lie a considerable distance from their nearest potential source relative to their size.

Thin-section analysis of the arkosic bonebed matrix reveals that it is uncompacted, indicating early cementation. Mineralogically it is dominated by angular to sub-angular feldspars (c. 40%, most of which is plagioclase), angular to well-rounded quartz (c. 30%), igneous and sedimentary lithic fragments (c. 20%) and smaller amounts of mafic minerals. The mineralogical and textural composition of the bonebed matrix is consistent with provenance from nearby gabbroic and tonalitic basement sources. A significant proportion (c. 11%) of quartz clasts are frosted.

Using molluscan assemblages, Herm (1969) regarded the omission surface on which the bonebed rests as having developed during the Pliocene, and the presence of teeth of *Carcharodon carcharias* (great white shark) in the basal bonebed supports this. Teeth of this taxon have been used extensively in South America to recognize the Pliocene (de Muizon & DeVries 1985; Walsh & Hume 2001; Walsh & Naish 2002). However, K–Ar dating of an ash layer that crops out around 7 m above the basal bonebed at Bahía Inglesa indicates an age of  $7.6 \pm 1.3$  Ma (Godoy *et al.* 2003), demonstrating that the unconformity was formed no later than the Tortonian. Consequently, this species must have arrived in southeastern Pacific waters earlier than was previously believed, and therefore teeth of *C. carcharias* should be used with caution for dating Neogene South American Pacific sequences.

The bonebed contains up to 77% vertebrate remains, including sharks, rays, bony fishes (Long 1993; Suárez *et al.* 2004), seabirds (Walsh 1999; Chavez 2001; Walsh & Hume 2001; Acosta Hospitaleche *et al.* 2002), crocodiles (Walsh & Suárez 2005), seals (Walsh & Naish 2002), whales and dolphins (Quilodran & Yañez 2000). Nearly all of the vertebrate material is disarticulated and fragmentary, and although most specimens are lightly abraded, severe abrasion is rare. Fracture patterns on the fossils (*sensu* Reif 1976) suggest that much of this material was already remineralized when it was exhumed. Fossil specimens of less than 5 mm diameter are extremely uncommon. The bones occur in a medium to coarse sand matrix, with silt filling voids in many specimens. Chi-square (goodness of fit) analysis of orientation data for long bones in the bonebed shows a significant ( $n = 129$ ,  $P = 0.025$ ,  $\chi^2 = 19.51$ ) departure from a random orientation. Rose diagram presentation of these data (Fig. 4) taken from a 5 km east–west transect of the bonebed reveal a major NW–SE trend, and a more minor east–west trend. Calcareous invertebrate fossils are absent from the bonebed, although the horizon is locally rich in phosphatized steinkerns of bivalves (mostly infaunal forms), gastropods and cirripedes. This absence of calcareous body fossils is probably attributable to diagenetic removal of calcite and aragonite.

The mix of temporally discrete taxa demonstrates that the accumulation is not the disarticulated evidence of a mass mortality event. These lines of evidence indicate that the material represents a lag deposit, probably derived by the removal of a local silt-rich, uncemented succession (see Martill (1999) for discussion on bonebed genesis). The presence of up to 13 m of

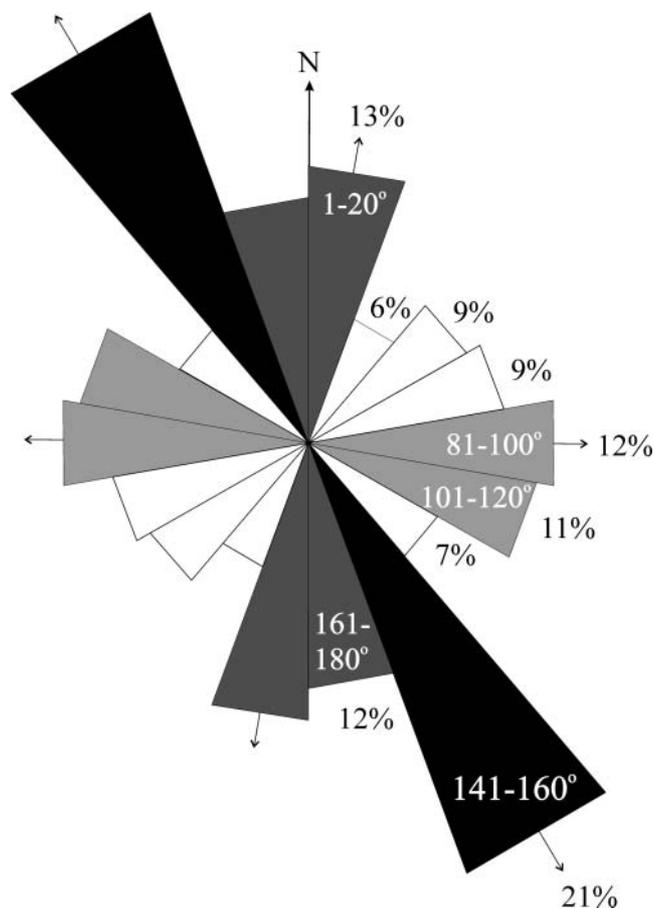


Fig. 4. Mirrored rose diagram representation of orientation data of 129 long bones in intervals of 20° for clarity of presentation. Values outside each segment represent observations expressed as a percentage of the total.

siltstone to the east of the inlier suggests that the missing siltstone succession may have been of comparable thickness. The coarse grain size and lack of small vertebrate remains, coupled with the scoured base of the bonebed, indicates that removal of this sediment pile occurred in high-energy conditions, with dissolution of shelly material acting to further concentrate the reworked bone accumulation. The restriction of this erosion to between the two largest inliers indicates that the event was localized, but the outcrop pattern of the inliers themselves (Fig. 2) would have prevented the vertebrate material from being transported into the area from inland as part of a gravity flow. The marine faunal composition of the bonebed makes derivation of the remains from terrestrial strata extremely unlikely. A tsunami event could, in theory, have reworked the vertebrate material from a sequence in a more distal setting and carried it upslope to where its transport was halted by the barrier of the inliers. However, evidence of such an event is absent from the succession in closely adjacent areas, where normal deposition is unbroken.

The concentration of *Skolithos* burrows at the base of the bonebed demonstrates that normal sedimentation did not resume after the accumulation was reworked. Because 56% of the long bone orientation observations are broadly parallel to the main inlier (between 340° and 20°) the main orientation trend appears to relate to this feature. This is interpreted to be a result of rolling in an oscillatory current on the erosion surface as it dips

away from the inlier. The more minor east–west orientation may represent a downslope dip in bones that were unable to roll. Movement of the bones on the sea floor is further supported by the development of *Skolithos* traces; these organisms would have been unable to colonize the scour surface unless it was occasionally uncovered. Infilling of these burrows by bonebed matrix demonstrates episodes where the matrix moved to cover them. This continued current action suggests that the reworking was a result of a relative lowering of sea level to within normal wave base, rather than the action of a major storm event. Again, the absence of this erosion surface elsewhere in the basin suggests that the sea-level fall was localized, and seems to be probably the result of tectonic uplift of a section of sea floor.

The rarity of severe abrasion on the fossils suggests that reworking of the unconsolidated parent succession was not a prolonged process, and is consistent with a rapid, possibly single episode of uplift and sediment removal. However, evidence that the accumulation was rolled around by wave action is at odds with the rarity of abrasion, and the lack of intense bioerosion on the fossils also suggests that exposure of the vertebrate accumulation was relatively short. Although the fossilized vertebrate material is today remarkably hard, reconciling its extended survival in a high-energy environment seems problematic.

One possibility is that the accumulation was to some degree protected by the early cementation noted above. Analysis of the phosphate cement using SEM identified possible microbial mats (Walsh 2002). Similar structures have been noted in phosphate deposits worldwide, and are considered to represent early microbial precipitation of phosphate cement (e.g. Slanski 1986; Soudry & Lewy 1988; Glenn *et al.* 1994). The covering of the sharp, planar upper surface of the bonebed by phosphate cement suggests that phosphatization occurred in the absence of overlying sediment. It seems possible that the accumulation may have existed as a phosphatic hardground (e.g. Lamboy 1994), but evidence for this is equivocal.

### *Igneous mega-boulders*

The mega-boulders are up to 6 m in diameter (Fig. 5). They form an irregular, somewhat chaotic topography of angular and sub-

angular blocks scattered on the soft slopes of the badlands. Their presence in the bonebed is a distinctive occurrence within the formation. Although beach conglomerates occur around the inliers, the gabbro cobbles are well sorted and do not contain large boulders. Large clasts are also absent from the sandstones and siltstones that lie above and below the bonebed. Mega-boulders are entirely restricted to the base of the bonebed, which is a broadly planar surface that dips NW away from the inlier at around 6° toward the present bay, downcutting into underlying horizontal strata to produce an angular unconformity. Only moderate scour is evident around even the largest examples.

All of the mega-boulders are brown weathered gabbros. Thin-section analysis of their lithology matches that of the adjacent basement inlier, as does their weathering colour. It therefore seems logical to deduce that they have been derived from this outcrop; other potential sources of gabbro occur several kilometres to the north, whereas the large inlier further west (Fig. 2) is tonalitic in composition. Igneous boulder size within the bonebed decreases away from the adjacent basement inlier, and at a distance of *c.* 1.5 km west of the inlier, mega-boulders are no longer present in the bonebed. Boulders are entirely absent east of the inlier. The mega-boulders are angular to sub-angular with typical subaerial meteoric weathering. The largest concentration of mega-boulders (>4 m diameter) occurs within *c.* 300 m of the point where the bonebed laps onto the basement, but several occur at distances of up to 1 km (see below).

The sub-angular nature of the boulders suggests that they were derived from fresh outcrops above the high-water mark, as boulders derived from the intertidal zone would be expected to exhibit a higher degree of rounding. The boulders clearly underwent transportation, because if they had merely fallen from a cliff the expected accumulation would fringe the inlier and display a mixture of small and large boulders with beach cobbles. The absence of the boulders to the east of the inlier demonstrates that the transport occurred in a single direction.

The accumulation of large quantities of disarticulated vertebrate remains at the boulder horizon (Fig. 6) is highly distinctive, and is interpreted to be a result of localized current reworking of a significant thickness of silt-rich sediment. The timing of this erosive event relative to boulder emplacement is problematic.



**Fig. 5.** A mega-boulder on the bonebed horizon, *c.* 300 m from the inlier, parts of which can be seen in the background. Boulders also can be seen in the valley below the main mega-boulder. These reached their present position when fluvial erosion removed the sediment pile beneath the bonebed, which is apparent as the dark layer at the top of each bluff, and is 0.2 m thick.



**Fig. 6.** One of the smaller boulders encountered *c.* 500 m from the inlier. Two boulders also can be seen in the background to the right of the main boulder. It should be noted that although bonebed material can be seen beneath the main boulder, it is not possible to determine whether this material truly lies under it or whether the visible bonebed matrix merely fills a cavity at the boulder's base.

The restriction of the boulders to the erosion surface strongly indicates that it was already present when the boulders came to rest. The absence of scour around the boulders supports this interpretation, although bonebed material under boulders has not been unequivocally observed (see Fig. 6).

### Interpretation of mega-boulder emplacement

The abundance and restriction of the mega-boulders to a single horizon within the Bahía Inglesa Bonebed Member indicates a single emplacement event. Although this is in part suggested by their occurrence at a single horizon, their near-pristine condition suggests that they did not rest on an exposed sea floor for a prolonged (e.g. 1000 years) period. Thus the mega-boulders represent an event rather than an accumulation by attrition over time.

The mode of emplacement of the mega-boulders is, however, somewhat problematic. Such large boulders could have been transported downslope by gravity as part of a debris flow, and the linear outcrop pattern of the inliers would ostensibly provide a channel through which a continental-derived gravity flow could pass. However, outcrops of basement to the SE would have prevented this, and no structures typical of such an event deposit (e.g. Le Roux *et al.* 2004) occur at this horizon.

A large tsunami potentially could have moved these boulders. Tsunamis occur frequently along the Pacific coast today and there is evidence for their occurrence in the past (e.g. Hartley *et al.* 2001). However, the mega-boulder horizon at Bahía Inglesa does not show the chaotic mix of clast sizes or the lack of sorting typical of deposits generated by tsunamis. Furthermore, the pattern of NE–SW-trending inliers would have protected the area occupied by the boulders from the effects of a tsunami unless it came from the NE. However, the erosion surface on which the boulders rest is entirely restricted to the area immediately west of the main inlier, and a tsunami would surely have left some trace in other parts of the region.

The relatively close proximity of the mega-boulders to the lithologically identical topographic high to the east suggests that

the boulders were derived from this high and transported to the west, downslope, under gravity. The trigger for their transportation may have been a consequence of toppling of a tor as a result of intense erosion, storm activity, or perhaps as a consequence of an earthquake. If a storm was responsible for triggering an intensely eroded outcrop it seems likely that similar events would have occurred at other times during deposition of the formation. Furthermore, the surrounding terrain is of insufficient area for the development of a large, fast-flowing water body to move the boulders (Fig. 2).

The number of mega-boulders ( $n > 20$ ) suggests that, rather than an isolated boulder rolling from a tor as a consequence of prolonged erosion, a substantial series of blocks of various sizes were toppled simultaneously. This would be consistent with collapse of an unstable cliff during an earthquake. The toppling of boulders from a tor or cliff would require considerable force, and we suggest that destabilization of a deeply fractured igneous outcrop may have been the result of an earthquake centred on a basement fault adjacent to the inlier, perhaps on its eastern flank (Fig. 2). The restriction of mega-boulders to the west of the igneous inlier might suggest that tilting of the basement block to the west toppled the boulders, accounting for their distribution and size grading in that direction. This evidence indicates that there were at least two tectonic events. The first was responsible for the uplift of a localized area of vertebrate fossil-bearing strata to form the bonebed accumulation. The second event was accompanied by tilting of the main igneous inlier to the west, resulting in the distribution pattern of the boulders observed today. The timing of these events is difficult to determine, although it seems very likely that they occurred in relatively close succession.

### Discussion and conclusions

The absence of mega-boulders in the rest of the succession surrounding the inlier is of particular note. This could be explained in part as a result of relatively rapid subsidence and subsequent burial of the inlier, rendering it less susceptible to

loss of material during earthquakes. However, it is likely that the earthquake that triggered the collapse of the mega-boulders was a particularly large and extremely rare event, otherwise localized boulders derived from the inliers would be encountered at other levels in the succession.

Mega-boulder emplacement by seismic events has been reported previously (e.g. Beaty 2001), and the presence of boulders susceptible to displacement has been used as an approximate guide to the frequency of large magnitude seismic events in regions prone to seismicity (e.g. Bell *et al.* 1998; Anooshehpoor *et al.* 2004). Intervals between such events have been estimated to have frequencies of at least 10 ka (Bell *et al.* 1998). However, this is an extremely short time period with regard to the age of the Bahía Inglesa sequence, which probably represents around 14 Ma (Godoy *et al.* 2003). Seismic events capable of ejecting mega-boulders from relatively fresh rock outcrops are exceedingly rare events.

Umeda *et al.* (1987) calculated ground velocities and acceleration of 4–16 *g* at frequencies of 5–10 Hz ejecting boulders of *c.* 5000 kg up to 1.2 m during the 1984 Western Nagano earthquake in Japan. The mega-boulders at Bahía Inglesa are considerably larger than those ejected at Nagano, but much of their transport was gravity induced and occurred in an aqueous medium. Thus it is not possible to reliably estimate the magnitude of the event that dislodged them using the method of Umeda *et al.* (1987). The distance travelled by the largest mega-boulders at Bahía Inglesa is estimated to have been at least 1 km (the exact distance cannot be determined as it is not possible to match the mega-boulders to specific parts of the inlier). Nevertheless, 1 km of transport over a gradient of *c.* 6° is considerable. Even in water, such transport would have required a considerable initial velocity.

Mega-boulders of 4 m diameter transported in water have been reported by Wylie *et al.* (1996) from submarine canyons in California where transport was gravity induced. However, no transport distances were reported. Wave-induced transport also has been reported for mega-boulders of up to 96 000 kg on a coastal rock platform in Hawaii, with transport distances of at least 30 m per tsunami event (Noormets *et al.* 2002). The distribution pattern of the Bahía Inglesa mega-boulders and their restriction to the erosional base of the bonebed suggests that gravity was the most important transport mechanism, although no plough marks have been observed.

The boulder field and bonebed at the base of the Bahía Inglesa Bonebed Member provide direct evidence of at least two phases of major late Miocene tectonism. Although stratigraphic truncation is a feature of the Bahía Inglesa Formation, the highly localized nature of sediment removal that resulted in bonebed formation is clearly linked to localized tectonic uplift rather than global eustasy. However, it is at present unclear whether the emplacement of mega-boulders on the resulting omission surface at the start of a deepening-upward succession (that was at least region-wide) was related to tectonism or eustasy. The timing of these events is consistent with an intensification of tectonic processes in the late Miocene that culminated in the rise to dominance of the NE–SW fault system. The absence of such boulder fields lower in the succession suggests that the tectonic events that resulted in the present geomorphology of Bahía Inglesa bay, such as the Pliocene uplift of the Morro Copiapó headland, probably began toward the end of the Miocene.

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