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Pie de Palo, Argentina: A cataclastic diapir

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ABSTRACT

The term cataclastic diapirism is proposed for the low-temperature extrusion of highly fractured rocks through more competent strata to produce domed topographies at the surface. The process is illustrated by reference to the geomorphology, neotectonics and microseismicity of the Pie de Palo, an elongated ridge in the western Sierras Pampeanas of Argentina composed of shattered and sheared Lower Palaeozoic rocks and subject to coseismic uplift. The Pie de Palo is conventionally interpreted as a fault-driven basement fold linked to low-angle eastward subduction of the Nazca plate beneath South America; the diapiric model implies instead that deformation is powered by regional compression from west-verging, near-surface, crustal shortening which results ultimately from Atlantic spreading.

1. Introduction

Diapirs are bulbous or cylindrical vertical intrusions which result from the upward movement of mobile materials beneath more competent strata (Goudie, 2004). They include giant magmatic plumes which rise from the surface of the Earth's core to the base of the upper mantle as well as near-surface mud intrusions, salt domes and granite batholiths a few kilometres in diameter (Fig. 1A, B). In the early 20th century the term was applied primarily to anticlines whose crest had been penetrated by mobile material (the diapir folds or piercement folds of Barton, 1926) in response to folding; more recent accounts have tended to ascribe diapir emplacement primarily to buoyancy effects arising from the density of the intrusion (as with halite plugs) or its temperature (as with batholiths), but differential loading is increasingly seen to be a more important driving force (Hudec and Jackson, 2007), with the requisite pressure sometimes being provided by sediment loading or the evolution of hydrocarbons rather than tectonic strain.

Diapirism is of interest to geomorphologists for its impact on the country rock as much as for the shape and evolution of the diapirs themselves (Goudie, 1989). Thus the upward growth of salt domes, which may locally exceed 10 mm/year, creates distinctive concentric structures in the sedimentary strata it punctures, distorts nearby shorelines, and displaces (or swallows) drainage systems. Moreover, the alignment of a series of diapirs is a valuable guide to the presence of major fault lines, and the very survival of salt plugs despite the depredations of solution, flow and gravitational collapse reflects not only continuing uplift but also the presence of an evaporite source at depth and hence a potential detachment surface over which folds can migrate in relative freedom.

Such parochial issues can have wider implications. For instance, the distinction between brittle and plastic flow is by no means clear-cut, and the behaviour of materials subject to diapirism (see for example Price and Cosgrove, 1990) allows the matter to be investigated in the field as one might the rheology of glacier flow. The monitoring of diapir emergence permits some assessment of the extent to which the process is being driven wholly by buoyancy independently of any regional deformation. Where the process is too slow, ancient or distant for direct observation, the use of hardware, computer or numerical models can exploit surface form to assess the role of diapirism. Such analyses are thought to support a diapiric origin for the circular coronae of Venus, and hence that the surface of the planet was resurfaced by volcanism ~500 million years ago, but quantitative analysis of Magellan imagery suggests that many of the coronae are in fact deformed impact craters over 3.9 Gy old (Hamilton, 2005; Vita-Finzi et al., 2005).

The novel mode of diapirism proposed here is illustrated by reference to the Pie de Palo, a rock mass near the eastern margin of the Sierras Pampeanas within the Andean foreland of Argentina (Fig. 2). The Sierras include a number of near-circular granite batholiths (Pinotti et al., 2002) but the topography is dominated by fault-bounded basement blocks which are generally ascribed to low-angle, eastward subduction of the Nazca plate (Barazangi and Isacks, 1976). One of these uplifted masses, the Pie de Palo (Figs. 2 and 3), is usually interpreted as a basement fold controlled by a basement wedge at a depth of about 15–20 km (Ramos et al., 2002). Geomorphological observations made in February 2006 suggested that its recent deformation is more consistent with extrusion analogous with that of a salt diapir in a compressive setting such as the Zagros Ranges of Iran (Koyi, 1988; Talbot et al., 1988; Vendeville and Nilsen, 1995; Koyi,

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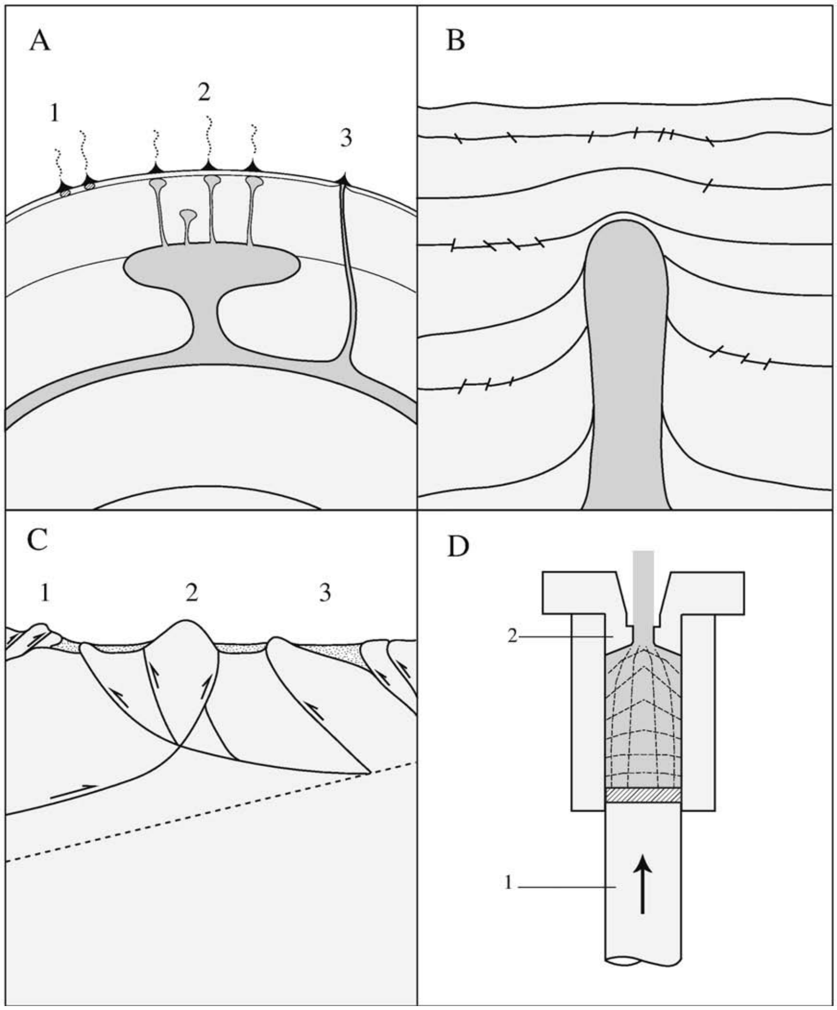

Fig. 1. Cartoons to illustrate potential mechanisms for diapiric effects. A: the three main plume/hotspot categories: 1: 'tertiary', linked to tensile stresses in the lithosphere and decompression melting; 2: 'secondary', possibly from the top of domes near the depth of the transition zone; and 3: 'primary', possibly coming from lower mantle boundary (after Courtillot et al., 2003). B: salt diapir and associated faulting (based on Davison et al., 2000). C: basement uplifts in the Andean foreland after Alvarado et al. (2005b): 1: Precordillera; 2: Sierra Pie de Palo; and 3: Sierra de Valle Fértil. D: cataclastic diapirism (this paper) whereby highly fractured rock is driven by regional compression (1: piston) at near-ambient temperatures through the country rock (2: die). Figure based on cold direct extrusion after Kalpakjian and Schmid (2002).

1998); in other words, that there is a class of diapir for which the main prerequisites are a rock mass susceptible to low-temperature bulk deformation and a favourable regional stress field.

2. Regional setting

East of the main Andean range three major tectonic subdivisions of the South America plate are generally recognised (Ramos and Vujovich, 1999; Fig. 2): from west to east, the Precordillera, which is subject to thin-skinned deformation; the Sierras Pampeanas, where reverse faulting is thought to extend into the basement; and 'cratonic South America', which makes up the bulk of the remaining subaerial part of the plate. Between the Equator and latitude 45° S the subducted oceanic Nazca plate can be divided into five segments according to the general eastward dip of the corresponding seismic zone. Evidence of active and Quaternary volcanism is found above the three segments with dips of 25–30° and not above the two with gentle (<10°) dips (Barazangi and Isacks, 1976).

Where the subducted plate dips steeply, crustal shortening is confined to the main Cordillera, whereas deformation above the flat slab between 28° and 33° S extends east well beyond the Cordillera (Régnier et al., 1992; Smalley et al., 1993). The area under review lies squarely within this belt. The Sierras Pampeanas are conventionally viewed as crystalline basement uplifts produced by rotation and shortening on thrusts (1C) (Kadinski-Cade et al., 1985).

Neotectonic activity in the central Sierras Pampeanas is concentrated in the Pie de Palo complex (Ramos et al., 2002), an elongated dome 30×80 km which trends NNE and rises to over 3000 m above sea level (Fig. 3). The structure consists of Precambrian and Lower Palaeozoic metamorphic and intrusive rocks (Bollinger and Langer, 1988), and is separated from other Sierras Pampeanas by Carboniferous and later deposits (Régnier et al., 1992).

According to the NUVEL-1A scheme, subduction of the Nazca plate beneath South America is proceeding at about 77 mm/year on an azimuth of N 79° E (DeMets et al., 1994). SLR, GPS and DORIS data, which evidently span only a few years, indicate the somewhat slower rate at the trench at latitude 17° S of 68 mm/year directed N 76° E, but it is not certain whether the difference represents a real change in rate or is an artifact of the data (Norabuena et al., 1998). GPS measurements suggest that 14±7 mm/year of the total convergence (~20%) is manifested as folding and thrust faulting in the foreland. Geological estimates of this shortening are 8–13 mm/year averaged over the last 25 million years and 27 mm/year averaged over the past 5 million years; seismic moments account for only 1–3 mm/year, which is taken

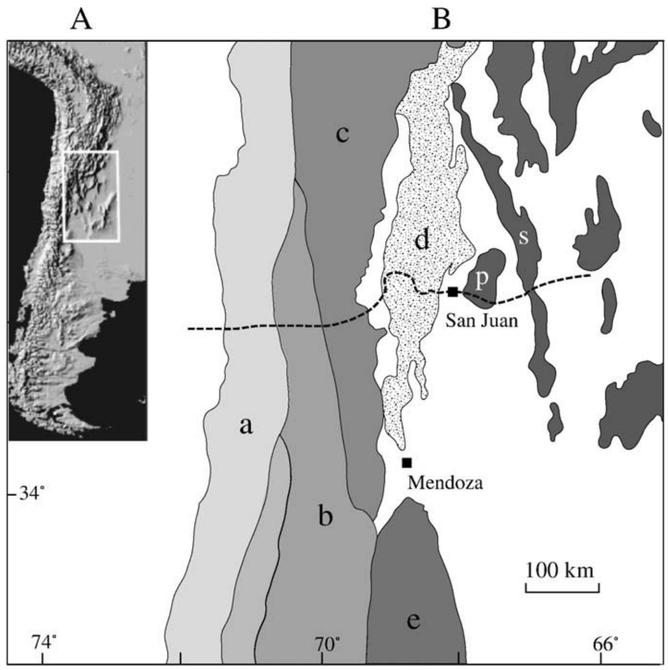

Fig. 2. A. Location of the study area. Relief after ETOPO5 (NOAA-NGDC website, June 2006). B. Major structural units of central South America: a: Cordillera de la Costa; b: Cordillera Principal; c: Cordillera Frontal; d: Precordillera; e: San Rafael Arch. The Sierras Pampeanas are shown by dark gray shading; p: Pie de Palo; s: Sierra de Valle Fértil. Intervening areas covered by alluvium. Dashed line shows course of 32° S traverse (adapted from Introcaso et al., 1992).

to imply that most of the shortening is aseismic (Klosko et al., 2002). How the low-angle subduction at depth is converted to near-surface shortening is not fully understood (Alvarado et al., 2005a).

The Sierras Pampeanas include a wide range of structural types and levels of tectonic activity which point to shortening concentrated in the shallow crust. The Andean deformation front in the Precordilleras and Sierras Pampeanas north of Mendoza (32°–33° S) is characterised by thrust systems which embody inherited structures and which can be divided into east-verging Precordilleran thrusts and west-verging Pampean thrusts (Costa et al., 2006). Some of the former are expressed by monoclinal scarps and propagation folds which are sufficiently recent to have deformed Pleistocene–Holocene alluvial units and which display dips of up to 12° (Costa et al., 2000). Progressive displacement of the Mendoza river from a W–E to a S–N course may reflect the growth of an active Pampean structure (Costa et al., 2006). Further evidence of recent deformation comes from the Los Molinos fault, in the Sierra de Comechingones NE of San Luis, which gave calibrated AMS ^{14}C ages of 985±185 and 1225±75 years BP (Costa and Vita-Finzi, 1996) indicating ~2.1 m of slip over the last ≤1300 years. Other faults in the region demonstrate repeated slip, some of it coseismic (Costa et al., 2000).

3. Sierra Pie de Palo as a diapir

Unlike its neighbouring ranges, the Sierra Pie de Palo is broadly symmetrical in plan view and its convex surface has a steeply dissected morphology suggestive of rapid uplift (Fig. 3). Some of the prominent erosion channels that cross it follow normal faults and pre-existing shear zones (Mulcahy et al., 2005). The major surface faults indicated on the geological map include a number of N–S reverse structures which bound the massif (Fig. 3). Hundreds of minor faults help to account for the weakness (*naturaleza frágil*) of the Sierra rocks (Ramos and Vujovich, 1995).

Two major stratigraphic groups have been recognised within the Sierra. The Pie de Palo Complex includes serpentinites and gabbros crosscut by dikes and sills. The Caucete group includes quartzites and carbonates. The contrasting lithologies may well mark a Lower Palaeozoic suture between Laurentian and Gondwana terranes (van Staal et al., 2002) but, as Mulcahy et al. (2005) observed, lower crustal sequences can embody a wide range of lithologies and rheological and thermal gradients which will complicate the pattern of deformation; moreover, crystallisation ages are notoriously elusive especially where metamorphism has been rampant. If the deformation episodes in question were characterised by low temperatures, as suggested below, the available radiometric ages can only serve as maxima at best.

The regional fault kinematic data yield compressional directions for the Precordillera and the Sierras Pampeanas which depart little from E to ESE (Siame et al., 2005), consistent with the NUVEL-1a model. The 1977.11.23 (M_s 7.3) Caucete earthquake was a double event, with the two shocks 21 s and 65 km apart and 17 km deep. Coseismic faulting included tensional features at the surface of the Sierra and overthrusting of its eastern margin by valley deposits (Kadinski-Cade et al., 1985). Tilted Quaternary deposits are found on the NE flank, close to one of the epicentres, and in the south where a small basement block was reactivated near the second epicentre (Ramos and Vujovich, 1999).

The 20,000 earthquakes recorded by a portable digital network in 1987–88 were strongly concentrated within the topographic limits of the Sierra (Fig. 3B). The distribution of events shallower than 20 km points to structures that are aligned both along and across strike; out of 120 focal mechanisms, 60% indicated reverse faults on roughly N–S nodal planes. The aftershocks (Figs. 3B and 4), taken together with the pattern of uplift, were initially taken to indicate that the main event amounted to 4 m of down-dip slip on a NS-striking buried fault dipping 35° W (Kadinski-Cade et al., 1985). A later analysis indicated a hypocenter at a depth of 25 km on an E-dipping fault which ruptured updip (Langer and Bollinger, 1988). Neither the aftershock record nor modelling of the deformation helps one to choose between the two options (Régnier et al., 1992). It would seem equally valid to infer pervasive coseismic deformation slightly distorted by existing faults. Analysis of 114 P and T axes gave a resultant σ_1 with an azimuth of 107°. In short, Pie de Palo is under ESE–WNW compression in the context of what Régnier et al. (1992, p. 2560 and 2566) describe as a 'sheared grid pattern of epicenters…in map view'; its constituent material 'is highly fractured and has several very active fault systems.'

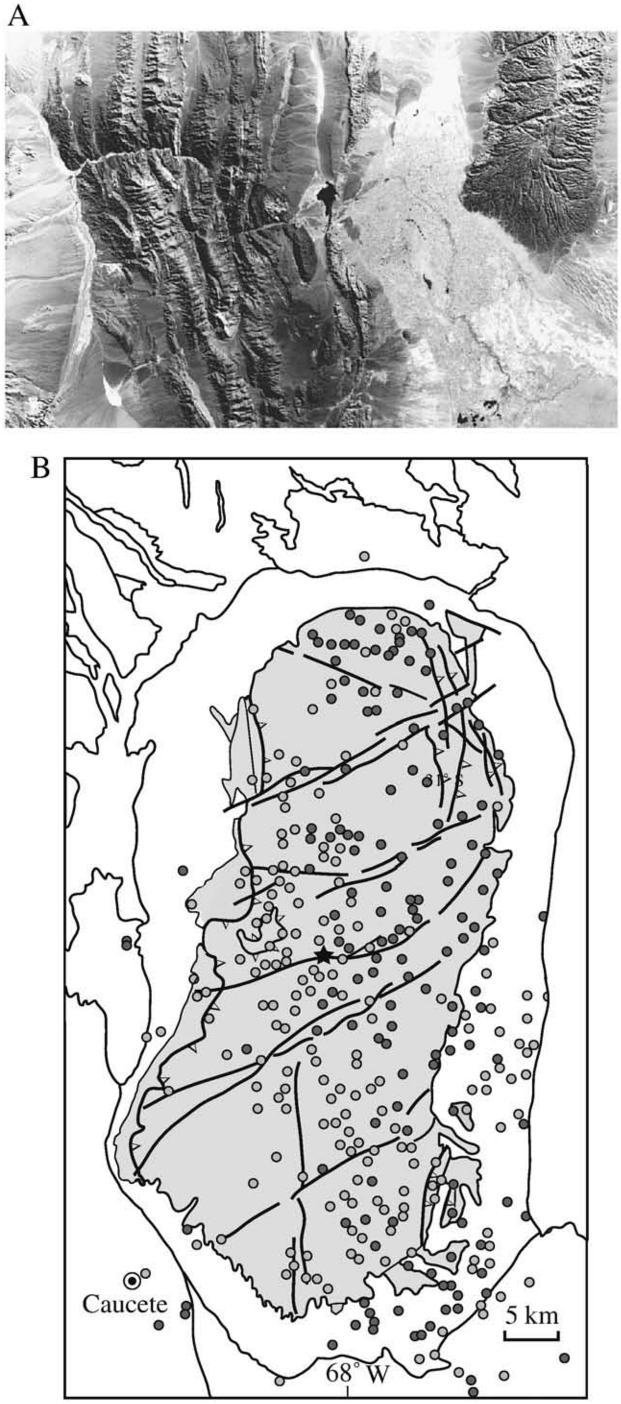

Fig. 3. A. LANDSAT image of Sierra Pie de Palo (upper right) and part of characteristic tilted-block morphology of Sierras Pampeanas. The Sierra has a maximum width of about 30 km. B. Major surface faults of Pie de Palo (teeth symbol indicates reverse faults; remaining faults are normal) after Ramos and Vujovich (1999), and location of shallow epicentres recorded during September 1987–May 1988 (dark grey: depth <20 km, light grey: depth 20–40 km; star marks epicentre of mb 5.3 event of 1988.3.25) after Régnier et al. (1992).

An E–W geodetic line (known as N23) runs at about 31°36′ S (Fig. 2b) between San Juan and Chepes, in La Rioja province. The line was first levelled in 1938 and resurveyed in 1967, 1975/6 and, following the Caucete earthquake (M_s 7.3), in 1978 and 1980 (Volponi et al., 1984). Uplift at Pie de Palo (the line ran around its southern rim) was in progress well before the 1977 earthquake and totalled 52.9 mm at one of the stations on the line (# 31) between 1938 and 1976, an average of 1.4 mm/year. Between 1976 and 1978 the same levelling station recorded a (presumably coseismic) rise of over 1085 mm. To judge from the graph published by Volponi et al. (1984) there was an additional rise of 10 mm in the ensuing 2 years (Fig. 5). These movements were accompanied by up to 700 mm of subsidence west and east of Pie de Palo, as might be expected if the uplifted mass draws upon a subsurface reservoir of polycrystalline material subject to tectonic compression.

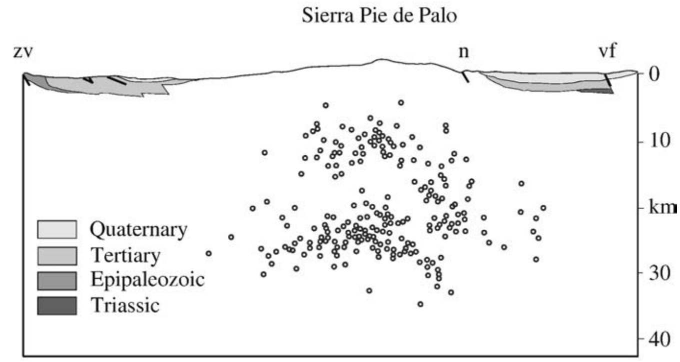

Fig. 4. Vertical distribution of aftershocks (after Ramos and Vujovich, 1999). zv: Zonda Villicum fault; n: Nikizanga fault; vf: Valle Fértil fault.

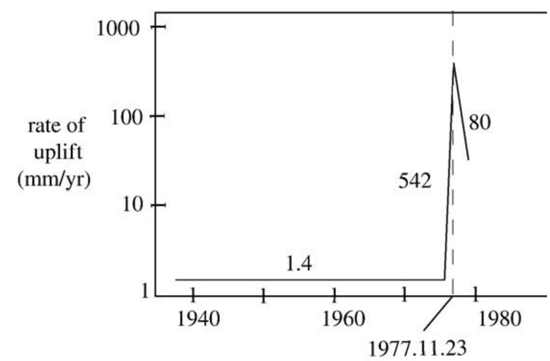

Fig. 5. Rate of uplift of southern margin of Pie de Palo (data from Volponi et al., 1984, Station 31, Table V).

4. Discussion

The proposed extrusion mechanism is here termed *cataclastic diapirism* because it is cognate with the mobility that is displayed by some fault materials, and also the cores of anticlines and synclines, after repeated or sustained motion has created a microbreccia whose texture presents little obstacle to further displacement (for example Lin, 1997). However, the pattern of seismicity demonstrates that the process is distinct from the localised cataclastic failure that may arise at thrust bends (Wibberley, 1997).

According to this scheme, continuous (though not necessarily uniform) extrusion will be temporarily accelerated by the high stresses accompanying seismic contraction.

Evidence of internal shearing comes from the distribution and mechanism of the aftershock epicentres mapped at Pie de Palo by Régnier et al. (1992), the field observation of numerous minor faults (Ramos and Vujovich, 1999), and the mylonites and ductile thrusts and folds that mark gross discontinuities in the stratigraphic sequence (van Staal et al., 2002). It may also be that some of the coseismic uplift is dilatant.

Cataclastic flow refers to deformation of polycrystalline solids at low temperatures which is accompanied by relative displacement, crushing and fracturing of individual grains (Ramsay, 1967). There is the interesting possibility that at very high confining pressures cataclastic flow might give way to low-temperature plasticity but the suggestion is difficult to explore experimentally because, as Murrell (1990) reports, laboratory simulation is currently limited to about 1500 MPa and in any case ductile behaviour in silicates requires high temperatures and low strain rates as well as high pressures. The term cataclastic is thus retained provisionally because the deformation in question is accomplished under high confining pressures (Meredith, 1990) but without any evidence of true plastic strain.

The process may be viewed as extrusion through a die (Fig. 1D) but that too has to be an imperfect analogy specially as cold working of metals tends to reduce ductility by the Hall–Petch effect (Louchet et al., 2006), whereby an increase in the number of dislocations resulting from a reduction in grain size can increase yield strength. Even so, any such effect will merely enhance the susceptibility to brittle deformation of the emerged rock mass. Some of the faults conventionally thought to govern block uplift in the Sierras may be secondary effects resulting from the shearing that occurs at the die wall during ram extrusion (Perrot et al., 2006).

The deformation front of the Precordillera has experienced a total shortening of some 40 km during the last 5 million years, of which 15 km are concentrated at the Sierra Pie de Palo (Ramos et al., 2002). The requisite forces are readily available once the primary source is seen to be near-surface, west-verging plate displacement rather than eastward Nazca subduction: a notion that is consistent with two depths of seismicity at the latitude of the Pie de Palo (Siame et al., 2006), one ('crustal') at 5–35 km and the other ('subduction') at about 100 km. In the GPS analysis by Brooks et al. (2003) the Pie de Palo is within an Andean microplate which is overthrusting the South America plate. The underlying décollement is viscously coupled to the microplate so that some stress transmission can occur across the boundary. Whether or not earthquakes at the Nazca boundary influence the tempo of creep, as Brooks et al. (2003) suggest, their model can accommodate a westward component in the regional control of surface deformation.

Silver et al. (1998) observe that the spreading velocity of the South Atlantic has remained roughly constant over the past 80 million years, even though northeastward absolute motion of the Africa plate slowed 30 million years ago to about 10 mm/year, with the implication that the South America plate accelerated westwards to 28 mm/year. The key point as regards this paper is that compression has been shallow, substantial, sustained and prolonged. Near-surface stresses would help to account for a positive anomaly of 50 mGal revealed over the Pie de Palo structure by a gravimetric survey at about 32° S (Fig. 2b). Introcaso (1987) invoked a crust thick enough to support the excess mass; yet the excess is easy to sustain if by regional compression rather than by isostasy.

5. Conclusions

Studies of diapirism in the literature of rock mechanics tend to focus on buoyancy forces supplemented, at most, by variations in vertical loading and with fold or fault movement acting as initiating trigger (e.g. Price and Cosgrove, 1990; Turcotte and Schubert, 2002); the emphasis here is on lateral compressive forces, with density differences as secondary factors. Compare, for example, the 'cold' diapirs and plumes identified in the Bushveld Complex, which rose at an average rate (~8 mm/year) and brought cooler material into higher crustal levels (Gerya et al., 1995) but were still given their buoyancy by temperature differences. In addition, as with the Cambrian Hormuz salt of the Zagros diapirs, the age of the constituent material is largely irrelevant to the issue of its emplacement.

The proposed mechanism may also apply to other settings where prolonged compressive forces act on suitable metamorphic material, such as the peridotite in the St Paul's Fracture Zone, part of the Mid Atlantic Ridge system, whose emplacement and intense mylonization was described by Melson et al. (1972) as the product of solid-state intrusion. It follows that cataclastic diapirs can serve as pressure gauges in intraplate areas under tectonic compression. Their initial identification lends itself to remote sensing as it is almost entirely a question of morphology.

Acknowledgments

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