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Lithospheric response to volcanic loading by the Canary Islands: constraints from seismic reflection data in their flexural moat

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ABSTRACT

We use multichannel seismic reflection profiles to determine the seismic stratigraphy of the flexural moat that flanks the Canary Islands. The moat stratigraphy has been divided into 5 units on the basis of internal character and correlation of distinctive reflections. The deepest units, I and II, which well-ties indicate are Eocene and older, thicken towards the east suggesting they are the consequence of sediment loading at the Moroccan continental margin. Units III, IV and V, which are Oligocene and younger and highly reflective, thicken concentrically around individual islands suggesting they are dominantly the result of volcanic loading. Distinct stratigraphic patterns of onlap at the base and offlap at the top of individual flexural units are seen on the across-moat profiles but they were not easily identified on our limited along-moat profiles. The thickness of the upper three units is in accord with the predictions of flexural loading models. Moreover, a model in which the volcanoes that make up the Canary Islands *progressively* load the underlying lithosphere from east to west generally accounts for the thickness variations that are observed in the region of individual islands. We date the shield building stages of the Fuerteventura, Gran Canaria and La Gomera as Oligocene to Early Miocene, that of Tenerife as Middle Miocene to Late Miocene and those of La Palma and El Hierro as Pliocene to Quaternary. The best overall fit to stratigraphic data in the northern moat is for an elastic thickness of the lithosphere, T_e, of 35 km, which is similar to the 30–40 km which would be expected for Oligocene and Neogene loading of Jurassic oceanic lithosphere. There is evidence that a contribution from the margin is required to explain the divergence of Units III, IV and V along the Moroccan margin. Detailed modelling of an along-strike seismic profile of the moat north of Tenerife and Gran Canaria, however, suggests that flexure due to island loading fully explains the stratigraphic patterns that are observed and does *not* require an additional contribution from the margin. The most likely explanation for this observation is that a 'barrier' had developed by the Oligocene, along the present trend of Fuerteventura and Lanzarote, which prevented sediments from the Moroccan margin infilling the northern parts of the moats caused by volcanic loading. Furthermore, there is evidence from differences in the thickness of Units I and II that a barrier may also have existed *prior* to the Oligocene which protected the northern basin from corrosive bottom currents that removed large amounts of late Cretaceous and Palaeogene age material from the southern basin.

Key words: Canary Islands, flexure of the lithosphere, seismic reflection, seismic stratigraphy.

1 PREVIOUS STUDIES OF OCEANIC ISLANDS

Many intraplate volcanic ocean islands broadly follow a three-stage evolutionary pattern, consisting of an early submarine stage, followed by a shield building stage and finally a subaerial differentiated stage (Staudigel & Schmincke 1984). The shield stage generally comprises 90 per cent or more of the total volume of an island, and consists primarily of basaltic magmatism. During this stage the volcano grows rapidly and, if sufficiently large, will flex the underlying lithosphere to form a bathymetric low or 'moat' around it and a high or 'bulge' some distance away. The geometry of the flexural moat depends on the size of volcanic load and the strength of the underlying lithosphere (commonly parametrized by its 'elastic thickness', T_e). Once formed, a moat will fill with sediments derived from adjacent volcanoes (e.g. mass wasting and subaerial ash falls) together with sediments of a non-volcanic origin (e.g. pelagic 'rain'). Volcaniclastic debris flows, formed by large-scale flank collapse, are thought to be particularly important late in the period of active shield growth, when an individual oceanic volcano is close to its maximum height (Moore *et al.* 1989). Deposits formed by these flows commonly form a drape over the central volcanic core (formed of intruded rocks and lava flows) to form an 'apron' and may contribute not only to the filling of the surrounding moat but also to the sedimentary succession far beyond the bulge (Weaver *et al.* 1992).

Previous studies have suggested that the stratigraphic patterns in flexural moats contain important information on both the rheology of the lithosphere and the tectonic control of sedimentation in the deep-sea. ten Brink & Watts (1985) predicted, for example, a pattern of offlap which represents the stratigraphic response to the decreasing width of the moat as the lithosphere is heated and weakened during volcano emplacement. Within each offlap 'sequence' these workers suggest that there is onlap which reflects the gradual filling of the moat. A similar model has recently been proposed by Watts & Zhong (2000), the main difference being that the offlap pattern results from a load-induced stress relaxation rather than lithospheric heating and weakening.

While offlap is the main pattern that would be predicted for isolated oceanic islands and seamounts, island chains, such as the Hawaiian islands, would be expected to show more complex patterns as new island loads modify the moats of pre-existing islands. According to Watts & ten Brink (1989), the net-effect is to produce a pattern of seismic reflections that is also dominated by onlap in their lower section and offlap in their upper section. These patterns of reflections will be observed on both along-strike and across-moat profiles, but they would be best-developed along-strike because of the alignment of these profiles in the general direction of load migration.

The progressive loading model was tested at the Hawaiian chain by Rees *et al.* (1993) who acquired a high resolution grid of seismic reflection profiles of the moat north of Oahu, Molokai and Hawaii. They confirmed that onlap is dominant on across-strike profiles. They failed, however, to find evidence for onlap along-strike. They attributed this to the contribution to the moat infill of a new island along the chain of older, pre-existing, islands. The Hawaiian surveys were followed by seismic studies of the moats flanking the Marquesas Islands in the Pacific (Wolfe *et al.* 1994) and Réunion (de Voogd *et al.* 1999) in the Indian Ocean. At Marquesas, the moat is overfilled with sediments. At Réunion, however, there is an absence of a moat and flanking bulge or any clear unconformity that separates the post- and preflexure sediments. Both the Marquesas and Réunion are associated with a topographic swell and it is possible that regional uplift due to deep mantle plumes has, in these cases, obscured the more local effects of lithospheric flexure.

In this paper, we present the results of a study of the seismic stratigraphy of the flexural moats that flank the Canary Islands in the central-east Atlantic. Unlike Hawaii, the Marquesas and Réunion, the Canary Islands lack some of the features normally associated with hot-spots such as a well-developed topographic swell and a long-wavelength gravity and geoid anomaly. The Canaries may therefore be ideal for the study of flexure that is generated by surface, rather than subsurface, loads. However, there are complexities in the Canary Islands region. The African plate has moved very slowly (<20 mm a^{-1}) during the past 60 Ma (Klitgord & Schouten 1986) so flexural interactions and hence, stratigraphic patterns, due to successive loads along the chain may be difficult to separate spatially. In addition, although there is evidence for an age progression along the volcanic chain, suggesting a hot-spot origin (Holik & Rabinowitz 1992), individual islands have unusually long eruptive histories (>15 Ma) and there are large overlaps in ages. Also, some of the islands (e.g. Tenerife) are formed by more than one distinct volcanic centre that was active at different times. Finally, the moats are close to the African coast and therefore would have been infilled, at least partly, by margin-derived sediments.

2 THE CANARY ISLANDS AND THEIR GEOLOGICAL SETTING

The Canary Island ridge, which has been constructed on the upper continental rise offshore Morocco (N.W. Africa), consists of seven main islands: Lanzarote and Fuerteventura in the east, Gran Canaria, Tenerife and La Gomera in the centre, and La Palma and El Hierro in the west (Fig. 1). The ridge is surrounded by a bathymetric moat and bulge with a vertical amplitude of about 500 m and horizontal wavelength of about 200 km. All the islands except La Gomera have been volcanically active within the last 5 ka (Schmincke 1982). Three of the islands (Gran Canaria, Tenerife and La Palma) are over 2000 m high, and Tenerife reaching 3700 m is the world's third largest oceanic volcano after Mauna Kea and Mauna Loa.

The Canary Islands are situated within the Jurassic magnetic quiet zone so the location of the ocean–continent boundary is unclear. However, at least the western and central islands are underlain by oceanic crust since magnetic anomaly M25 (~ 160 Ma) lies just west of La Gomera (Roest *et al.* 1992) and crust with an oceanic seismic velocity structure underlies Tenerife (Watts *et al.* 1997).

Radiometric (K–Ar) dating of the oldest subaerial volcanic rocks found on each island indicate an age progression from east to west along the group. Ages compiled by Schmincke (1994) are summarized in Fig. 1 and range from 20 Ma on Fuerteventura to 2 Ma on El Hierro. However, there is controversy regarding the dating of the oldest subaerial rocks on Fuerteventura. Le Bas *et al.* (1986), for example, deduced a K–Ar age >48 Ma for the island from a ring dyke. Storetvedt (1980) also obtained a late Cretaceous/earliest Tertiary age for a subaerial lava on the island and suggested that K–Ar ages are too prone to thermal resetting to be a reliable age indicator.

Although the subaerial history of individual Canary Islands is reasonably well known the age of their submarine edifice is poorly constrained. Evidence for this early stage comes from uplifted and deeply eroded marine sections exposed on the islands (Robertson & Stillman 1979; Staudigel & Schmincke 1984), deep-sea drilling (von Rad *et al.* 1979; Schmincke *et al.* 1995) and stratigraphic relationships on seismic reflection profiles (Funck *et al.* 1996). A problem for establishing the onset of magmatic activity is the widespread occurrence of major Cretaceous and Palaeogene unconformities in this part of the eastern Atlantic (Fig. 2b). To date no continuous section spanning the Neogene to Lower Cretaceous is available to resolve the issue of when submarine volcanism started.

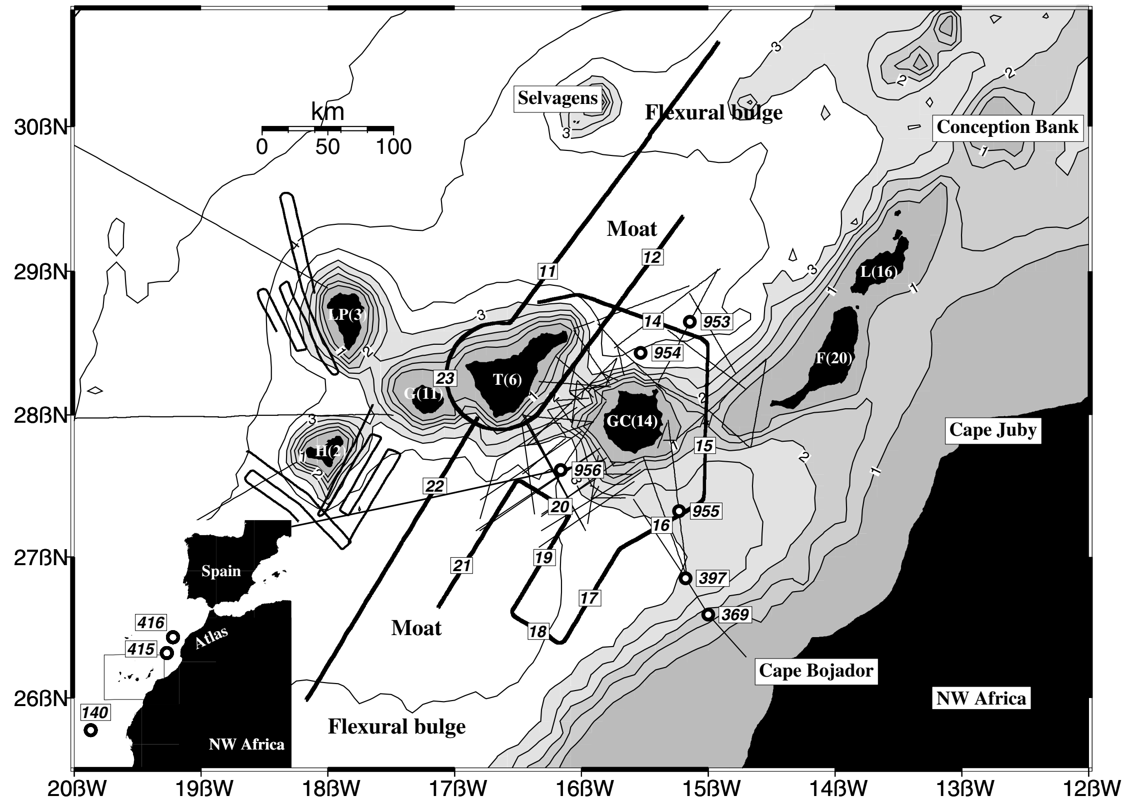

Figure 1. Location of the Canary Islands. Individual islands are as follows: L = Lanzarote, F = Fuerteventura, GC = Gran Canaria, T = Tenerife, *G* = La Gomera, LP = La Palma, and H = El Hierro. The numbers in brackets are the ages of the oldest subaerial volcanic rocks on each island in Ma given by Schmincke (1994). RRS *Charles Darwin* (cruise CD82) seismic reflection profiles (11–22) presented in this study are marked with bold annotated lines. Other seismic reflection profiles are marked with fine lines and include R/V *Meteor* profiles across the Cape Bojador slope and rise (cruise M46, Wissmann 1979), around Gran Canaria (cruise M16, Geisslinger *et al.* 1996 and M24, Funck *et al.* 1996); RRS *Charles Darwin* around El Hierro and La Palma (cruise CD108, Gee 1999) R/V *Poseidon* in the southern basin (line 236 Müller *et al.* 1999) and commercial seismic lines west of the islands (Banda *et al.* 1992). Open circles show DSDP and ODP drill holes used in this study. Contours are bathymetry (in km), with depths shallower than 3 km shaded.

The basal complex on Fuerteventura (Rothe 1968; Robertson & Stillman 1979; Ancochea *et al.* 1996) consists of a 1.5 km section of Lower Cretaceous (Valanginian to Aptian) deep-water fan complex sediments (turbidites, black shales and redeposited carbonates) overlain by Upper Cretaceous marls, clastics and chalks. Comparison with cores drilled on the neighbouring upper continental rise [Deep Sea Drilling Project (DSDP) site 416 in particular but also DSDP sites 415 and 397] shows this section to be typical of ocean-floor sedimentation during this period (Robertson & Bernoulli 1982). Above the Upper Cretaceous sequence there is a shallow submarine (water depth <100 m) pillow lava and hyaloclastite of uncertain age followed by interbedded shallow-water Oligocene sediments and volcaniclastics. The latter series is not disputed and so represents the oldest confirmed volcanic deposit from the Canary chain. However, considerable debate has focused on whether the first volcanic rocks are conformable with the Upper Cretaceous series. Le Bas *et al.* (1986) consider the contact to be conformable and also report an interbedded Santonian chalk and volcaniclastic unit at a different Fuerteventura location and so propose that magmatism started in the Upper Cretaceous ($\sim$85 Ma).

At DSDP site 397, four submarine and subaerial volcaniclastic layers dated 17.6–16.5 Ma and 15 subaerial ash fall deposits dating from 19.3 Ma, but mostly 14–0.3 Ma, were found (Schmincke & von Rad 1979). Unfortunately, below the Neogene section there was a 100 Ma hiatus, and so it could not be established whether volcanism started in the Palaeogene or earlier. More recent Ocean Drilling Program (ODP) holes (sites 953–956) close to the islands (Schmincke *et al.* 1995) bottom in Miocene rocks and so do not help resolve this issue. Current data therefore only constrain the timing of the inception of magmatic activity to be after the Cenomanian (start of the Upper Cretaceous) and before or during the Oligocene.

Major unconformities in the Upper Cretaceous and Palaeogene are a feature of most of the holes drilled in the upper continental rise and slope (Fig. 2b). The sedimentary history here is influenced by the rate of subsidence, sediment supply from the continent (Africa drifted 6° north during the evolution of the margin into increasingly more arid conditions) together with global fluctuations in sea level, climate and ocean circulation. A generalized lithological and accumulation rate log for the continental rise is shown in Fig. 2(c). The early history of the margin was dominated by the deposition of a thick carbonate platform on the shelf. This sequence was overwhelmed in the Early Cretaceous by out-building of deltaic sediments which deposited a thick sequence of turbidites on the rise. From Late Cretaceous onwards sedimentation rates fell sharply due to reduced terrigenous supply from the adjacent continent as the African plate drifted northward. As a result the continental slope changed from active progradation to erosion with the

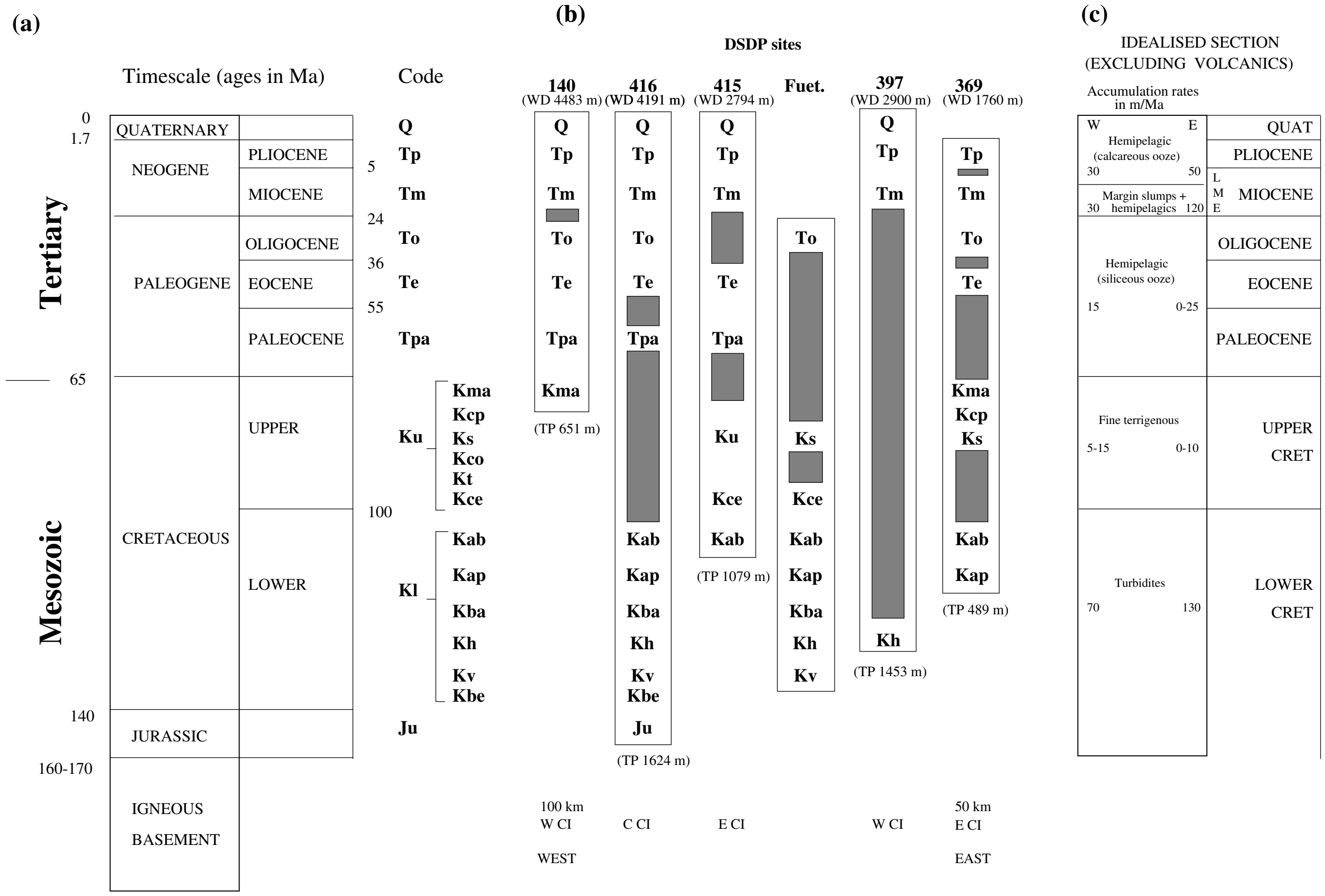

Figure 2. Summary stratigraphy. (a) Reference timescale. (b) Summary sections showing temporal distribution of major sedimentation hiatuses (marked by shaded bars). Data sources: DSDP site 140, Hayes *et al.* (1972); DSDP sites 415 and 416, Lancelot *et al.* (1980); Fuerteventura section (Fuet.), Robertson & Bernoulli 1982; DSDP site 397, von Rad *et al.* (1979) DSDP site 369, Lancelot *et al.* (1978). WD is water depth and TP total penetration. The sections are arranged as a transect from the mid continental rise (DSDP site 140) to the mid continental slope (DSDP site 369). See Fig. 1 for section locations. The Canary Ridge spans the part of the rise about 100 km landward of site 140 to 50 km seaward of site 369. (c) Idealized lithologic section based on a combination of the drilling results and summary given by von Rad & Arthur (1979). Average sediment accumulation rates are shown for positions on the rise equivalent to the westernmost and easternmost Canary Islands. These averages were made from DSDP holes not containing volcanic sediments from the Canaries and so represent expected 'background' rates from margin and pelagic sources.

cutting of deep canyons shifting the depocentre to the upper rise (von Rad & Wissmann 1982). In addition to falling terrigenous supply, shoaling of the calcium compensation depth (CCD) in the late Cretaceous led to dissolution of biogenic carbonates on the upper rise. The major hiatuses recorded in logged sections are therefore thought to be due to processes such as the development of slope incision and gravitational slumping, together with deep geostrophic contour currents linked to major changes in ocean circulation (e.g. Arthur *et al.* 1979). Most of the drillholes show complete Neogene sequences although many record distinct intervals of slumping off the slope and shelf which may be linked to Alpine deformation in the Atlas Mountains of northern Morocco. Otherwise conditions have been relatively quiet on the rise since the Oligocene with oceanographic upwelling resulting in high accumulation rates of calcareous hemipelagic sediments.

Geophysical logging at DSDP site 397 showed a significant acoustic impedance contrast between volcanic components and both the margin (generally quartz and feldspar) and biogenic deposits (Funck & Lykke-Anderson 1998). Discrete volcanic layers are therefore potentially good seismic reflectors provided they are thick enough (as a rule of thumb a thin layer needs to be of the order of one thirtieth of a wavelength to be detected—for 10–20 Hz typical of deep seismic data this is equivalent to a few metres). At site 397, the volcaniclastic units, which are generally a few metres thick, were shown to correlate with discrete, high amplitude reflections whilst the ash fall deposits, which are generally thin (<5 cm thick) and commonly disturbed by burrowing did not (Wissmann 1979). Funck *et al.* (1996) and Geisslinger *et al.* (1996) confirmed that prominent reflections mapped over geographically extensive areas correlated with distinct volcaniclastic units drilled in ODP sites 953–6.

3 DATA ACQUISITION, PROCESSING AND ANALYSIS

The data presented here were collected in 1993 during the R.R.S. *Charles Darwin*, cruise 82. A total of 2300 km of multichannel seismic reflection profiles were acquired in the northern and southern flexural moat of Tenerife and Gran Canaria (Fig. 1). In general the profiles were aligned either across the strike of the flexural moat (lines 11, 12, 17, 19, 21, 22) or along its strike (lines 14, 18, 20). The across-strike profiles are approximately parallel to the continental margin trend and oceanic crustal isochrons. The longest lines 11 and 22, which extend from the seismically chaotic apron, across the moat and onto the flexural bulge, were instrumented with ocean-bottom seismometers, complemented by landstations on the island of Tenerife, to provide wide-angle seismic data (Watts *et al.* 1997). The seismic reflection profiles were acquired with a 2.4-km long, 48-channel hydrophone streamer. Two different tuned airgun arrays were used: for lines 11, 12 and 22 a 12-gun, 4566 in^3 array fired every 40 s ($\sim$100 m); for the other lines (14–21) a 10-gun, 3442 in^3 array was fired every 20 s ($\sim$50 m).

The data were processed using LANDMARK's PROMAX 2D (version 6.0) software. The processing scheme is detailed in Table 1. Care was taken throughout processing to preserve relative amplitudes. The final migrated stacks were displayed as both 'true amplitude' (with only time-varying gains applied) and 'amplitude balanced' (with a 200-ms automatic-gain-control operator applied) sections. The former display parameters were used to identify prominent reflections for correlation and the latter for determining the overall geometry of all reflections. Depth conversion of the data was undertaken using a 2-D velocity field devised from a combination of semblance velocities, wide-angle velocity profiles (Watts *et al.* 1997) and sonic velocities from ODP site 953 (Schmincke *et al.* 1995).

Unmigrated time sections were input to GeoQuest's IES interpretation software and prominent reflections picked, correlated and mapped. There was an element of ambiguity in correlating reflections in the northern and southern basins from the seismic data alone because of the presence of the seismically chaotic volcanic ridge that separates the two basins. Within the northern and southern basins all the Darwin profiles intersect except lines 11 and 22. Line 11 required an 8 km extrapolation from line 14 (this gap was caused by an equipment failure during acquisition). Event picking of line 22 was validated by correlation with Poseidon cruise 236 profile 28 (Müller *et al.* 1999) which crosses both it and lines 20 and 21. Dating of key reflectors and their correlation in the southern and northern basins was made with ODP site 953 via Meteor 24 line 134 (Funck & Schmincke 1998) to Darwin line 14; with ODP site 955 directly with Darwin line 16; with DSDP site 397 via Meteor 46 line 37 (Wissmann 1979) and Meteor 24 line 127 (Funck *et al.* 1996) to Darwin line 16; and with ODP site 956 via Poseidon 236 line 28 (Müller *et al.* 1999) to Darwin lines 20, 21 and 22 (Fig. 1).

4 SEISMIC STRATIGRAPHY

Stacks of all the seismic profiles are shown in Figs 3–7. The overall clarity of the seismic images is good which we attribute to the high flux of background sediments and the acoustic impedance contrasts between them and the volcanic sediments. Most of the true amplitude seismic sections (e.g. Fig. 3) show a similar overall pattern of reflectivity with increasing travel time consisting of (i) a high amplitude and coherently reflective upper region (ii) a relatively weakly reflective and less coherent middle region and (iii) a high amplitude diffractive lower region. We interpret the deepest region to be the Late Jurassic igneous oceanic crust because of its diffractive seismic character, gross morphology (distinctive saw-tooth shapes on the across-moat/close-to isochron profiles 11, 12 and 22) and seismic velocity ($Vp > 5$ km s^{-1}, Watts *et al.* 1997). The top of the oceanic crust can be picked on all but the most marginward profiles (lines 15, 16 and 17) where the combination of shallowing bathymetry and thickening sediments places it below the strong water bottom multiple.

Within the relatively transparent region that immediately overlies the oceanic basement a distinct high amplitude event/unconformity was seen on many of the profiles. In our interpretation we therefore divided this weakly reflective region into two seismic units (Units I and II). Within the upper highly reflective zone we note two particularly bright reflections which were readily correlated and mapped throughout the survey area and so in our interpretation we divided this upper series into three seismic units (Units III, IV and V). Isopachs of each of these units are shown in Fig. 8, and their characteristics and interpretation are summarized in Table 2 and described below.

Table 1. Seismic reflection data processing steps.

	Process	Details
1.	Demultiplex	4 ms sample rate, 12 s record length
2.	CDP sort	25 m bins
3.	Bad trace editing	
4.	Velocity analysis	Every $\sim$100 CDP, supergathers of 4 combined CDPs.
5.	Sp. Division correction	With stacking velocity field
6.	Nmo	25 per cent stretch mute
7.	Stack	12-fold (lines 11, 12 and 22) 24-fold (lines 14–21)
8.	f-k filter	Pass slice 3–60 Hz, -2.0–2.0 km s^{-1}
9.	Deconvolution	Min. Phase Weiner-Levinson Predictive, 248 ms operator, 32 ms gap
10.	f-k migration	Constant velocity 1500 m s^{-1}
11.	Time-varying BP filter	0–5.5 s TWT, 8–60 Hz; 5.5–6.5 s TWT, 8–50 Hz; 6.5–12 s TWT, 5–40 Hz
12.	Trace mix	5-fold, weights 1.0, 2.5, 3.0, 2.5, 1.0
13.	Time-varying gain	4 db s^{-1} (to account for anelastic absorption, scattering, etc.)
14.	Front mute	To seabed
15.	Plot	True-amplitude scaling
16.	Depth convert	Combined stacking velocity field with wide-angle results at depth

Table 2. Summary of seismic facies units in the Canary Island Moat.

Unit	Upper boundary Reflector characteristics and geometry	Interpretation [Previous nomenclature] (Age ± 1Ma)	Internal Reflector characteristics and geometry	Interpretation
V	Uppermost reflector	Seafloor	High reflectivity Parallels seafloor mainly Ponded close to islands	Pliocene-to-Recent Western islands moat
IV	Bright reflector	Pliocene volcaniclastic [R3] (4 Ma)	High reflectivity Wedge shape Onlap bulge at base, offlap at top	Mid-to-Late Miocene Central islands moat
III	Exceptionally bright, laterally continuous reflector	Mid Miocene volcaniclastic [R7] (16 Ma)	High reflectivity Wedge shape Onlap bulge at base, offlap at top	Oligocene-to-Early Miocene Eastern islands moat
II	First bright and laterally continuous reflector	Onset of significant supply of volcanic sediments to basin	Low reflectivity Moderately stratified reflectors Unconformable contacts with Unit I	Late Cretaceous-to-Early Palaeogene Margin sediments
I	Laterally coherent, bright, conformable reflection in north becoming unconformable to south	Unconformity [BGR 'red' reflector]	Low reflectivity Reflector geometry controlled by underlying basement	Jurassic-to-Early Cretaceous Margin sediments
Igneous Crust	Discontinuous reflections and diffractions forming irregular, blocky surface	Top igneous crust (160 Ma)	Reflective with many scatterers Individual reflectors subparallel to upper boundary	Jurassic oceanic crust

Unit V. The base of this uppermost unit is marked by a high amplitude, laterally coherent reflection that is readily correlated across our profiles. The reflection correlates with one named R3 by Wissmann (1979) and RN by Funck et al. (1996) which has been widely mapped on previous seismic profiles in the region. At ODP sites 953, 954 and 956 the reflection correlates with a volcaniclastic deposit dated 4.3–3.4 Ma (early Pliocene). However, a similar deposit was not found at the two sites closest to the margin—ODP site 955 and DSDP site 397. At ODP site 955 the reflection was correlated with a section characterized by abundant non-volcanic sand/silt interpreted as a slumped block but at DSDP site 397 it did not correlate with any specific lithologic unit. These drilling results are consistent with our southern basin seismic lines which show the reflector to become increasingly broken up to the east (from lines 18, 17–16), and on line 16 is clearly disrupted by slumping.

Internally seismic Unit V is characterized by several, bright, coherent reflections. On most lines individual reflections parallel the seabed throughout the unit. However on the northern across-moat line 11, towards the bottom of the unit individual

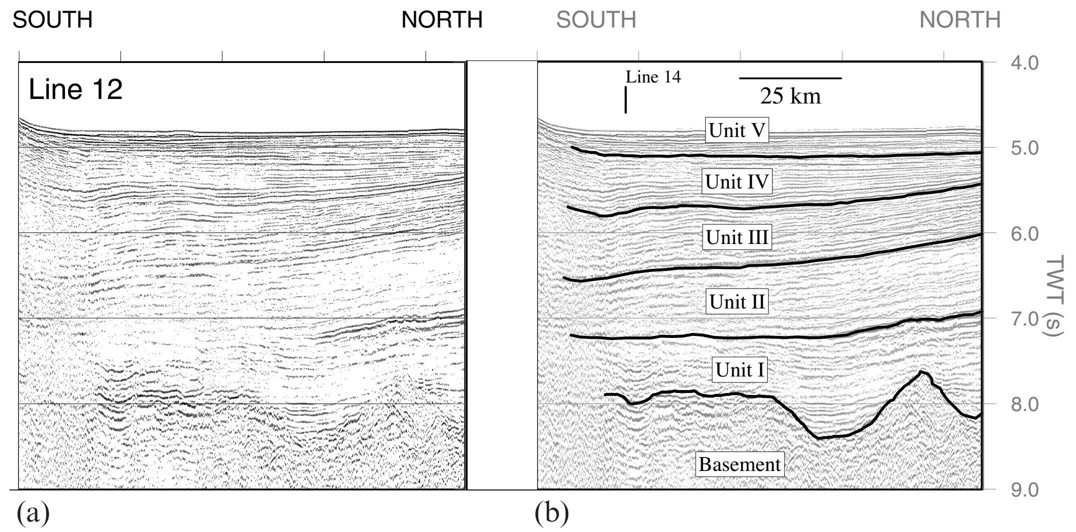

Figure 3. Across-axis seismic line 12. (a) True amplitude scaled section which emphasizes relative reflection strengths. (b) Amplitude balanced section which permits all reflections to be seen. All other seismic sections shown in Figs 4–7 have this amplitude balancing.

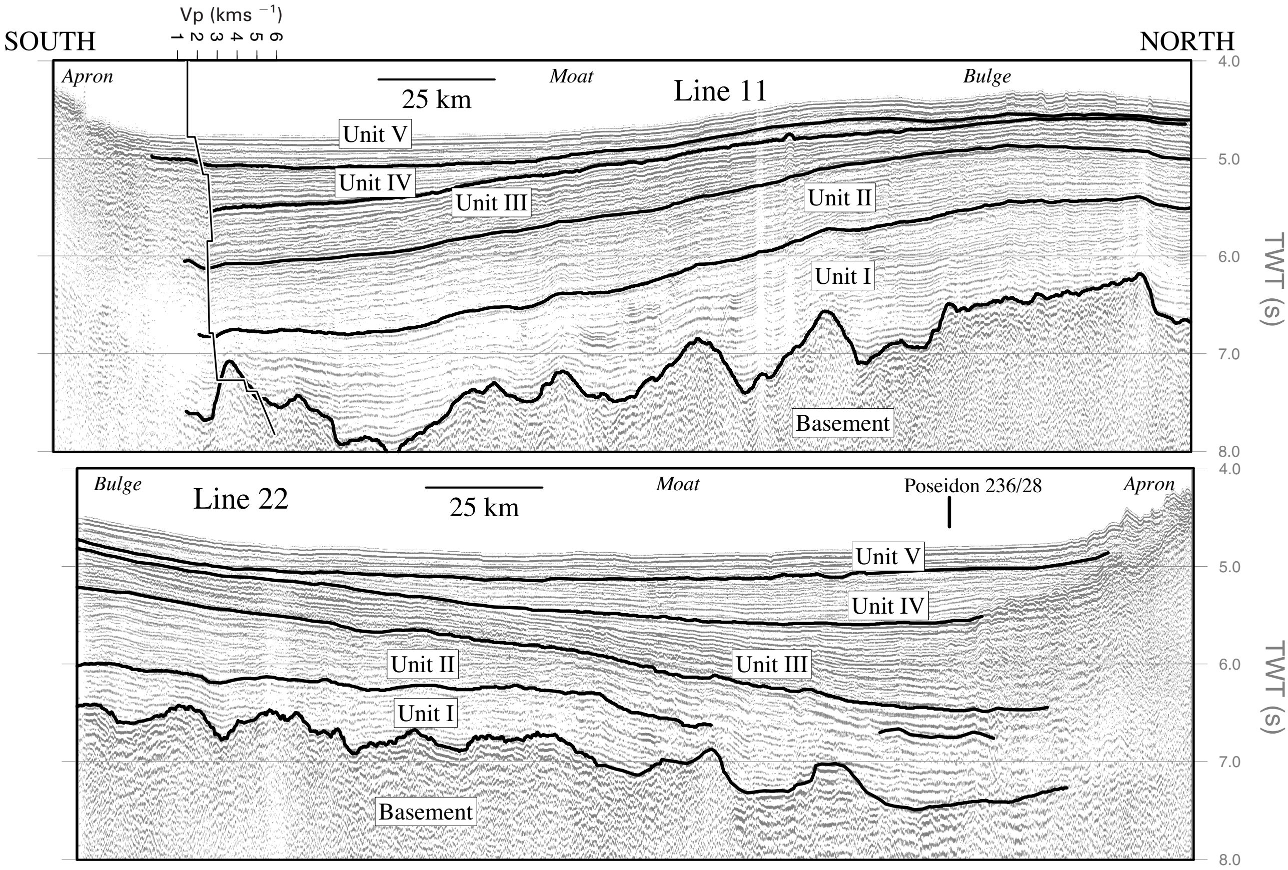

Figure 4. Across-axis seismic lines 11 and 22. These long profiles show the edge of Tenerife's apron, moat and peripheral bulge seaward of the moat. Overlain line 11 is a velocity depth profile determined by inversion of ocean-bottom seismometer data (Watts *et al.* 1997).

reflections, whilst remaining parallel to the seabed, terminate against R3 close to the islands. The terminations onlap both the bulge and the apron giving the appearance of being 'ponded' in the deepest parts of the flexural moat. We interpret this geometry as evidence for the absence of any significant moat development or modification (and hence volumetric shield growth) during the last 4 Ma. The observed internal stratigraphy is reflected in its isopachs, which show (where we have data) the unit to be thickest beneath the present-day bathymetric moat and thinning towards the bulges and eastward towards the margin. Although the thinning trends are the same in both basins, overall the unit is about 100 m thicker in the south than in the north.

We attribute the overall lower sediment flux in the northern basin to its effective shielding from margin sedimentation by the Canary Ridge. This deduction is supported by the virtual absence of slumped deposits during this period in drillholes to the north, and the damming of the sediments at the active Fuerteventura/Gran Canaria submerged ridge seen on line 15. The contrasting erosional patterns between the deeply eroded wet north-northeastern sides of the present islands and their dry southern sides only exacerbate this trend. Assuming a duration of 4 Ma for the unit, the average unit thicknesses of the northern (275 m) and southern (375 m) moats indicate sedimentation rates of about 70 and 90 m Ma^{-1}, respectively. These rates compare well with that of 66 m Ma^{-1} for units of the same age in ODP site 953 in the northern basin and 80 m Ma^{-1} in DSDP site 397 in the southern basin. The thickening of Unit V towards the west, particularly in the southern basin (counter to the direction expected for the margin component) implies that the volcanic sediment source was dominantly west of the survey area (i.e. La Palma and El Hierro).

Unit IV. The base of seismic Unit IV is also marked by a prominent reflection which is readily mapped on all lines. The reflection is equivalent to one named R7 by Wissmann (1979) which correlates in DSDP site 397 with the top of a 110 m thick series of volcaniclastic debris flows dated 15.5–17 Ma (Wissmann's reflection R8 marks its base). The last unit drilled in ODP site 953 was a 270-m unit of lapillistones and tuff. R7 correlates with the top of this unit which is dated as 14.8–15.8 Ma. R7 was not penetrated by any of the other ODP holes around the islands. ODP site 955 terminated in middle Miocene nannofossil rich clays dated 14–17 Ma which is close to the base of our seismic Unit IV on line16. Here we assign an age of 16 Ma (early middle Miocene) to the base of Unit IV.

Internally Unit IV is characterized both in the northern and southern basins by numerous, bright, coherent reflections. Individual reflections are generally more regular in the north than in the south (e.g. compare lines 11 and 22) suggesting that, like Unit V, there was at least some protection from margin slumping during this period also. However note the reflection irregularities in both the upper two units at the northern end of line 11 suggest a source of slumped material is reaching this part of the basin (perhaps from the continental slope north of Lanzarote). On the across moat profiles 11, 12, 21 and 22 the unit forms a characteristic wedge. On the more westerly pair of lines (11 and 12) there is clear onlap towards the present-day

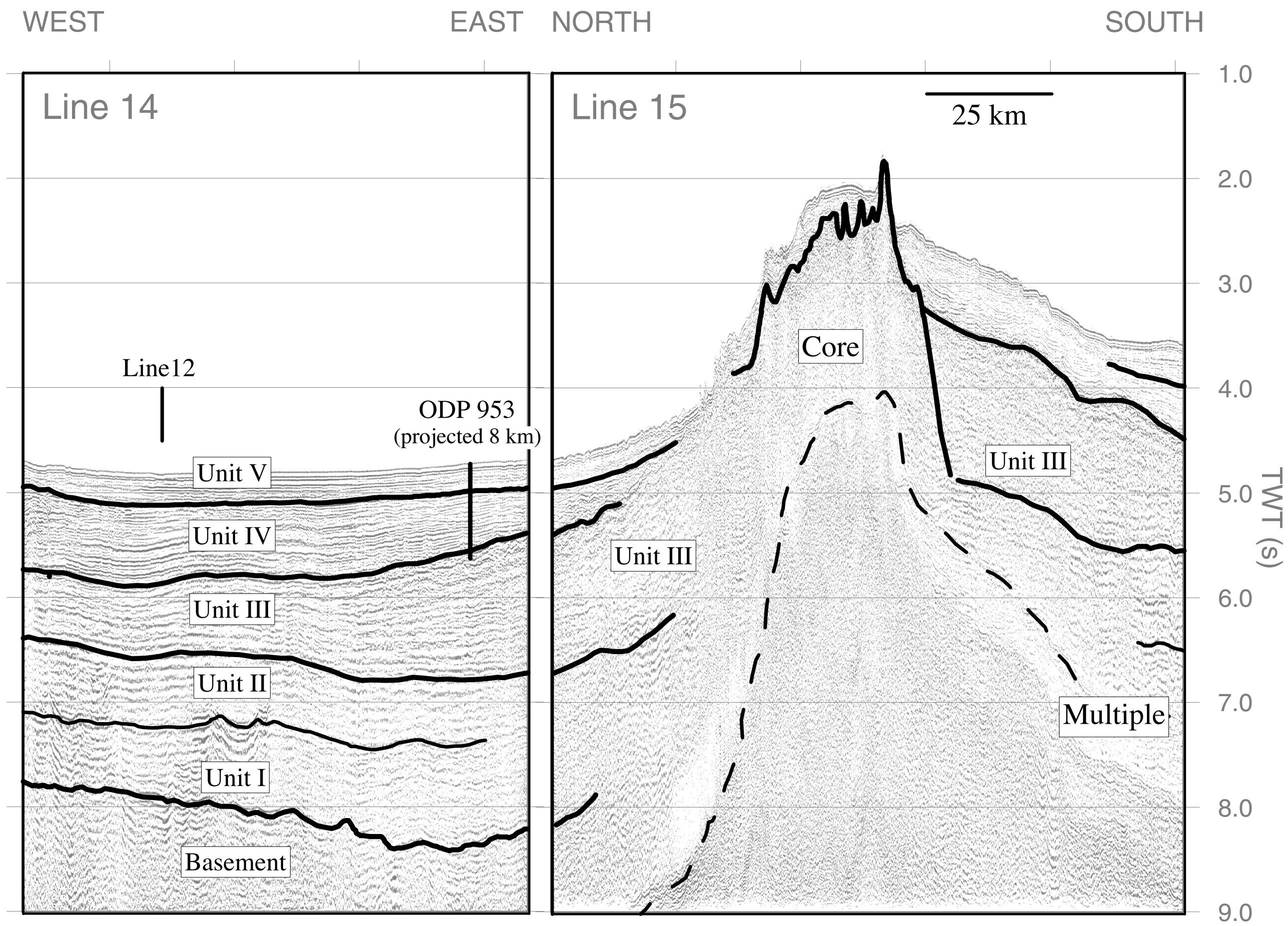

Figure 5. Seismic lines 14 and 15. Thick vertical line on Line 14 shows the location of ODP site 953 which terminated in early late Miocene lapillistone dated <17.4 Ma, Schmincke *et al.* (1995). Line 15 crosses the submarine ridge between Gran Canaria and Fuerteventura sometimes referred to as the Amanay Ridge in the literature.

bulge at the base of the unit and offlap at the top. This pattern is not clearly seen on the other two, shorter lines. The unit also forms a wedge with thinning to the east on the across-moat line 14, although as on lines 12 and 21 no simple onlap/offlap pattern of individual reflections is seen. The isopachs shows approximately concentric thickening towards Tenerife/Gran Canaria, suggesting active moat development at this time. The unit reaches a maximum thickness in the northern basin which, given that there appears to have been at least partial protection from margin slumps, implies a greater supply of volcanic material to the north.

Assuming a duration of 12 Ma for the unit, the average unit thicknesses of the northern (800 m) and southern (650 m) moats indicate sedimentation rates of about 55 and 65 m Ma^{-1}, respectively. The rates compare well with those of 50 m Ma^{-1} at ODP site 953 and 30–60 m Ma^{-1} at ODP site 955. The thickening of Unit IV towards the central Canary Islands suggests that the volcanic sediment source was dominantly from these islands.

Unit III. The base of seismic Unit III is marked by the deepest, bright and laterally continuous reflection. This event is easily correlated across profiles in the northern and southern basin, and its character makes us confident that it is the same event in both basins. We interpret the base of Unit III as marking the onset of supply of significant volcanic material to the basin. It is difficult to date this event, as it was not drilled during ODP leg 157, so we are reliant on correlation over a lateral distance of 45 km along M46-37 to DSDP site 397. At the intersection of our line 16 and M46-37 Wissmann's R10 (the deepest interpreted reflection on the Meteor line which correlates with the DSDP site 397 Neogene/Cretaceous unconformity) is expected at 5.2 ± 0.1 s TWT, but our base Unit III is observed at 5.85 s TWT. There is no evidence for a major unconformity at the base of our Unit III. Therefore as R10 has a minimum age of 24 Ma, this suggests that the base Unit III is Oligocene or older.

Another method of placing bounds on the age of the base of Unit III is to use sediment accumulation rates. At ODP site 953 the early Miocene sedimentation rate is 70–118 m Ma^{-1}. At the position of this site our seismic Unit III is about 1500 m thick which would imply a time duration of 13–21 Ma and so an age of the base of the unit of 29–37 Ma (i.e. mid-to-early Oligocene). Similarly, using the 140–180 m Ma^{-1} early Miocene rate recorded at DSDP site 397 for the whole of Unit III (thickness about 1750 m), implies a duration of 10–13 Ma and age of base 26–29 Ma (late-to-early Oligocene). A problem with this argument is that the rate of volcanic supply strongly influences the bulk sedimentation rates, and this may not have been the same in the Oligocene as it was in the early Miocene. However we conclude that the base of Unit III is probably Oligocene in age.

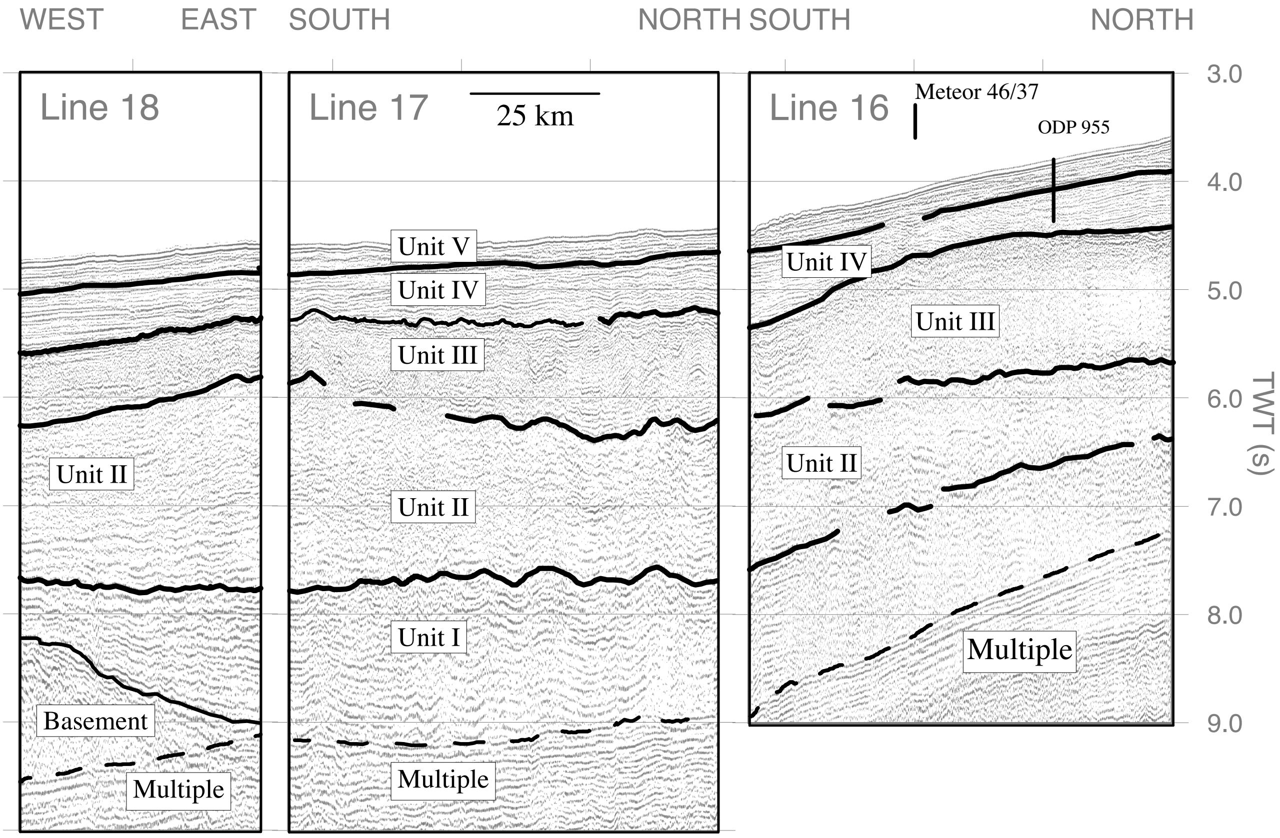

Figure 6. Seismic lines 18, 17 and 16. Thick vertical line on Line 16 shows the location of ODP site 955 terminated in middle Miocene sediments dated 14–17 Ma, Schmincke *et al.* (1995).

Internally this unit is characterized by many coherent reflections like the overlying two units. On across-moat profiles the unit forms a wedge, with reflections deep in the wedge having larger dips towards the islands than reflections higher up. The overall stratigraphic pattern is one of progressive onlap of the flexural bulge in the lower section, offlap migrating back toward the islands in the upper section. This geometry suggests that the unit formed during a period of active moat development. The northern basin lines show greater reflection coherency suggesting that this basin was somehow at least

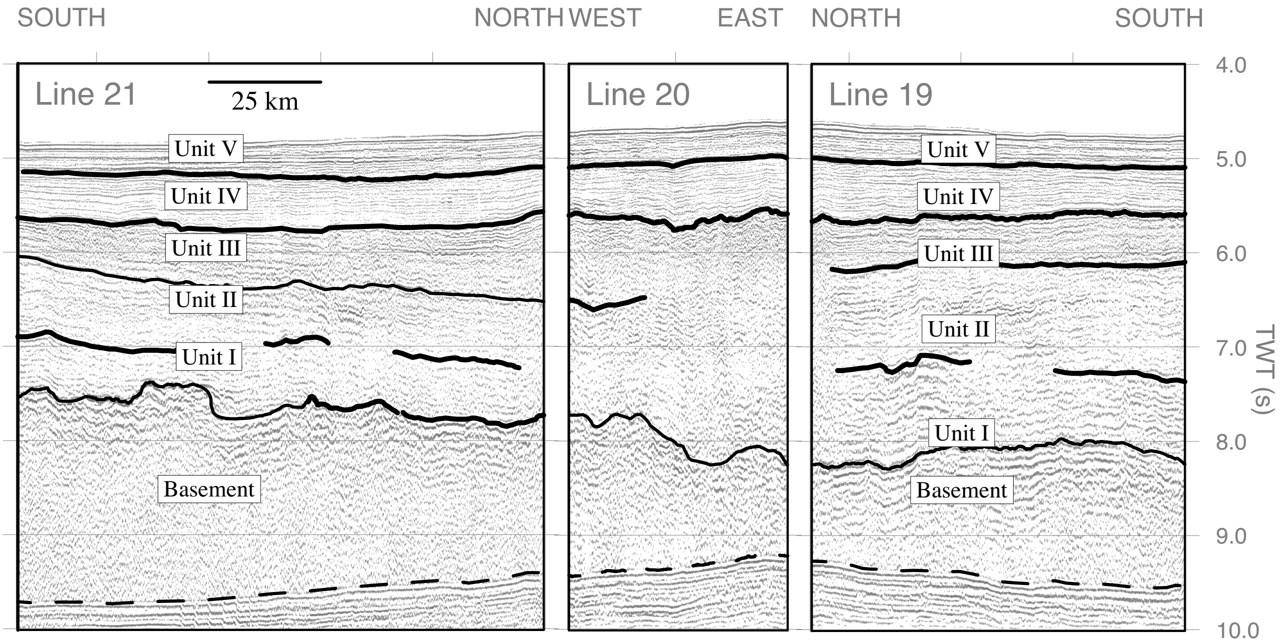

Figure 7. Seismic lines 21, 20 and 19.

partially protected from the margin during this period. Unit III is particularly thick and chaotic on lines 15 (south) and 16.

The isopachs of seismic Unit III show it to thicken in a concentric manner towards the eastern islands of Fuerteventura and Gran Canaria. However, there is a secondary maximum just offshore Tenerife/La Gomera in the southern basin.

Unit II. The base of Unit II was picked as the uppermost and brightest event of a 4–5-reflection packet. On some profiles this event is clearly an erosional unconformity, for example on lines 12 and 11. On Line 11 the unconformity is best seen close to the present day island of Tenerife, becoming more conformable to the north. In the middle of Line 14 the top of the unit forms a small basin shape bounded by raised sides which may be a channel and levee structure. We cannot definitively date the base of Unit II, but a plausible interpretation is that it is equivalent to the 'red' reflector mapped throughout the NW African margin (Kolla *et al.* 1984). Our reflector has a similar character to this reflector, consisting of either a 4–5 bright reflections or an erosional event. Where the 'red' reflector was drilled at DSDP sites 415 and 416, it was dated as Cenomanian (95 Ma). If this interpretation is correct, the thickness of Unit II which varies from ~ 3000 m in the east to 300 m in the west gives accumulation rates of 50–5 m Ma^{-1} (assuming a complete section extending from 95 Ma to 36 Ma). The likely presence of hiatuses in this unit would make the accumulation rates even higher. The rate in the east of our survey area is higher than expected for Palaeogene and Upper Cretaceous time (Fig. 2c), suggesting that the base of the unit is probably older and so includes some of the rapidly deposited turbidites from the Lower Cretaceous.

Internally Unit II is weakly reflective with semicoherent reflections. Wide-angle data from lines 11 and 22 are consistent with the bulk seismic velocity of this unit being lower than that of Unit III. The isopachs show the unit to thicken approximately linearly towards the Moroccan margin. No Canary Island concentric trend is present, which is consistent with an interpretation of the unit as being formed of margin-derived sediments deposited before the influx of significant volcanic sediments. We cannot rule out however, the possibility that early growth of a submarine volcanic ridge was occurring at this time. The transition from conformable to unconformable contact in the north at the base of the unit towards the present day Canary Islands may be significant.

Unit I. This unit overlies the oceanic basement and its internal stratigraphy shows draping and infilling of the rough basement topography. Basement relief is rougher in the northern basin, suggesting a greater number of fracture zones and smaller-order discontinuities in the seafloor spreading fabric here. The isopachs show an overall similar trend to that of Unit II with approximately linear marginward thickening. On average, the unit is around 500 m thicker in the northern basin.

5 FLEXURE MODELLING

5.1 Relative role of Neogene sediment and volcanic loading

As detailed above, two main features characterize the isopachs shown in Fig. 8: a regional thickening towards the Moroccan continental margin and a local thickening toward individual islands. The regional thickening is best displayed by Units I and II and we attribute it to sediment loading at the Moroccan margin. The local thickening, however, is best displayed by Units III, IV and V and we attribute it to volcanic loading at one or more of the Canary Islands. Fig. 9 compares the combined thickness of Units I and II with that of Units III, IV and V. According to the well-ties discussed earlier, Units I and II are Mesozoic-to-Palaeogene in age while Units III, IV and V are Oligocene and younger. Units III therefore reflect the early stratigraphy of the distal regions of the Moroccan margin while Units III, IV and V reflect the post-Oligocene loading of the islands but might also include a significant margin component.

In order to better understand the relative role of sediment and volcanic loading in determining the moat stratigraphy, we have carried out 3-D elastic plate flexure modelling. Fig. 10 illustrates the approach taken. First, bathymetric grids (Fig. 10a) were constructed from all available shipboard data and were used to isolate the main island loads from the margin (Fig. 10bc). The island loads were then used to compute the flexure of the lithosphere (Fig. 10d) assuming that the moats formed were infilled by sedimentary material up to a horizontal surface, a load and infill density of 2600 kg m^{-3}, and a T_e of 35 km. Comparison of the computed flexure (Fig. 10d) with the observed thickness of the moat fill (Fig. 10e) shows broad similarities although there are discrepancies. In particular, observed thickness contours diverge towards the Moroccan margin whilst the contours of the calculated thickness are more in the form of an ellipse centred on the islands of Tenerife and Gran Canaria. The discrepancy suggests that sediment loading associated with the Moroccan passive margin (e.g. Hinz *et al.* 1982) may contribute, at least in part, to the observed thickness.

We can test this possibility by considering models that show how sediment loading at the margin may have over-deepened the Canary island flexural moats. Unfortunately, the distribution of Neogene sediments along the Moroccan margin is too poorly known to compute this effect directly. We have therefore estimated the margin contribution from the relative thickness of the units before and after volcanic loading. Units I and II, for example, suggest that the sediment thickness varies from about 1 km in the west to about 6 km in the east of our study area (Fig. 9). Although we cannot be certain that significant time gaps are contained within these units, it is reasonable to assume that Units III, IV and V represent approximately 20–30 per cent of the time represented by Units I and II. We therefore assumed a margin contribution during the time that volcanic loading was forming the moats of 25 per cent of the thickness of Units I+II (Fig. 10f). The inclusion of a margin contribution of 25 per cent significantly improved the fit between observed and calculated flexure. The fit in the west is largely unchanged. In the east, however, the observed and calculated contours are in better agreement. In particular, the predicted sediment contours diverge along the Moroccan margin, in general agreement with the observations.

Fig. 11 shows the sensitivity of the calculations to T_e. The best overall fit to the observations is for T_e in the range of 30–40 km. This range of T_e explains the general shape of the flexural moat, especially the trend of individual thickness contours observed on the across-moat profiles (e.g. lines 11, 12 and 22). Lower values produce a moat depression that is narrower and deeper than is observed while higher values produce a moat that is too wide. There are indications that the maximum thickness of sediments in the moat is better matched

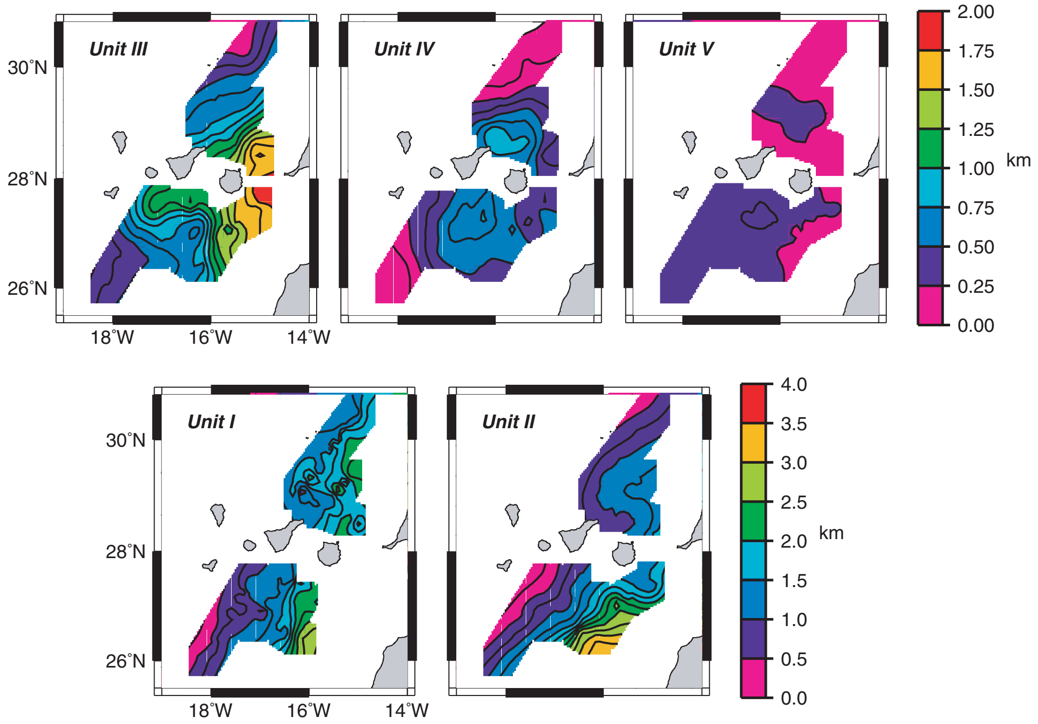

Figure 8. Isopachs of Units I to V calculated by depth converting the travel time picks shown in Figs 3–7. Note that these isopachs contain no estimation of the thickness of units within the seismically defined volcanic apron surrounding individual islands on the ridge. Note how Units III, IV and V appear to thicken towards the islands, whilst Units I and II thicken towards the African continental margin.

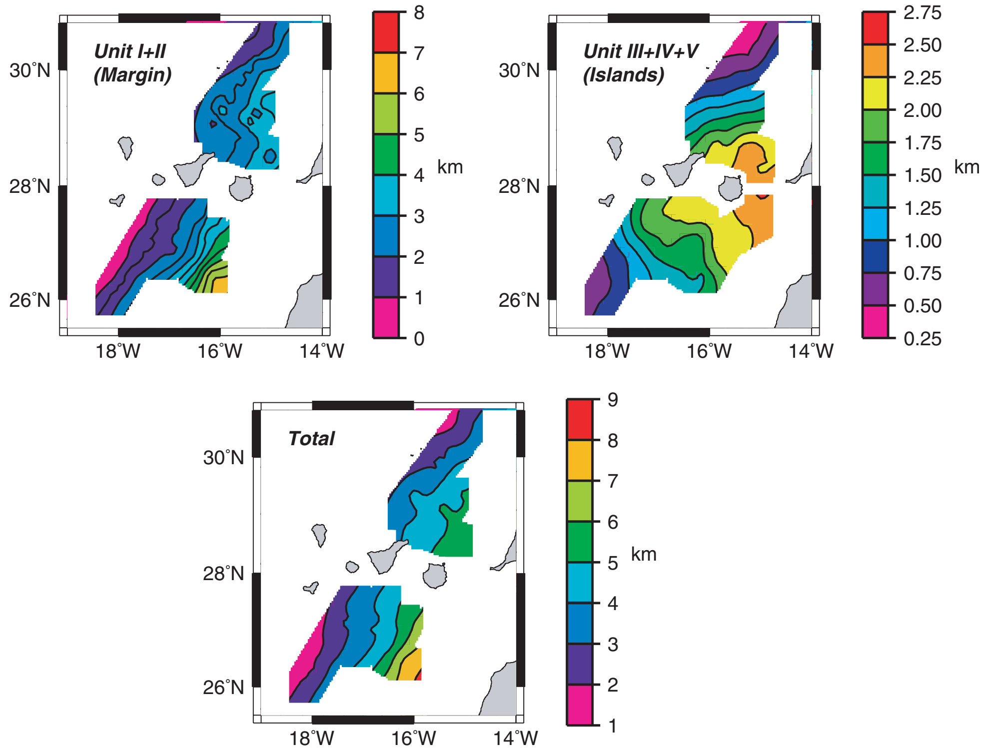

Figure 9. Combined isopachs of Units I and II (which are attributed to the margin); Units III to V (which are attributed mainly to the islands) and all sediments (Units I to V).

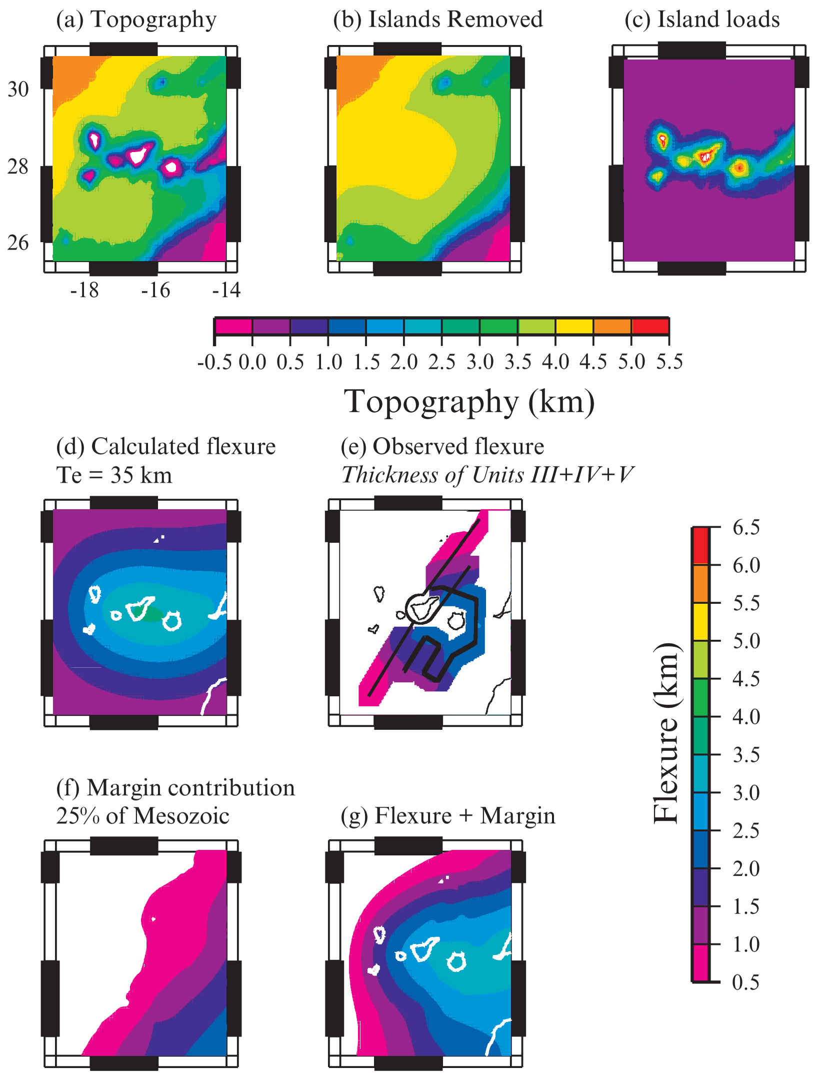

Figure 10. Comparison of observed thickness of moat sediments to calculated thicknesses based on an elastic plate model. (a) Observed topography. (b) Observed topography with the island loads removed. (c) Island loads. (d) Calculated moat sediments. The calculations assume that the flexure due to the islands is infilled up to a horizontal predeformation surface by sediments, a load and infill density of 2600 kg m^{-3}, and $T_e = 35$ km (e) observed sediment thickness, as determined by the combined thickness of Units III, IV and V. (f) estimated contribution of margin sedimentation to the moat stratigraphy. The margin contribution has been estimated from Units I and II which are interpreted as representative of the 'background' sedimentation of the region prior to formation of the Canary Islands. (g) Calculated combined sediment thickness from volcanic island and sediment loading (i.e. d and f).

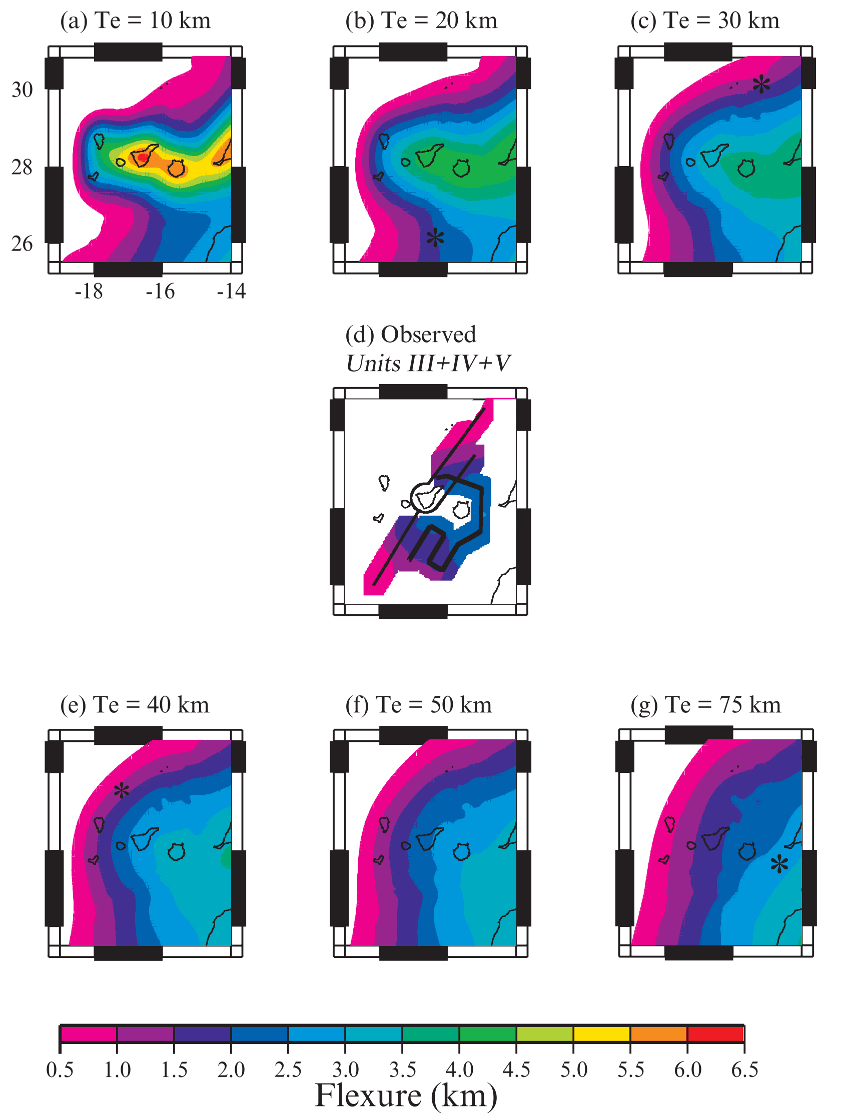

Figure 11. Comparison of calculated and observed thickness of moat sediments showing the sensitivity of the calculations to changes in T_e. (a) $T_e = 10$ km (b) $T_e = 20$ km (c) $T_e = 30$ km (d) Observed combined thickness of Units III, IV and V (e) $T_e = 40$ km (f) $T_e = 50$ km and (g) $T_e = 75$ km. The best overall fit to the observations is for $30 < T_e < 40$ km. Values lower than this produce too narrow a moat and too large a thickness while values higher produce too wide a moat and too small a thickness.

by the higher values, but this is probably because of the lack of resolution in our data on the flanks of individual islands, especially east of Gran Canaria.

5.2 Progressive loading

As described above the isopachs of seismic Units III, IV and V thicken concentrically towards the eastern, central and western Canary Islands, respectively. Our observations are therefore consistent with geological data which suggest that there has been a progression in the main volcanic load centres from east to the west along the chain. In order to validate this interpretation, we used the bathymetry grid to divide the chain into three subloads: an eastern load of Gran Canaria, Fuerteventura and Lanzarote, a central load of Tenerife and La Gomera and a western load of La Palma and El Hierro. Fig. 12 shows the pattern of moat infill that would be expected for each of the three subloads independently, assuming $T_e = 35$ km. To simulate progressive loading we then calculated the cumulative response of the eastern subload, followed by the central subload and finally the western subload. Fig. 13 compares the calculated response of this progressive loading flexural model with the stratigraphic patterns observed on the along-strike seismic Line 14 of the northern flexural moat. Models were constructed with and without a margin component and with values of T_e of 20, 35 and 50 km. The best overall fit to the observed increase in thickness of Unit IV towards Tenerife and the increase in thickness of Unit III towards Gran Canaria is for no margin component and for $T_e = 35$ km. A margin component produces too great a thickness for all cases of T_e. Lower values of T_e (e.g. 20 km) cause too great an increase in thickness while higher values (e.g. 50 km) predict too little. There is evidence, however, that Unit V is best fitted by a higher T_e. A value of $T_e = 35$ km, for example, produces too narrow a depocentre in the region of Line 14.

6 DISCUSSION

6.1 Onset of magmatism along the Canary Islands ridge

From our stratigraphic correlations of the base of Unit III we suggests an Oligocene or older age for the start of a significant supply of volcanic material to the Canary basin. On the basis of earlier studies of the supply of sediment to the surrounding basin during volcanic growth, we conclude that this represents a late submarine to subaerial stage of part of the chain. The data presented here also suggest that a significant submarine barrier may have existed even earlier. Our detailed modelling along seismic Line 14, for example, showed that no margin component is required in the moat to explain the thicknesses of units V, IV and III to the north of Tenerife and Gran Canaria (Fig. 13). The greater reflector coherence in the northern basin compared to that of the southern basin throughout these units support the conclusion that a significant marine barrier might have existed throughout the Neogene which protected the northern basin from margin-derived sediments. Evidence for the blocking of a substantial amount of sediment is seen on line 15 where there is a bathymetric drop of more than 1 km from south to north across the Canary Ridge. Unit III is particularly thickened and chaotic immediately south of the barrier here (lines 15 south and 16). It is possible that this contains some of the pre-Miocene sediments formerly deposited higher up

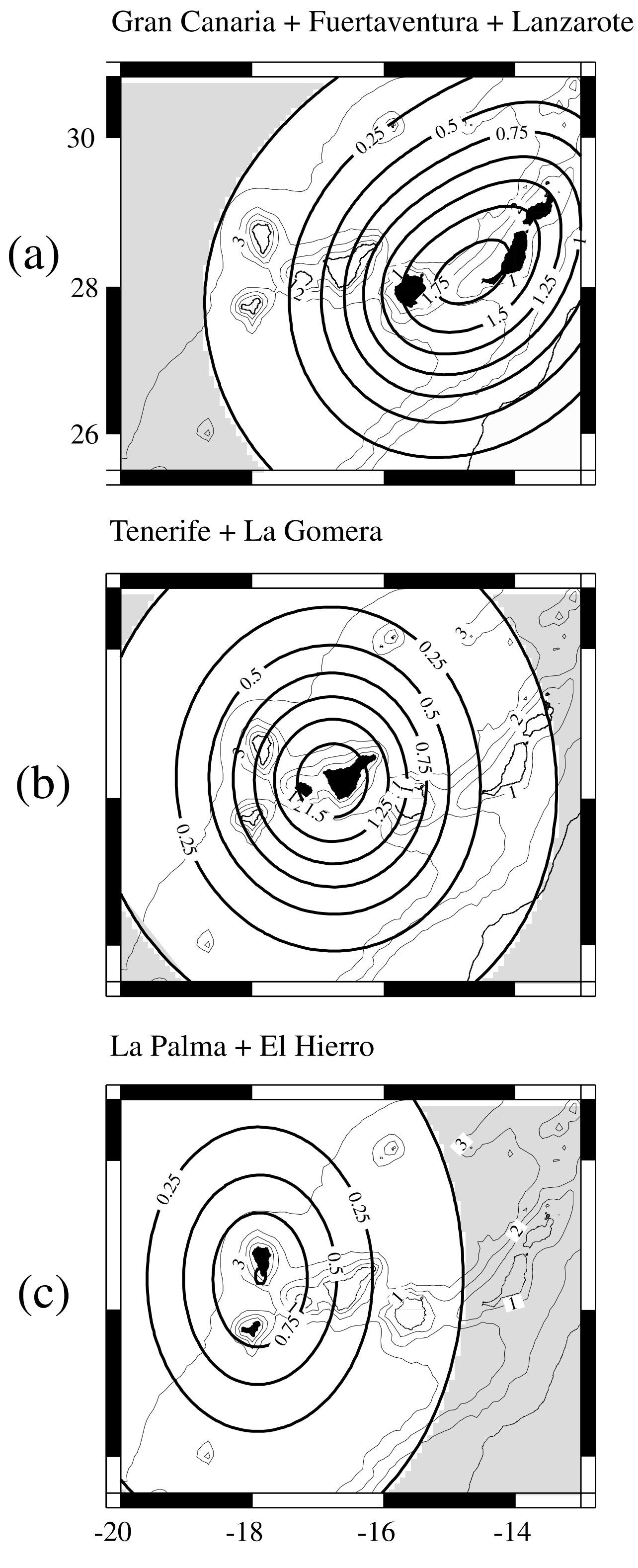

Figure 12. Calculation of the contribution to moat sediment thickness (in km) of individual loads along the Canary Islands chain. (a) Grand Canaria, Fuertaventura and Lanzarote (b) Tenerife and La Gomera and (c) La Palma and El Hierro. Units III, IV and V indicate the observed units that are interpreted as being the result of these individual loads (black = load above sea level). Shading indicates uplifted regions.

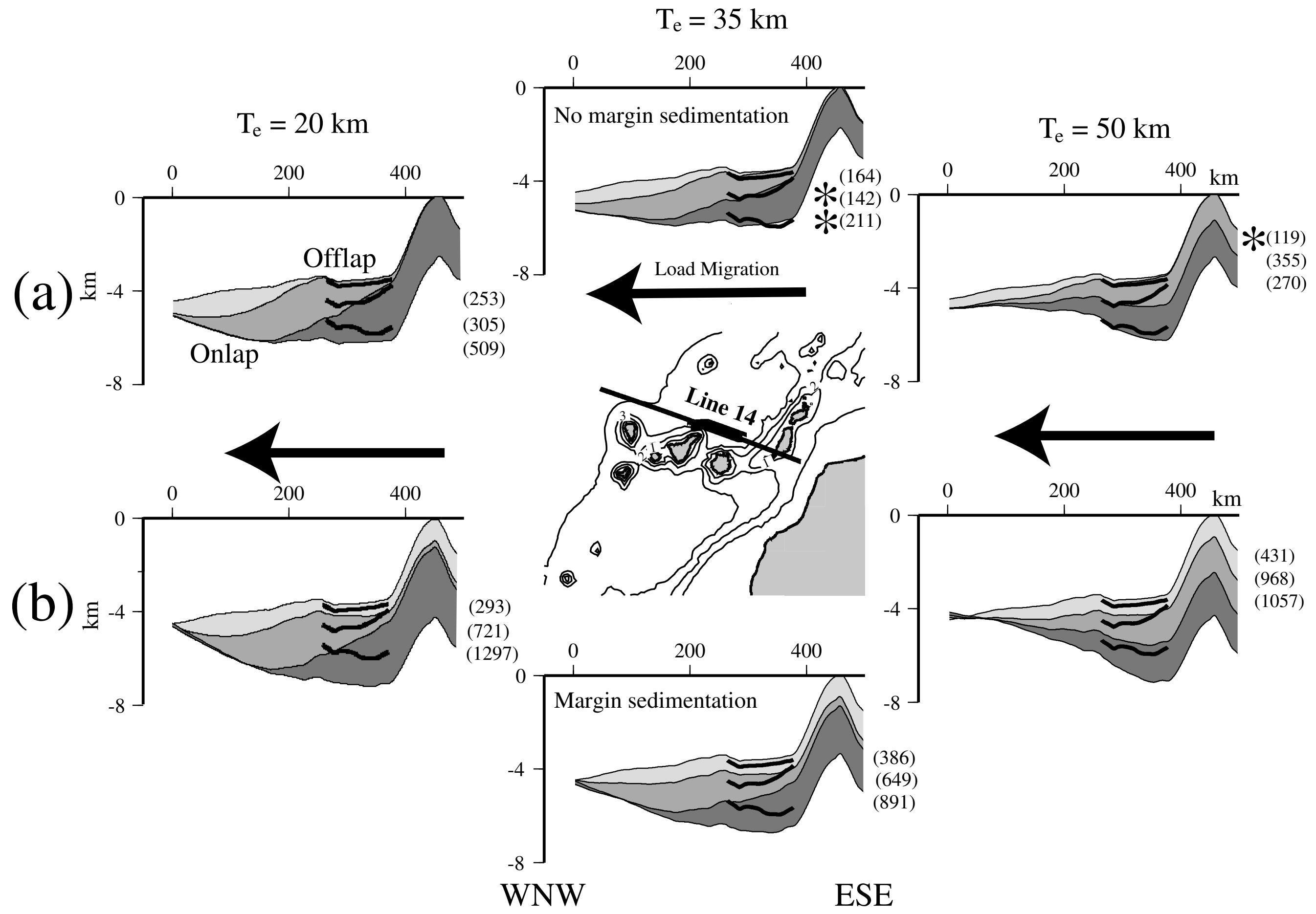

Figure 13. Comparison of observed stratigraphy of Line 14 along the northern moat to predictions based on a flexure model with the main load centres migrating from east to west. Individual flexures are based on Fig. 12. The observed data are based on picks of the Units V, IV and III on Line 14. The calculated data are based on $T_e = 20$, 35 and 50 km (a) No margin contribution (b) Margin contribution. The numbers in brackets are the Root Mean Square (RMS) difference in m between observed and calculated surface that define the base of seismic Units V, IV and III. Note the largest RMS errors are for models with a margin component. The smallest RMS errors (marked by asterisks) are for $T_e = 35$ km (Units III and IV) and $T_e = 50$ km (Unit V).

the continental rise around DSDP site 397. Rather than being eroded by a bottom current as suggested by Arthur *et al.* (1979), the new evidence presented here points towards the unconformity also being closely linked to the emergence of a submarine volcanic ridge during this period. The most likely site for such a barrier would have been Fuerteventura and Lanzarote, which are known to be the oldest islands in the Canary chain. These islands trend subparallel to the margin and a barrier close to their present day location would almost certainly have prevented margin-derived sediments from reaching the deepest parts of the moat to the north of Tenerife and Gran Canaria.

There is also evidence that seismic Units I and II are similarly influenced by the present position of the Canary Islands Ridge which leads us to speculate that an early submarine barrier may have existed as far back as the Upper Cretaceous or even, the Lower Cretaceous and Jurassic. The thickness of both Units I and II, for example, are greater to the north of the Canary Islands than to the south. Either there was higher sediment deposition or lower sediment erosion to the north compared to the south. Given the widespread sedimentary hiatuses in this region the latter is the more likely. Also the unconformity at the Unit I/II boundary may have a spatial relationship with the present-day position of the ridge. Our interpretation of a channel and levee system at the base of Unit II on line 14, for example, could have been caused by bottom water channelling related to early ridge emergence.

6.2 Progressive flexure model and ages of volcanic loads

Our stratigraphic observations and modelling are consistent with the available geological data that show the main centres of volcanic loading and, hence, flexure has, overall, progressively migrated from east to west along the chain. This has occurred *despite* the long history of volcanic activity that is observed on individual islands in the chain. One explanation of our observations is that the volume of the subaerial volcanism that forms most of the surface rocks and, hence, provides dates on the islands is significantly smaller than the volume of the submarine rocks that make up the edifice of the islands. For example, on Gran Canaria subaerial volcanics are estimated to constitute only 2.6 per cent of the total volume of the island (Funck & Schmincke 1998). Therefore, while the products of subaerial volcanism would dominate the age estimates, the volume of material that is added contributes little to the moats flanking the islands.

From the stratigraphic correlations and well ties, we date the shallow shield building stages of Fuerteventura, Gran Canaria and La Gomera as Oligocene to Early Miocene, Tenerife as Middle Miocene to Late Miocene and the western islands of El Hierro and La Palma as Pliocene to Quaternary. We note that the youngest islands do not appear to have significantly altered the flexural moat formed by the older islands. This deduction is supported by single channel reflection profiles collected west of El Hierro and La Palma by Urgeles *et al.* (1998) that show that rather than deepening toward the islands (as would be expected for a developed moat) the igneous basement shallows. As Fig. 12 shows these islands have grown large enough to cause a response so the most likely explanation is that there has been insufficient time for the flexure to develop.

Although distinct stratigraphic patterns of onlap at the base and offlap at the top of individual flexural units are seen on the across-moat profiles they were not easily identified on our single continuous along moat profile 14. This may simply have been due to the data coverage. More likely, however, is the problem of the proximity of the contributing volcanic centres and their temporally overlapping extrusion histories. A further complication is the strongly directional high-flux margin component. This component was effectively minimized on across-moat profiles by orienting them parallel to the margin trend but this was unavoidable on the along moat profiles. However, although individual reflections do not show a clear pattern of onlap and offlap the thicknesses of the units clearly display thickening towards the active volcanic centre and so supports the gross predictions of the progressive flexural loading model.

6.3 Previous T_e estimates

There has been much debate about the T_e structure of the Canary Islands region. Early studies were based on forward modelling of the geoid and gravity field. Filmer & McNutt (1989) used ETOPO5 topography and satellite-derived geoid anomaly data, and suggested values as high as 48 km, Watts (1994) used shipboard bathymetry and gravity data, however, and obtained values as low as 20 km, Dañobeitia *et al.* (1994) carried out the first admittance and coherence study of the Canary Islands, suggesting an average T_e of 23 km for the region. However, when they minimized the effect of the margin by averaging spectral estimates orthogonal to the local trend of the Moroccan margin, their best-fit estimate increased to 35 km.

The study by Watts *et al.* (1997) was the first to compare the crustal structure derived from wide-angle seismic refraction data and the predictions of the flexure model. They suggested a T_e that was similar to the value derived earlier by Watts (1994), although they pointed out that it could be as high as 30 km and still explain the refraction data. Here we have argued from seismic reflection profiles (e.g. Fig. 13) that T_e of the lithosphere that underlies the Canary Islands is $\sim$35 km. This is similar to the expected value of 35 km, based on a predominantly Neogene loading of Jurassic age oceanic lithosphere (e.g. Watts & Zhong, 2000).

The question that remains is what is the cause of the differences in estimates of T_e between the gravity, geoid and seismic studies? The value derived by Filmer & McNutt (1989) is probably too high because of the poor resolution of the geoid for determining crustal structure. In addition, their study was based on the ETOPO5 bathymetric grid which did not adequately take into account the topography of the islands. The values derived by Watts (1994) and Watts *et al.* (1997), on the other hand, are probably too low because of the high load and infill densities that these workers assumed. For example, Watts (1994) assumed a density of 2800 kg m^{-3} for the load and infill and deduced a T_e of 20 km. However, as Watts (1994) also showed, the observed gravity anomaly can be equally well explained by a T_e as high as 30–35 km, provided that a load and infill density of 2600 kg m^{-3} is assumed. A density of 2600 kg m^{-3}, while low compared to those used in most flexure studies (e.g. in the Pacific), is in accord with the seismic refraction data. These data, for example, indicate a maximum density of 2720 kg m^{-3} which is limited to the central core of the Canary Island ridge. The remainder of the ridge is associated with lower density units which lower the mean density of the load.

In Figs 10–13, we have assumed a load and infill density of 2600 kg m^{-3}. Therefore, our best fit estimate of $T_e = 35$ km is generally consistent with those of previous studies. The important point here is that our estimate, together with previous results, suggests that T_e in the Canary Islands region is not significantly different from what would be expected for the load and plate age. Therefore, the lithosphere that underlies the Canary Islands does not appear to have been weakened by the thermal effects of the hot-spot that generated the islands. This is consistent with the presence of a relatively small-amplitude swell (Canales & Dañobeitia 1998) and the absence of a long-wavelength gravity and geoid anomaly that is centred over the crest of the Canary Islands (Watts 1994). The existence of 'normal' Te values at other islands which are associated with a large-amplitude swell and long-wavelength gravity and geoid anomalies, such as Hawaii, therefore suggests that either thermal effects are also limited at these islands or that mid-plate swells are supported by some form of dynamic effects in the underlying asthenosphere (Watts 1994).

7 CONCLUSIONS

(1) The stratigraphy of the flexural moat that flanks the Canary Islands can be divided into five main seismostratigraphic units based on internal reflective character and correlation of prominent reflections.

(2) The two lowermost units (Units I and II) thicken towards the east, have low seismic reflectivity and are interpreted as prevolcanic sediments deposited on the upper Moroccan continental rise.

(3) The three uppermost units (Units III, IV and V) thicken concentrically toward individual islands, are highly reflective and are interpreted as material that has infilled topographic depressions produced by the volcanic loads of the islands.

(4) A distinct stratigraphic pattern of onlap at the base and offlap at the top of individual flexural units is seen on the across-moat profiles but were not easily identified on our limited along moat profiles.

(5) The moat stratigraphy is consistent with the available geological data that show the main load centres and, hence, flexure has, overall, progressively migrated from east to west along the chain. We date the shield building stages of the Fuerteventura, Gran Canaria and La Gomera as Oligocene to Early Miocene, Tenerife as Middle Miocene to Late Miocene and the western islands as Pliocene to Quaternary.

(6) The thicknesses of Units III, IV and V can be explained by a model in which the lithosphere responded to loading by the Canary Islands as would an elastic plate that overlies a weak fluid substratum.

(7) The best fit to the observed thickness of units III, IV and V is for an elastic thickness, T_e, of 35 km, which is similar to what would be expected for Oligocene and Neogene loading of Jurassic age oceanic lithosphere. There is evidence that Unit V may require a higher T_e than Units III and IV, possibly because it is associated with the youngest load in the chain and isostatic compensation may not yet be complete.

(8) Differences in the thickness of individual units between the northern and southern moats are attributed to topographic 'barriers' which *either* prevented margin-derived sediments from reaching the flexural moats *or* protected them from the effects of corrosive bottom currents. There is evidence that the first emergence of a submarine volcanic ridge may have occurred in the Upper Cretaceous, or earlier.

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