SEGMENTATION OF THE NAMIBIAN PASSIVE MARGIN

by

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ABSTRACT

The post-Pan-African sedimentary sequence of the Namibian passive margin is divided into major tectono-stratigraphic sequences. Inversion, uplift and erosion separated the Karoo Rift Phase and Post-Rift Phases. The subsequent "Atlantic" Rift Phase culminated in continental break-up, to be followed by the Transitional and Drift Phases.

The Karoo Namib Rift developed as part of the early break-up of West Gondwanaland. Up to 10 km of lower Karoo sediments are preserved in this rift. A Karoo sequence is identifiable in the south, but no large-scale rifting is evident. The thinner upper Karoo Post-Rift sequence onlaps the lower Karoo. The "Atlantic" rift system is divisible into three major sequences. The initial rift sequence is largely confined to the Lüderitz Basin. It dies out where the cross-cutting Damara Fold Belt interrupted northwards rift propagation. The second rift sequence extends along the entire continental margin. The last "Atlantic" rift sequence is overlain in the west by seaward-dipping reflectors. The break-up unconformity marks marine flooding across much of the new continental shelf. The Drift Phase sequence is dominated by listric faulting and thrusting, slumping and canyon-cutting along the passive margin.

The timing of continental break-up is diachronous along the passive margin. It occurred in discrete major segments, becoming younger to the north. Major segment boundary zones partition the timing of break-up. In the composite Cape Cross Segment Boundary Zone, basement fabrics interacted with subsequent rifting and led to a complex rift margin. Smaller examples of segment boundary zones are confined to the Lüderitz Basin. Rift segments follow the Pan-African Fold Belt consistently along the passive margin. The segment boundary zones are interpreted as zones accommodating stresses developed in the rift system around the Lüderitz Arch. There is no evident relationship between segment boundary zones of the Namibian passive margin and oceanic fracture zones.

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INTRODUCTION

1.1 Aims of this study

The main aims of this study are as follows:

i) to examine whether the Namibian passive margin is segmented by structural cross-elements;

ii) to determine the relationship between any structural cross-elements and the rift and drift sequences; and

iii) to determine what conditioned the location of any structural cross-elements.

In the following chapters, these structural cross-elements are referred to as 'segment boundary zones', for reasons described in *Chapter 2.*

To achieve these aims, a full geophysical interpretation of the Namibian passive margin has been carried out. This examines the rift sequence leading to the break-up of the South Atlantic, and subsequent drift sequences. However, to understand the evolution in space and time of these sequences, it is necessary to examine any pre-rift sequences and the basement structural domains. This provides an insight into what has controlled the location of any segmentation.

1.2 Scope of the interpretation

The Namibian passive margin was selected to carry out this study on segmentation because of its apparently simple geometry. The margin is described by Dingle (1976) as a tensional, clean break crust, locally displaced by 'transverse marginal fracture zones'. It is uncomplicated by sectors of transform margin; these occur in the Central Atlantic and the southeastern margin of southern Africa. Aptian evaporites obscure Rift sequences of other sectors of the South Atlantic north of the Walvis Ridge - Rio Grande Rise. On the remaining South American and southwest African conjugate sectors Amerada Hess, the sponsors, provided an excellent seismic data coverage of the Namibian passive margin. This data forms the basis of this study.

There are few wells providing geological control on the Namibian sector of the southwest African passive margin. These are located in the Kudu gas accumulation in the south of the

Namibian passive margin. There is also limited access to other well data, but none penetrates the syn-rift sequence leading to break-up of the South Atlantic. Well and seismic data coverage are reviewed in *Chapter 4*.

This very limited well data particularly limits our understanding of the timing of structural events in the history of the Namibian passive margin. These can only be correlated with related structural events which are recorded in the onshore geology of southern Africa. Onshore preserved sedimentary sections that were laid down, or later affected by tectonic events at the same time as the offshore sedimentary section, are limited. Therefore, the correlation with the offshore geological history is only loosely constrained.

There is no raw gravity or magnetic data available that was acquired with the seismic data. Thus potential field data is limited to maps published in pre-existing studies. Consequently, no crustal or subsidence modelling integrating potential field data with seismic data has been carried out in this study. This study is therefore largely limited to a structural seismic interpretation. This alone has proved to be very fascinating and fruitful enough to work towards understanding the processes of passive margin segmentation, and relate these to rift segmentation. Interpretation of the potential field data is used in an ancillary role, mainly to support the identification of basement trends derived from the seismic interpretation.

1.3 Location of the study area

The geographical boundaries of the studied area of 200,000 km^2 are confined by the Walvis Ridge in the north (19°S) and the Namibian/South African offshore political boundary offshore from the Orange River in the south (29°S) (Fig. 1.1). Fortunately, these geographical boundaries coincide with important segment boundary zones. Between these two structural boundaries are two major basins, the Lüderitz Basin and Walvis Basin. The seismic database limits detailed study to a 200 km strip along the continental margin and slope. It does not quite extend to the assumed 'continent-ocean boundary' of Gerrard and Smith (1982). This marks a change below the break-up unconformity (Falvey 1974) from parabolic diffractions west of the boundary to smooth-structured reflections to the east. This

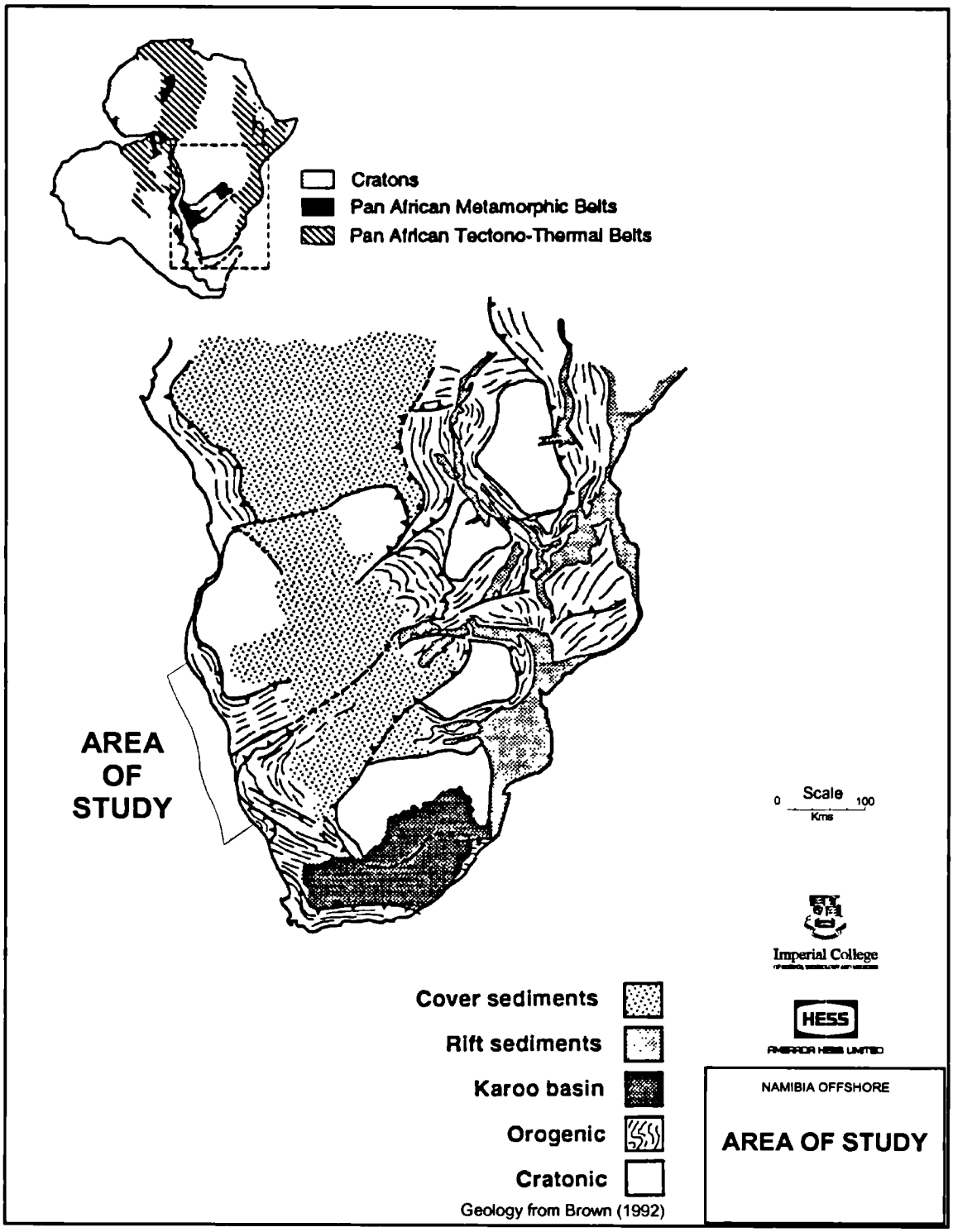


Figure 1.1 Area of study (geology from Brown 1992)

boundary marks the eastern limit of oceanic crust of normal thickness (Gladczenko *et al.* 1995). Relevant geological and structural information from southern Africa are integrated into the study.

1.4 Chronostratigraphic time scales

The time scale adopted by this study is that of Gradstein *et al.* (1994). It integrates biostratigraphic, magnetic anomaly and radiometric data used to constrain the stage boundaries of a Mesozoic time scale. This spans the majority of the geological history of the Namibian passive margin.

Many time scales have been produced over the last twenty years. The crucial period involving continental break-up, the middle Cretaceous, is a period subject to large differences in the identified periods of up to 15 m.y. in age (Fig. 1.2). Thus the base of the Paraná-Etendeka flood basalt province, with $^{40}Ar/^{39}Ar$ ages in Namibia of 135-132 Ma (Milner *et al.* 1995b), may be anything from latest Tithonian (Haq *et al.* 1988) to Valanginian (Gradstein *et al.* 1994). It is imperative of studies producing a tectono-stratigraphic history based on the integration of absolute ages and biostratigraphic data to refer to the adopted time scale. This has not always been the case.

1.5 Layout of the thesis

All line drawings of seismic sections are 'squashed' horizontally at a ratio of 2:1 from their original display scale to reduce the size of regional sections. Seismic sections are displayed to illustrate more local structural or stratigraphic features. They are shown at the same relative horizontal and vertical scales as the original sections, although reduction factors vary. Scale bars depict scales pertaining to each section.

Chapter 1 introduces the scope and subject of the thesis and the area studied. It also briefly discusses the choice of time scale to which all chronostratigraphic ages and absolute dating are referred.

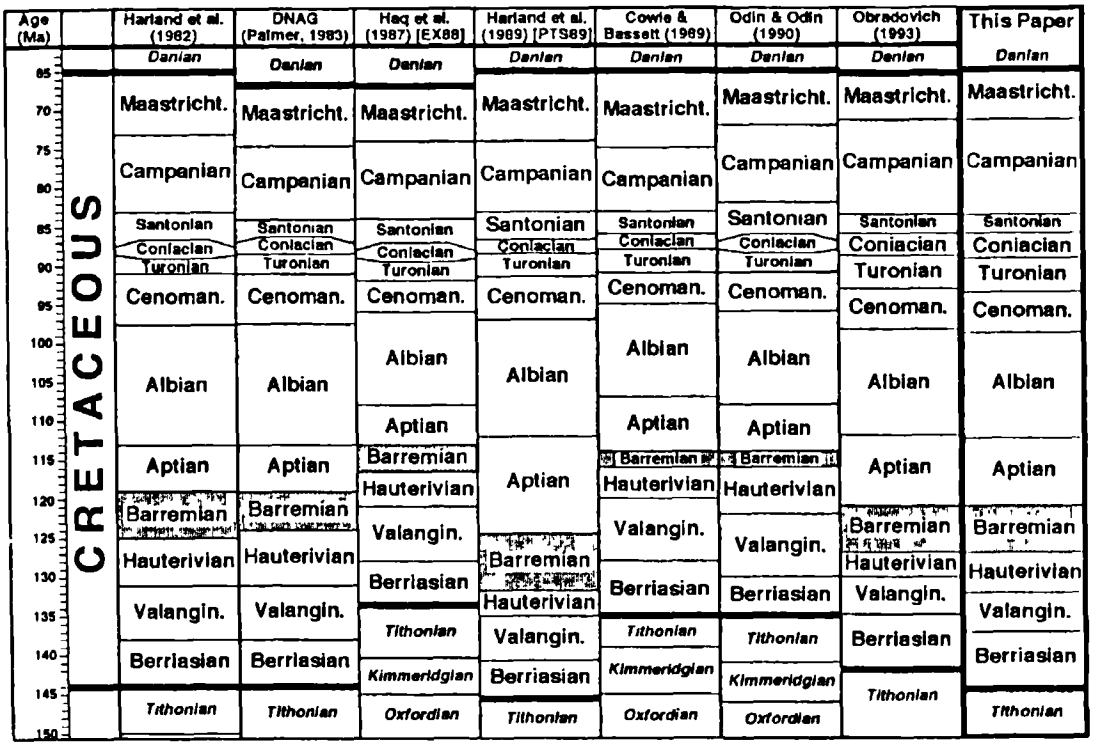


Figure 1.2 Comparison of Cretaceous time scales (from Gradstein et al. *1994)*

Chapter 2 reviews previous studies of the segmentation of rifts and passive margins. This sets the scene of what may be expected on the Namibian passive margin.

In *Chapter 3*, the relevant onshore geology of southern Africa is summarised. The stratigraphic data is largely limited to the crystalline basement and the Karoo and Etendeka Groups of Namibia. Structural events are garnered from the wider subcontinental area of southern Africa. Relevant information from the conjugate margin of South America is also integrated into the study. The interpreted structural history of the offshore basins is constrained by the onshore structural and stratigraphic history.

A regional interpretation of the Namibian passive margin is carried out in *Chapter 4*. This identifies and maps the major seismic markers bounding major tectono-stratigraphic sequences and assembles a tectono-stratigraphic history. This encompasses two major rift events, the Karoo and "Atlantic" Rift Phases, a Karoo Post-Rift Phase and an "Atlantic" Transitional and Drift Phase. *Chapter 4* also identifies segment boundary zones and the stratigraphic relationships across these zones.

Chapter 5 carries out a detailed interpretation of Block 2213A, an exploration licence formerly operated by Ranger and in which Amerada Hess were partners. This block lies in the most complex part of the Namibian passive margin. It is ideally located to understand how basement fabrics and basement structural elements influenced subsequent rift geometries.

The subject matter in *Chapter 5* is separated specifically to satisfy the logistical requirements of the commercial sponsors of this thesis. The seismic databases for *Chapters 4* and *5* are described in each chapter rather than in the *Introduction* of *Chapter 1* in order to maintain self-contained interpretation modules as much as possible.

Chapter 6 describes the geometry of each segment boundary zone, what has controlled the location of the zone, and how it has behaved through time. It also assesses whether they partition the timing of rifting and continental break-up and their role in the propagation of rifting and break-up.

Chapter 7 puts the Namibian passive margin in a plate tectonic setting, examining the intraplate stresses that led to Karoo rifting. The relationship of the segment boundary zones with South Atlantic fracture zones and offsets of the Mid-Atlantic Ridge is briefly assessed. Finally, the lithospheric evolution that led to continental break-up is explored.

Chapter 8 draws together the major conclusions of the structural history and segmentation of the Namibian passive margin.

2

A REVIEW OF STRUCTURAL CROSS-ELEMENTS OF RIFTS AND PASSIVE MARGINS

There have been many studies of the segmentation of within-plate rift systems, but relatively little examination of the segmentation of passive margins. This is despite the evolution of continental rifts into passive margins *via* continental break-up.

Theoretical and existing examples of structural cross-elements that are an integral part of rift evolution have been widely described (see below). However, the role of such elements on passive margins has not been examined in any detail. Theoretical models have been produced (Bally 1981, Lister *et al.* 1986) but their practical application to the South Atlantic (Lister *et al.* 1991) is arguable (Standlee *et al.* 1992).

Structural cross-elements may be localised within a rift and be shallow in depth, or may be plate-wide and penetrate the lithosphere. However, the nomenclature applied to these elements is diverse and confusing. Various examples are described in chronological order to highlight the widening recognition of different cross-elements and the confusing evolution in nomenclature.

In the Kenya Rift of East Africa, Griffiths (1980) identified faults linking overlapping rift shoulder faults across the relay ramp at high angle, and termed them 'box-faults' (Fig. 2.1). Griffiths (1980) linked them with changes in orientation of the rift shoulder faults. However, they resemble attempts to breach the relay ramp (Trudgill and Cartwright 1994).

Bally (1981) illustrated model 'transform faults' as cross-elements extending completely across rift systems and allowing changes in rift polarity and partial or complete offset of the rift margins. The listric faults and, by inference, the continental transform faults, are rooted in the lower ductile crust. The continental transforms are shown as evolving into oceanic transform faults (Fig. 2.1).

'Transfer faults' were defined by Gibbs (1984) as within-rift cross-faults allowing 'leakage' between extension faults with differing slip rates in extensional terranes (Fig. 2.1). They are confined to the upper brittle crust and distinct from Andersonian wrench faults.

In a short but very important paper, Bosworth (1985) investigated changes in the asymmetry of rift polarity at 'accommodation zones'. These accommodation zones separate rift basin

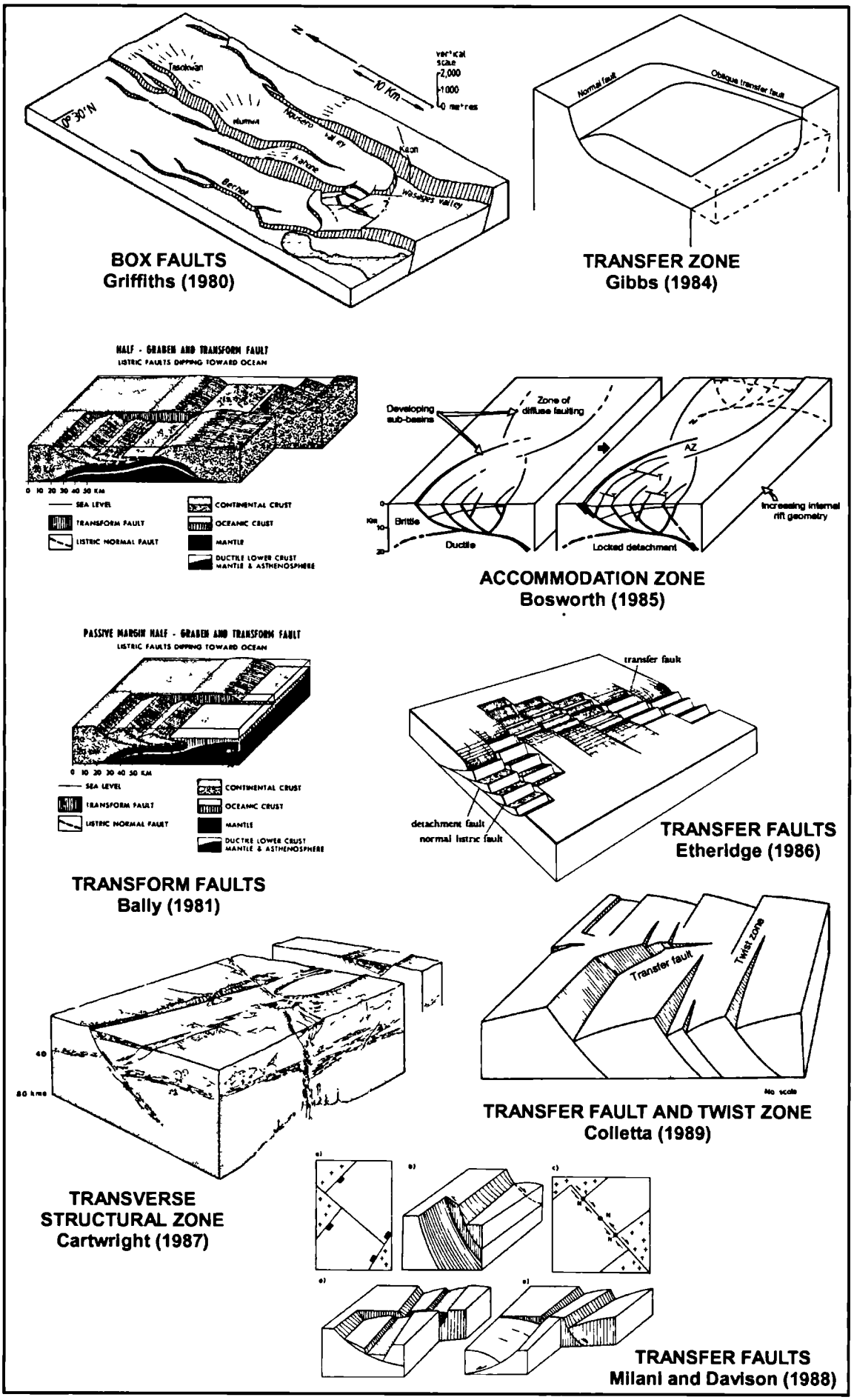


Figure 2.1 A selection of structural cross-elements

segments. Symmetrically opposed detachment systems are coevally active during the earliest phase of rifting (Fig 2.1). The mechanical inefficiency of opposed symmetrical detachments leads to one system to lock, with the rift system evolving thereupon as an asymmetric half-graben of one polarity. He ascribed cross-faults *within* the rift segments as kinematically similar to the 'transfer faults' of Gibbs (1984).

Nomenclature of these cross-elements following these early papers is even more confusing. Etheridge (1986) discussed the kinematics of cross-elements and described examples in the Bass Strait Basin of Australia (Fig. 2.1). They perform a very similar role to the transform faults of Bally (1981) but are addressed as 'transfer faults'. Lister *et al.* (1986) extended this model to complete continental rupture and the development of passive margins. Their 'transfer faults' are seen to be a general feature of extended terranes, and expected to be common on passive margins. As in Bally (1981), a detachment penetrating the entire lithosphere is central to this model. Major transfer faults cut both the 'upper plate' and 'lower plate', ie. the entire lithosphere. Other, minor, transfer faults are confined to the upper plate and affect only the fault block geometry. Some major transfer faults may pass laterally into oceanic fracture zones but this is not always the case. Bosworth (1985) does not see cross faults as being perpendicular to the rift trend faults, or parallel to the direction of regional extension, but as oblique to both.

Chénet *et al.* (1987) describe 'transverse faults' in the Suez Rift. Their relationship with normal faults parallel to the rift axis closely resembles the 'transfer faults' of Gibbs (1984). These transverse faults have no continuity across the rift.

Cartwright (1987), in a study of the Central North Sea Rift, recognised the importance of pre-existing basement trends and extended 'transverse structural zones' beyond the bounds of the rift system (Fig. 2.1). At higher structural levels of the North Sea rift fill, he noted the lack of continuous wrench faults. Only minor horizontal displacement was inferred in the 'transverse structural zones'. Deeper structures were interpreted to be continuous across the graben. The 'transverse structural zones' were shown to have reactivated pre-existing lineaments. Rather than functioning as structures accommodating free rotation of individual graben segments (eg. Bally 1981, Gibbs 1984), they are argued to offset rift segments as a consequence of large scale crustal shear. Despite the large size of the structures, strike-slip

displacement need not be large. This model is elaborated in Cartwright (1992) but also introduces the term 'transverse shear zone'.

'Transfer faults' *sensu* Gibbs (1984) are identified in the South American Recôncavo-Tucano-Jatobá rift system by Milani and Davison (1988). These examples may extend across the rift basin (Fig. 2.1). Pre-existing basement lineaments play an important role. They also identify 'transfer zones' that resemble accommodation zones of Bosworth (1985).

Both smaller, less important 'transfer faults' (*sensu* Gibbs 1984) and 'intracontinental transform fault zones' are recognised by Chorowicz (1989). However, 'transfer faults' in the Suez Rift are extended to include fault zones extending across the rift but not beyond the margins. They are regarded as parallel to the direction of extension and link the major faults bordering asymmetric rift segments. On the basis of their scale they are regarded as upper crustal features. This broadened definition of transfer zones perhaps more resembles the 'accommodation zones' of Bosworth (1985). 'Intracontinental transform fault zones' can be regarded as akin to oceanic transform faults (Wilson 1965) where, for example, right-lateral motion corresponds to left-lateral stepover of the oceanic ridge. In oceanic cases, the trend of the oceanic transform parallels the relative motion of the diverging plates. The heterogeneous continental crust leads to a complex fault arrangement in 'intracontinental transform fault zones'. Examples in East Africa rework basement lineaments. These features resemble the 'transverse structural zones' of Cartwright (1987) and may, like these, be discontinuities on a lithospheric scale.

It is becoming clear that there are within-rift cross elements confined to the upper crust and deeper seated, possibly lithospheric, cross elements that extend beyond the limits of a rift and may link widely spaced rift systems (intracontinental transform fault zones). Within-rift cross-elements include cross-faults linking normal faults (transfer faults) and zones of faulting, or flexing accommodating changes in rift polarity (accommodation zones).

Further studies are a variation on these themes, but the confusion in nomenclature persists. Colletta *et al.* (1989) refer to 'transverse faults' in the Suez Rift in the same way that Chorowicz (1989) applies 'transfer faults' to the same elements. Parts of the 'transverse faults' of Colletta *et al.* (1988) are activated as 'transfer faults' *sensu* Gibbs (1984). 'Twist

zones' occur in accommodation zones (Fig. 2.1). These terms are pursued in Pinet and Colletta (1990). Tankard *et al.* (1989) includes 'transfer faults' *sensu* Gibbs (1984) in rifting in the Jeanne d'Arc Basin of the Grand Banks passive margin.

Morley *et al.* (1990) attempted to classify 'transfer zones' from examples in East Africa. This is dominated by 'accommodation zones' *sensu* Bosworth (1985) and includes 'transfer faults' *sensu* Gibbs (1984), but these are regarded as uncommon. Transform-type fault zones are not favoured by Morley *et al.* (1990) yet they form an important foundation to the work of Castaing (1991) in East Africa. He identifies 'transverse fault' systems developing along major basement structures and linking rift zones. These resemble the 'transverse structural zones' of Cartwright (1987). They had been identified by Rosendahl (1987) and addressed as 'pre-transform faults'. Alternatively, Nelson *et al.* (1992) call them 'rift jumps' in their discussion on rift segment interaction in East and Central Africa. They also refer to the 'compartmentalisation faults' of Brown (1984) as performing some roles in 'rift jumps'.

Rumph *et al.* (1993) discuss closely spaced 'transfer zones' on the extended continental crust of the North Atlantic passive margin in the West Shetland area. However, this follows the model of Etheridge *et al.* (1985), Etheridge (1986), Etheridge *et al.* (1987) and other co-workers, whose long, closely spaced transfer zones appear to be kinematically unrealistic (see also *Chapter 6*).

Gawthorpe and Hurst (1993) return to more realistic structural models of rift geometries. In these, they classify 'inter-basin transfer zones' linking individual half-graben, and localised 'intra-basin transfer zones' confined to a half-graben. The former resemble 'transverse structural zones' (Cartwright 1987). The latter includes 'transfer faults' *sensu* Gibbs (1984) and 'accommodation zones' *sensu* (Bosworth 1985) and also relay ramps.

It is clear that a bewildering array of names encompasses a wide variety of structural features. Two major elements stand out, for which any terms should be mutually exclusive. These are within-rift structural cross-elements confined, like rift faulting, to the upper, brittle crustal layer and lithospheric scale, inter-basinal structural cross-elements linking otherwise isolated within-plate rifts or within-plate rifts to rifted passive margins.

Within-rift structural cross-elements involve little movement in accommodating changes in structural style or in transferring displacement between fault segments. On this basis, 'accommodation zone' *(sensu* Bosworth 1985) is preferred above 'transfer zone' (*sensu* Gawthorpe and Hurst 1993). The use of 'accommodation zones' can be broadened to include the elements of Gawthorpe and Hurst (1993). 'Transfer fault' is retained but confined to the usage of Gibbs (1984).

Inter-basinal structural cross-elements linking within-plate rifts or within-plate rifts to rifted passive margins may involve strike-slip displacements of up to tens of kilometres (e.g. the Central African Shear Zone, Fairhead 1988). Although they may be transferring displacement in a sense, this may be major or minor in relation to the degree of extension in the linked rifts. Therefore, the use of 'transfer' is avoided and 'transverse structural zones' *sensu* Cartwright 1987 is preferred. A classification based on these previous examples is given below.

	Intra-basinal structural cross-elements	Within-rift structural cross-elements
Depth of influence	Full lithosphere?	Upper brittle crust only
	Transverse structural zone Cartwright (1987)	Transfer fault (Gibbs 1984) Accommodation zone (Bosworth 1985, Gawthorpe and Hurst 1993)

Where does 'segment boundary zones' - yet another term - fit into this classification? This term, as will be seen in coming chapters, encompasses several different structural elements that play a role in segmenting the Namibian passive margin. They may broad or narrow, may or may not include lateral displacement, may or may not extend into the adjacent continental interior and may or may not temporally partition the timing of rifting. Therefore, this non-generic term has been adopted that describes their geometrical context on the passive margin.

3

OVERVIEW OF THE REGIONAL GEOLOGY

3.1 Basement framework

The long geological history of southern Africa records one of ancient Archaean core cratons onto which were welded successively younger orogenic belts. These, in turn, were fused to create the Gondwana supercontinent. The central Kaapvaal craton stabilised at ±2.6 Ga (de Wit 1992). It forms the core of the east of southern Africa and has had no direct influence on the southwest African passive margin. The Kaapvaal craton has a very thick lithosphere of 170-230 km (de Wit 1992).

The Namaqua-Natal province is wrapped around the west and south of the Kaapvaal craton (Fig. 3.1) and stabilised between 2.0-1.0 Ga (de Wit 1992). The crust is 42-45 km thick out of a total lithospheric thickness of <150 km (de Wit 1992). In this province, the Kalahari craton (Fig. 3.1) (stabilised ±1.0 Ga) lies southeast and adjoins the Damara and Gariep Pan-African Fold Belts. The crust is 44-48 km thick adjacent to the Damara Fold Belt (Baier *et al.* 1983). The Congo craton lies north of the Damara Fold Belt.

3.2 The Pan-African Fold Belt

The Late Proterozoic-Early Palaeozoic Pan-African/Brasiliano cycle fused the cratonic elements to produce the Gondwana supercontinent. The passive margin of west Africa follows the grain of the Pan-African Fold Belts over much of its length (Fig. 3.1) (Porada 1989). Additionally, a SW-NE oriented Pan-African element, the Damara Fold Belt, extends into the continental interior towards Zambia (Coward 1981, Miller 1983). The coast-parallel elements and the Damara Fold Belt are arranged as an orogenic triple-junction. The coast-parallel elements are dominantly composed of southeast-verging thrusts and folds (Coward 1981). The Damaran arm is more complex, having bi-vergent symmetry and consisting of several prominent subvertical basement lineaments. These include the important Omaruru and Autseib Lineaments that will be shown in later chapters to have influenced subsequent rifting along the Atlantic margin. The basement terranes of the Pan-African Fold Belts in northwest Namibia are shown in Figure 3.2.

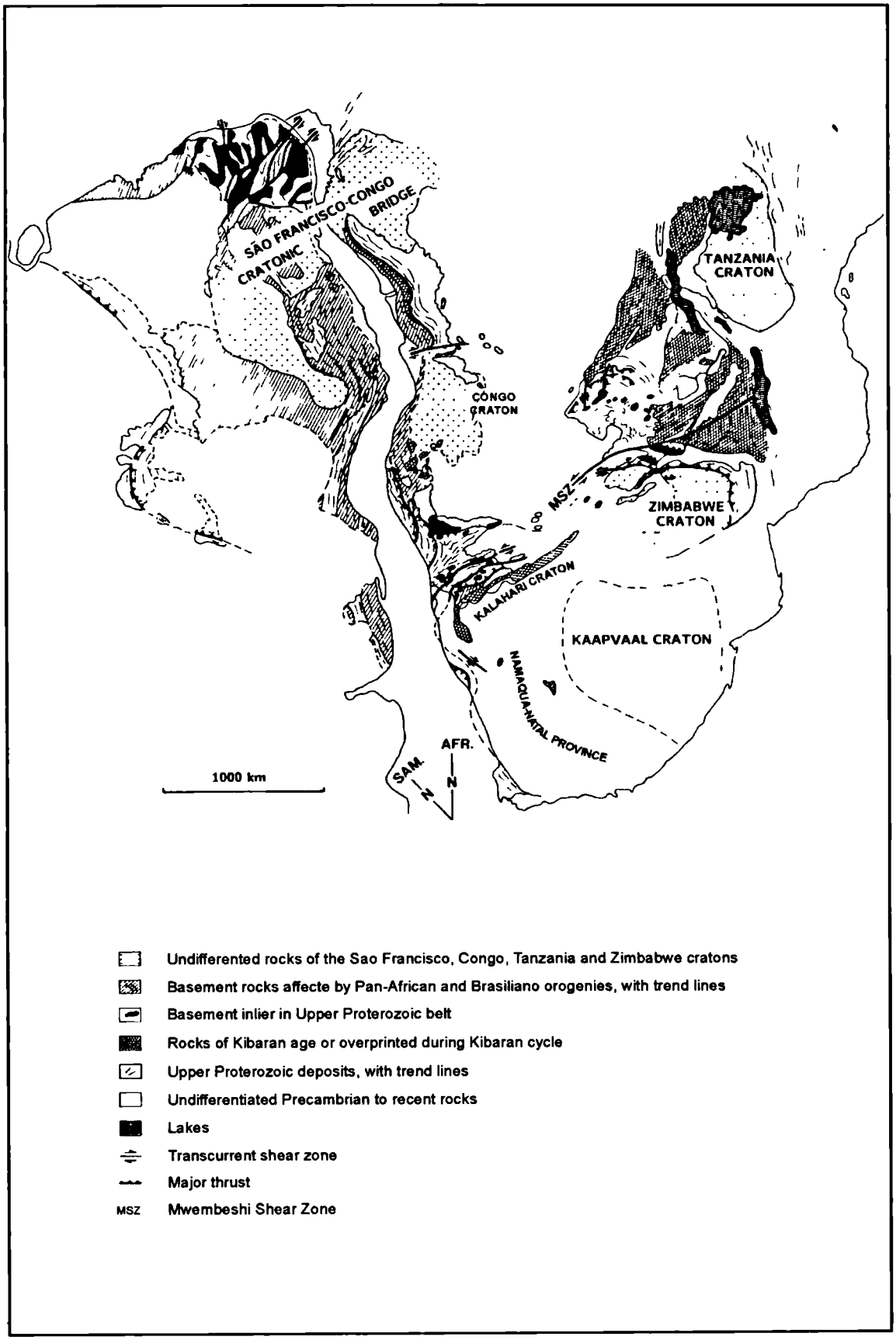


Figure 3.1 Selective geological map of southern Africa and eastern South America, showing the relative positions of the Pan-African and Brasiliano belts on a pre-drift reassembly (modified from Porada 1989).

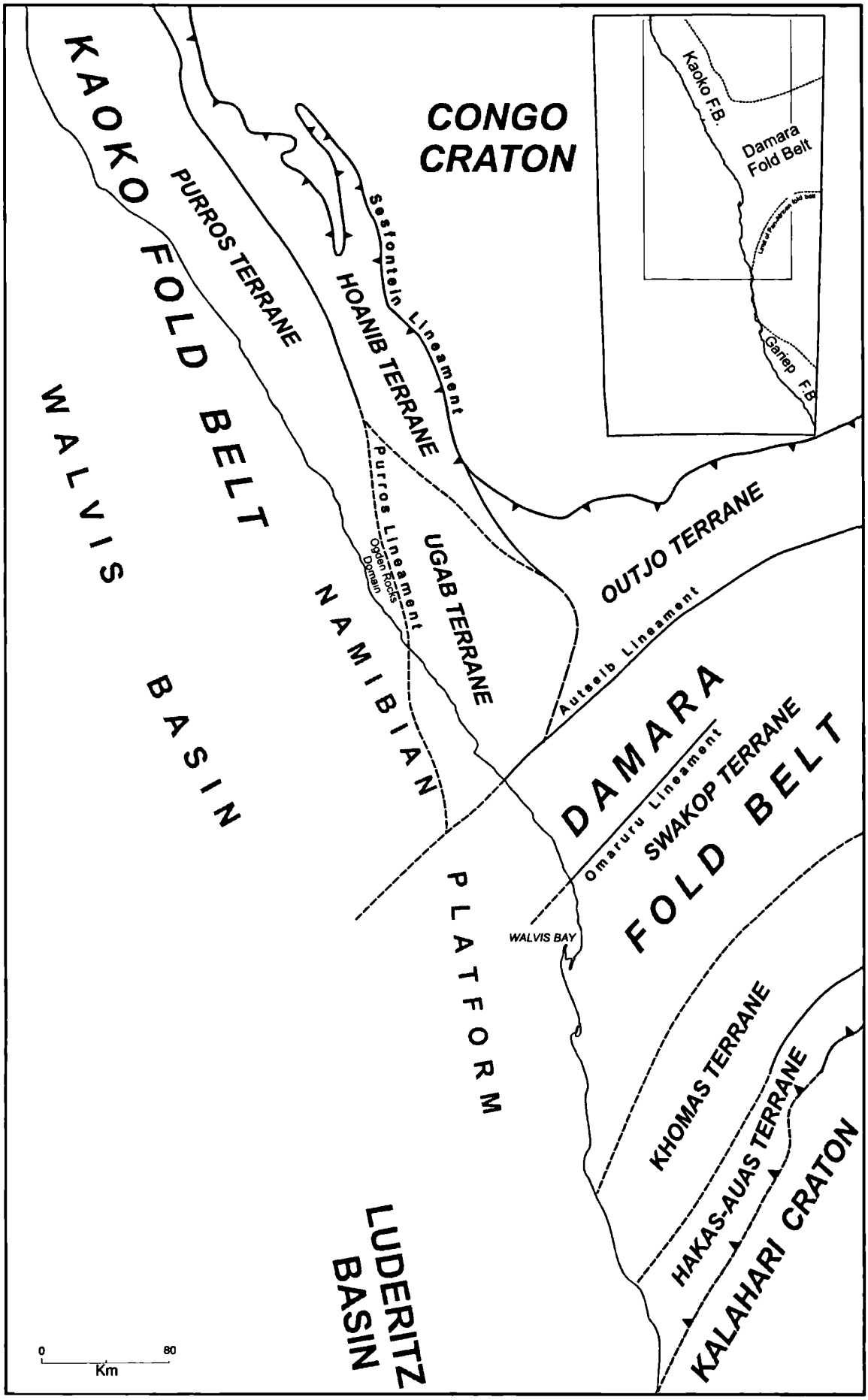


Fig. 3.2 Basement terranes of the Kaoko and Damara Fold Belts, northwest Namibia

The Damara Fold Belt is interpreted as the product of the opening and closing of a small oceanic basin (Kukla and Stranistreet 1991 *in* Dingledey *et al.* 1994). The Gariep and Kaoko arms (Fig. 3.2) are believed to have been part of a much larger ocean basin (Stanistreet *et al.* 1991 *in* Dingledey *et al.* 1994). The Damara Fold Belt incorporates sediments deposited between *c.* 1000-750 Ma (Hawkesworth *et al.* 1986). Compressive deformation is accepted as ending about 550 Ma, but continuing to 500 Ma on the southeastern margin (Hawkesworth *et al.* 1986). Post-tectonic granite intrusion continued until 450 Ma (Hawkesworth *et al.* 1986). The Gariep Fold Belt is similar in age, and may be linked to the Damara Fold Belt offshore beneath the Lüderitz Arch (see *Chapter 4*).

The last metamorphic event of the Kaoko Fold Belt is also believed to have been at *c.* 550 Ma (Ahrendt *et al.* 1983 in Dingledey *et al.* 1994). A separate metamorphic event at 460 Ma (Ahrendt *et al.* 1983) is believed to be a retrograde overprint (Dingledey *et al.* 1994). Therefore, the end of deformation in the Damara and Kaoko arms of the Pan-African Fold Belt is almost contemporaneous. Structural relationships at their junction south of the Etendeka flood basalt province indicate that compressional activity terminated in the Kaoko Fold Belt before it ceased in the Damara Fold Belt (unpublished field guide, Geological Society of Namibia, 1996) (Fig. 3.2).

The Purros Terrane of the Kaoko Fold Belt lies along the coast to the north of the Etendeka flood basalts. To the south, the coastal terrane is the Ogden Rocks Domain. They may be linked beneath the Etendeka basalts (unpublished field guide, Geological Society of Namibia, 1996). The east of the Purros Tectonic Unit is tectonically bound by the Purros Lineament. Therefore, by inference, the Purros Lineament also extends south to the coast as the tectonic boundary to the eastern margin of the Ogden Rocks Domain (Fig. 3.2).

The Pan-African Fold Belt has exerted a fundamental influence on later rifting and break-up of southwest Africa. It is widely considered that Pan-African basement fabrics exercised significant control on Late Mesozoic rift geometries (Uchupi 1989, Uchupi and Emery 1991, Binks and Fairhead 1992, Maslanyj *et al.* 1992, Standlee *et al.* 1992 and others). The evidence cited to support this view is: (i) a strong similarity in orientation of offshore extensional faults with immediately onshore basement fabrics and (ii) low-angle reflections within basement offshore in the south of the Lüderitz Arch that are interpreted as shear

zones or thrusts reactivated as Mesozoic extensional faults (Light *et al.* 1993 and *Chapter 5*). In addition (iii), the extensional N-S trending Ambrosius Berg Fault Zone traverses the main Etendeka flood basalt outcrop. This was active during and after eruption of the basalts (Milner and Duncan 1987). These faults are mapped to the north, where they offset basement rocks west of the west-dipping Purros Lineament (Dingledey *et al.* 1994). The Mesozoic extensional fault may link onto this lineament at depth. (iv) In southern Namibia, the Mesozoic Mehlberg dyke (134 Ma) closely follows the regional boundary between the Gariep Group and the Namaqua-Natal basement (Reid and Rex 1994). This thesis defines the offshore extensions of the Damara and Kaoko Fold Belts where they meet, and attempts to show the influence of basement fabrics on Karoo and Permian to Lower Triassic rifting and Mid-Triassic inversion (*Chapters 5* and *6*).

The Damara Fold Belt is obscured by cover sediments in eastern Namibia but is believed to continue northeast to join the Zambezi Belt in Zambia and Zimbabwe (Porada 1979). An important element, the long-lived Mwembeshi Shear Zone, is a SW-NE oriented, steeply dipping structural lineament extending across the east of southern Africa (Fig. 3.1) (eg. Versfelt and Rosendahl 1989). Coward and Daly (1984) interpreted it as separating the Pre-Cambrian Congo and Botswana/Zimbabwe cratons and penetrating to a deep crustal level with both vertical and horizontal displacements. De Swardt *et al.* (1965) referred to it as a 'fundamental crustal structure' and recognised its influence on subsequent Karoo sediment distribution.

Daly *et al.* (1992) identified Permo-Triassic reactivation of the Mwembeshi Shear Zone/Damara Fold Belt. Karoo sediments were deposited in a rift setting along the trend of the Mwembeshi Shear Zone. They interpreted this rifting to be a consequence of sinistral strike-slip movements along the Mwembeshi Shear Zone/Damara Fold Belt and suggested that it was driven by collision on the southern margin of Gondwanaland.

The Mwembeshi Shear Zone/Damara Fold Belt appears to have been a continent-wide weak zone, with pre-existing lineaments reactivated in Karoo times, before the breakup of West Gondwanaland. This allowed southern Africa to behave independently, albeit to a small degree, from central Africa. However, there are no identifiable discrete through-going transform faults, such as in the Central African Shear Zone (Fairhead 1988, Fairhead and

Binks 1991, Binks and Fairhead 1992, Genik 1992). Mesozoic strain was distributed across and along the Mwembeshi Shear Zone/Damara Fold Belt. It did not become focused on individual lineaments, as might have been the case had relative movement been larger. Mesozoic displacement across the Central African Shear Zone is estimated to be *c.*50-60 km (Fairhead and Binks 1991), much larger than any possible displacement between central and southern Africa. The kinematics of this Karoo reactivation are discussed in *Chapter 7.*

3.3 Upper Palaeozoic-Mesozoic cover

Onshore in Namibia, the cover sediments are subdivided into sedimentary sequences by major unconformities that can be related to offshore seismic sequences. This onshore-offshore relationship is described in *Chapter 4.* A Namibian tectono-sedimentary framework (Fig. 3.3) encompasses the major sequences and the unconformities with tectonic events, some of which occurred outside Namibia, but nevertheless exerted a profound influence on the Namibian continental margin.

The main tectonic events that set the framework are Permo-Triassic Karoo rifting, the Cape Orogeny, and Late Jurassic-Early Cretaceous rifting and continental break-up that created the South Atlantic. This is called the "Atlantic" Rift Phase. The Karoo rifting occurred in i) offshore areas of Namibia, ii) in basins created by reactivation of the Damara Fold Belt/Mwembeshi Shear Zone, and iii) in East Africa. Changes in intraplate stress created by the Cape Orogeny terminated this rift phase in Namibia. Far-field effects led to a regional hiatus (Cole 1992) and more localised inversion in pre-existing weak crustal areas such as rift basins or fold belts (Daly *et al.* 1991, 1992). Subsequent cratonic sedimentation was interrupted by Early to Late Mesozoic rifting and continental break-up.

Early tectono-stratigraphic schemes were based on prevailing knowledge that led to nomenclature perhaps not applicable to Namibia. For example, Rust (1975) used the term 'Zambezian' to describe rift sequences mainly seen in East Africa, but applied to all of southern Africa. The diachronous nature of continental rifting and break-up from the Middle Jurassic to Early Cretaceous around eastern, southern and then western Africa renders this scheme non-applicable in Namibia.

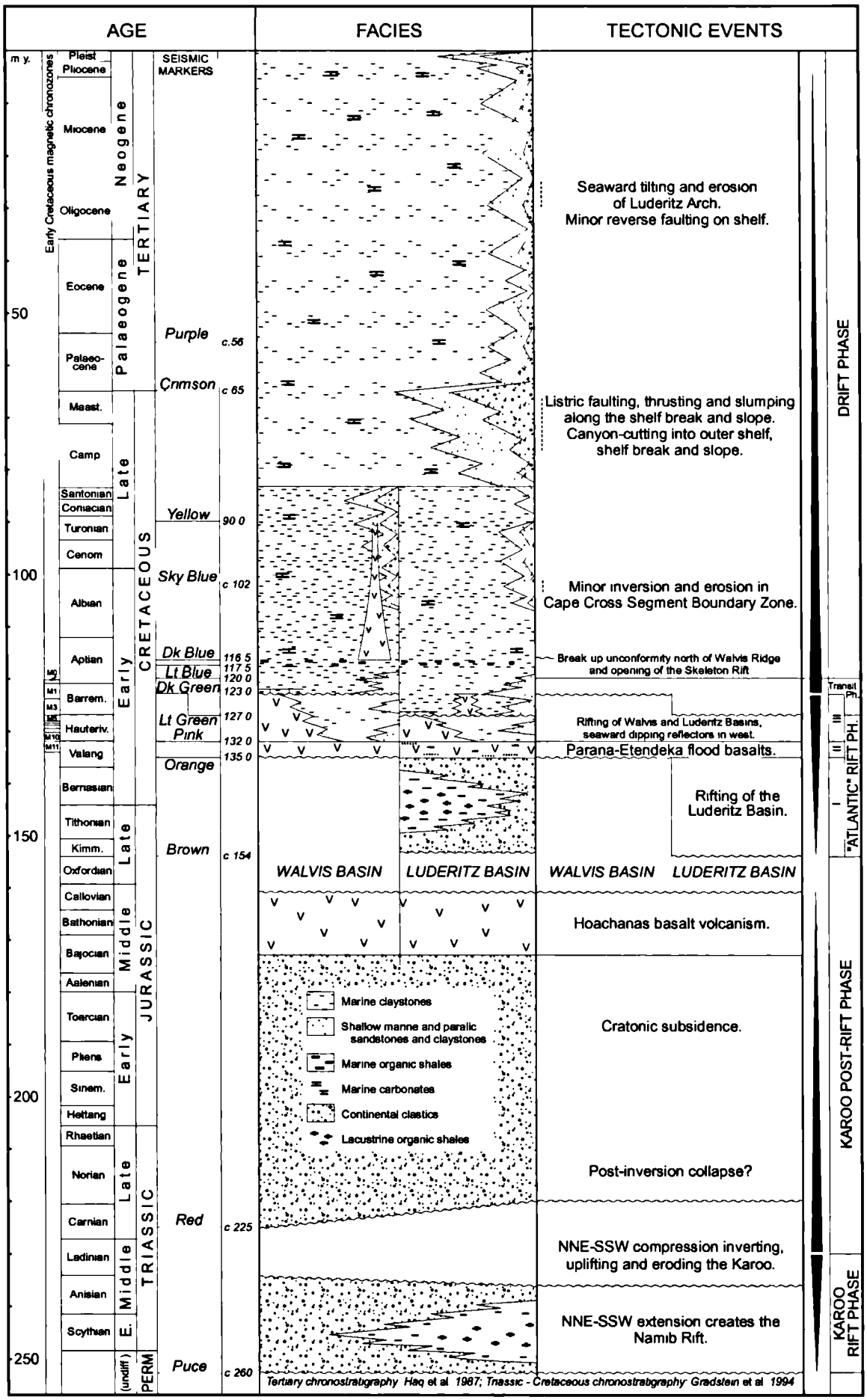


Figure 3.3 Extensional tectonic history of the Namibian passive margin

Lithostratigraphic terms in the past have been over-generalised, specifically the 'Karoo'. This has been applied to the entire Carboniferous to Early Cretaceous succession of glacial, marine, lacustrine, deltaic, aeolian and volcanic sediments. More recently, Milner *et al.* (1994) have given group status to the Lower Cretaceous Etendeka Formation and the underlying conformable Etjo Formation sandstones. This thesis follows this nomenclature and retains the term 'Karoo' for the onshore ?Carboniferous to Late Triassic succession. This may extend to the Middle Jurassic in offshore areas. Lithostratigraphic units of the Namibian onshore Karoo have been named by Johnson *et al.* (1996) after the sub-divisions of Horsthemke *et al.* (1992). However, the Etjo Formation used in the thesis follows the definition of Milner *et al.* (1994). Triassic sandstones of this name in Johnson *et al.* (1996) are here called the Plateau Sandstones after Dingle *et al.* (1983) (see below).

The tectono-stratigraphic scheme adopted by this thesis (Fig. 3.3) is dominated by the Karoo Rift and Post-Rift Phases and the "Atlantic" Rift Phase, Transitional and Drift Phases.

3.3.1 Karoo outcrops

The Karoo succession occurs in two major areas in Namibia; the Etjo Outlier in central Namibia and the Huab area south of the main Etendeka flood basalt outcrops (Fig. 3.4). It is subdivided into the lower and upper Karoo, separated by a regional Mid-Triassic hiatus (Dingle *et al.* 1983) (Fig. 3.5). The lower Karoo corresponds to the Omingonde Formation (Beaufort Group) of the Etjo Outlier (Dingle *et al.*1983) and Gai-as Formation and older Karoo (Ecca Group) of the Huab area (Horsthemke *et al.* 1990). The upper Karoo corresponds to the Carnian-Rhaetian Plateau Formation sandstones (Dingle 1983). The Mid-Triassic hiatus is coeval with the last phase of compression and uplift at *c.* 230 Ma in the Cape Fold Belt (Fig. 3.6) (Cole 1992).

The lower Karoo succession outcropping in the Huab area reaches a stratigraphic thickness of 250m (Horsthemke *et al.* 1990). This comprises a minor sequence of Permian and possibly Carboniferous basal tillites, unconformably succeeded by fluvio-lacustrine sediments of the Ecca Group. It is possible that the tillites are part of the Karoo rift sequence seen offshore, but the unconformity and facies change at the top of the tillites

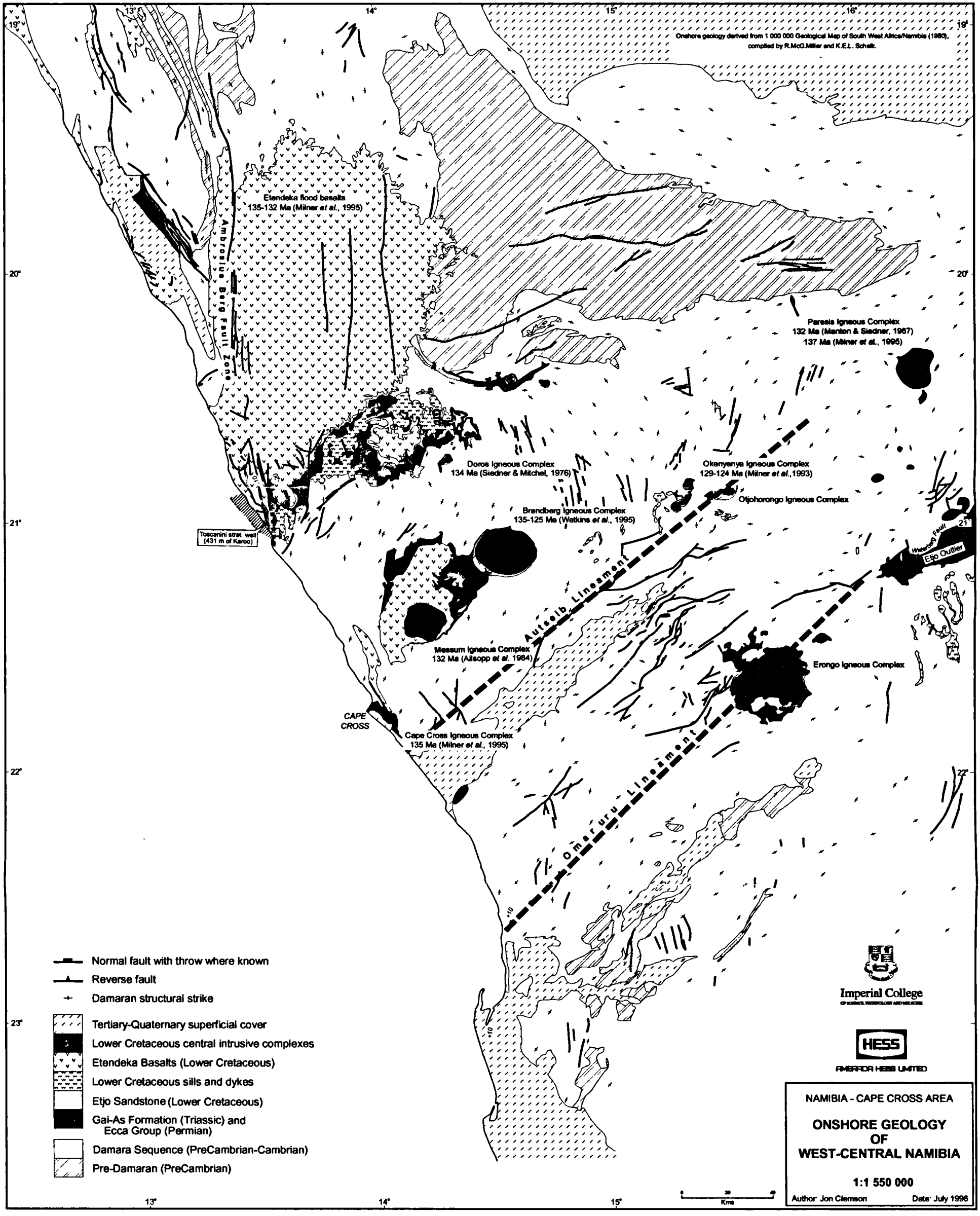


Figure 3.4 Onshore geology of west-central Namibia

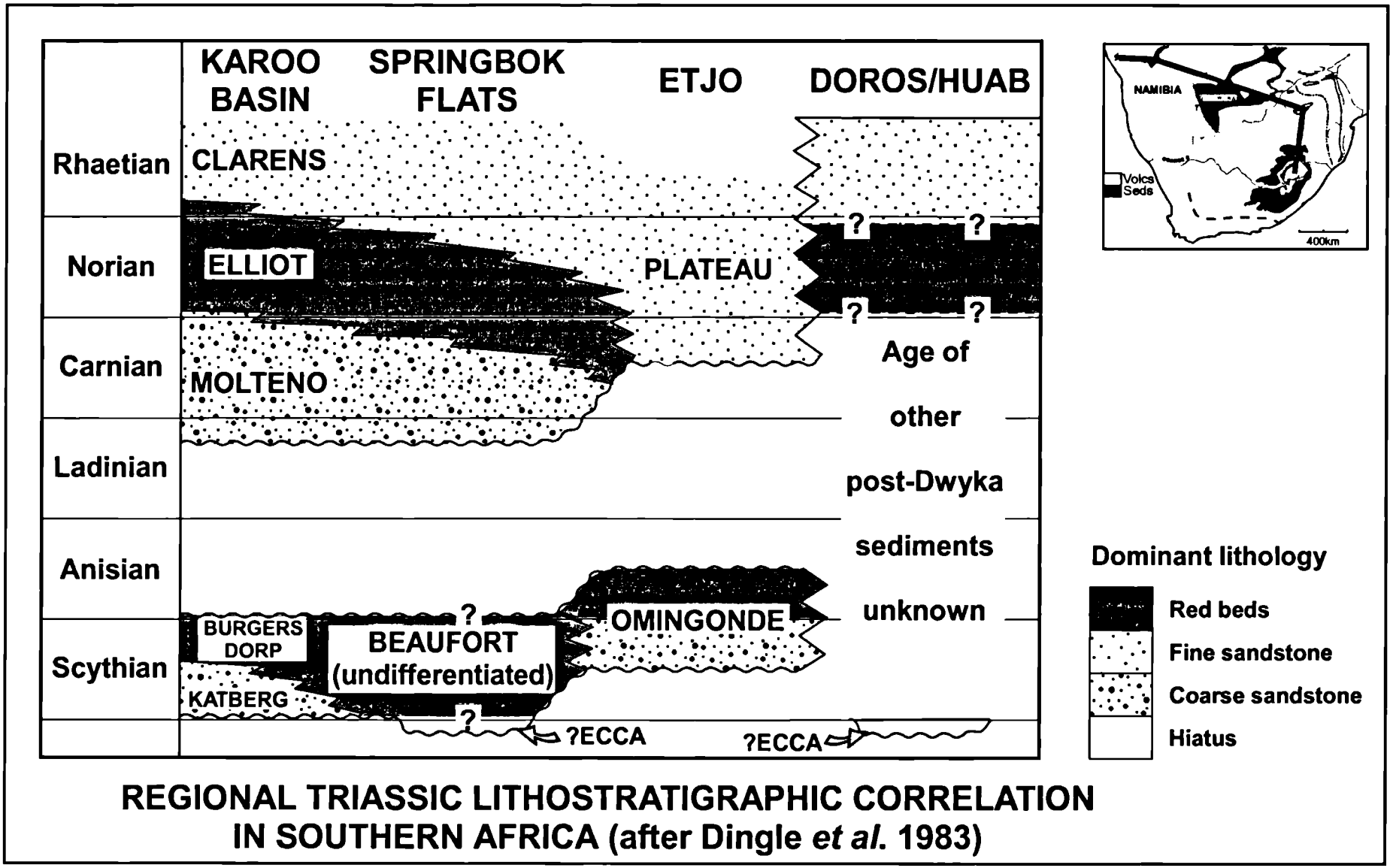


Figure 3.5 Regional Triassic lithostratigraphic correlation in southern Africa (after Dingle et al. *1983)*

Figure 3.6 Distribution in time and space of Late Carboniferous to Early Jurassic units of the Karoo Basin (after Cole 1992)

suggests that they may belong to a pre-rift sequence. Ice movement directions are interpreted to be from Namibia westwards to the Paraná Basin (Martin 1975 *in* Horsthemke *et al.*1990), i.e. across the location of the Karoo rift system. The succeeding fluvio-lacustrine sediments were deposited in a cratonic basin and have been correlated with similar successions in South America (Horsthemke *et al.* 1990). In South America, the equivalent succession extends into the Early Triassic. In Namibia, they are Permian in age but a significant part of the succession may be eroded. Just onshore, the Toscanini stratigraphic well tested a thickness of 431m of Karoo before drilling almost 1000m of crystalline basement (well summary sheet (1972), Du Preez Exploration).

Similar successions are described in the Colorado Basin of South America (Stoakes *et al.* 1991). Here, over 1500m of sediments include a thick monotonous sequence of dark shales and poorly sorted sandstones of possible lacustrine origin. Palaeontological data suggests a Permian age. The sediments are typical of those from the Permo-Triassic of South Africa and South America. Significantly, the relationship of this sequence with the Mesozoic rift-fill is that of a coherent layered succession truncated by an angular discordance. A similar relationship is evident offshore in the Cape Cross - Walvis Bay area. Here though, this sequence is also truncated by the basal unconformity of the upper Karoo as well as the base of the "Atlantic" Drift sequence (see *Chapters 5* and *6*).

The Late Triassic-Early Cretaceous arid succession has presented difficulties for stratigraphers, being hampered by a lack of palaeontological control. The Plateau Formation of the Etjo Outlier was formerly called the Etjo Sandstone. This was correlated with sandstones that interfinger with the basal flows of the Etendeka flood basalts (for review, see Dingle *et al.* 1983, p. 70). In consequence, these have also been called the Etjo Sandstones. A significant unconformity is now recognised between the Gai-as Formation and Etjo Formation in the Huab area (Horsthemke *et al.* 1990). Above the Mid-Triassic unconformity in the Etjo Outlier, the Upper Triassic Plateau Formation is correlated with the Clarens Formation in the main Karoo outcrop in South Africa (Dingle *et al.* 1983). The Lower Cretaceous Etjo Sandstones are now termed the Etjo Formation in the Huab area (Milner *et al.* 1994).

Similar confusion has also occurred in their South American equivalents. Horsthemke *et al.* (1990) compared the Late Triassic-Early Cretaceous arid succession with the Botucatu Sandstone of southern Brazil. These have similar problems with palaeontological dating. They have been described as Cretaceous and late Triassic to early Jurassic (for review, see Horsthemke *et al.* 1990).

In the Etjo Outlier, the Mid-Triassic hiatus extends from the Anisian to Carnian (Dingle *et al.* 1983). This corresponds to an hiatus of Anisian-Ladinian age, seen elsewhere in southern Africa (Dingle *et al.* 1983). Veevers (1991) links this hiatus to epeirogenic uplift of southern Africa, related to the final coalition of Pangaea. It also corresponds to the last phase of crustal shortening and uplift in the Cape Fold Belt (Fig. 3.6) (Cole 1992). This hiatus is correlated with the mid-Karoo unconformity seen offshore (see *Chapter 4*).

3.3.2 The Etendeka Group

This is dominated by the flood basalts of the Etendeka Formation, At the base, they are interbedded with aeolian sandstones of the Etjo Formation. There are also many central igneous complexes similar in age to the flood basalts (Fig. 3.4).

Geochemical and dating studies of the flood basalts and central igneous complexes have been carried out for many years but it is the advent of $^{40}Ar/^{39}Ar$ dating analysis that has realistically constrained their age. Geochemical and dating analyses together have only recently allowed reliable correlation between the Etendeka and Paraná flood basalts (Milner *et al.* 1995a).

The flood basalts comprise two major lithologies; basalts, interbedded with quartz latites. The precise eruptive source or sources of the basalt lava flows are unknown but the quartz latites are regarded as ignimbrites (Milner 1986) sourced from the Messum Complex (Milner *et al.* 1992).

The basalts are divided into northern and southern geographical areas by high or low Ti and Zr respectively in both the Paraná and Etendeka provinces (Peate *et al.* 1992; Milner *et al.*

1994). They are believed to be products of partial melting of the continental mantle lithosphere (Hawkesworth *et al.* 1992).

An intraformational disconformity with onlap of younger units in the north is identified in the Etendeka (Renne *et al.* 1996) and Paraná provinces (Milner *et al.* 1995a). This is regarded as supporting a northward migration of the locus of volcanism (Peate *et al.* 1990, 1992) over 135-132 Ma (Milner *et al.* 1995b), as against a southward migration with eruption over 10 m.y. (Turner *et al.* 1994). In the much larger Paraná province, Stewart *et al.* (1995), supplementing geochemical stratigraphy with $^{40}Ar/^{39}Ar$ geochronology of surface *and* borehole samples, see a NW-SE migration of magmatism over 138-126 Ma.

The central igneous complexes of Namibia were active over 137-124 Ma with individual centres active for 5-10 m.y. (Milner *et al.* 1995b). This exceeds the 3 m.y. of flood basalt volcanism but compares closely with the 138-126 Ma timespan for the much more extensive Paraná flood basalts (Stewart *et al.* 1995). The complexes have a roughly linear distribution in two NE-SW trending belts. They are not believed to be a hot spot track but to have exploited lithospheric weaknesses related to the Damara Fold Belt (Milner *et al.* 1995b).

3.3.3 Early Cretaceous faulting

Two distinct fault trends are identifiable onshore in west-central Namibia (Fig. 3.4). The N-S trend corresponds with the Kaoko Fold Belt and the SW-NE trend corresponds with the Damara Fold Belt. The identification of the age of most faults is hampered by the absence of sedimentary cover over the Pan-African basement. It is only possible to constrain their age in the Etjo Outlier and the Huab-Etendeka areas.

The north-south Ambrosius Berg Fault Zone bisects the main outcrop of the Etendeka flood basalts (Fig. 3.4). The volcanics are downthrown to the west by *c.* 750m (Milner *et al.* 1990). West of the fault zone, the volcanics dip between 5°-30° eastward to the faults. The increasing eastward dip in successive fault blocks to the west of the fault zone suggests that the faults are listric in character (Milner 1986). In this area, *c.* 900 m (*c.* 0.35 seconds TWT) of volcanics are preserved (Milner 1986). Some fault hangingwalls contain east-dipping sequences consisting of fining-up cycles of conglomeratic units. These comprise detritus

entirely derived from the Etendeka volcanics. Preserved sedimentary structures indicate a western provenance for the conglomerates (Ward and Martin, 1987). Most fault activity post-dates the lavas (Milner 1986).

The reverse Waterberg Fault forms the northwest boundary to the Etjo Outlier. The Omingonde and Plateau Formations of Scythian-Rhaetian age lie to the southeast in the hangingwall of the fault. In this outlier, thick pebble and boulder conglomerates near the base of the lower Karoo Omingonde Formation are interpreted to be partly water-lain and partly scree (Gevers 1936). The screes suggest syn-sedimentary fault activity of the Waterberg Fault. This is interpreted as a reactivation of the Damaran Omaruru Lineament.

Another Damaran element, the Autseib Lineament (Fig. 3.4), has also been reactivated. A reverse fault bounds the southeast margin of a small outlier of Permo-Triassic sediments near the Otjohorongo Igneous Complex (Fig. 3.4). This margin has been overthrust by Damaran basement. It also cuts the ring dyke of the Otjohorongo Igneous Complex (pers. comm., R. McG. Miller). This complex is not dated but the nearby Okenyenya Igneous Complex has been dated as 129-124 Ma (Milner *et al.* 1993). If the Otjohorongo Igneous complex is of a similar age, then the reactivation of the Autseib Lineament is also Early Cretaceous or younger. The Autseib and Omaruru lineaments have the same NE-SW orientation. If their post-Karoo reverse activity is correlated with Late Albian/Cenomanian uplift and inversion seen offshore on these lineaments (see *Chapters 5* and *6*), then the onshore fault inversion is also probably Early Cretaceous in age.

3.4 Conclusions

a) Much of the Namibian coastline is parallel to the structural fabric of the Kaoko and Gariep arms of the Pan-African fold belts. In the Walvis Bay area, the Damara Fold Belt cuts across this coast-parallel trend. In the north of the Lüderitz Arch, the western boundary of the Kalahari Craton extends just offshore. Pan-African basement fabrics exercised significant control on subsequent Karoo and Atlantic rifting.

b) The tectonic framework encompassing Upper Palaeozoic to Mesozoic sediments is dominated by the Karoo Rift and Post-Rift Phases, and the "Atlantic" Rift and Drift Phases. They are represented onshore by the Karoo and Etendeka Groups. A Mid-Triassic hiatus subdivides the onshore Karoo into lower and upper Karoo. This hiatus is coeval with the last compressive event of the Cape Orogeny and correlates with the mid-Karoo unconformity seen offshore.

c) Dating of the Etendeka flood basalts at 135-132 Ma is well constrained by $^{40}Ar/^{39}Ar$. They comprise two major lithologies, basalts and quartz latites. The basalts of the Paraná and Etendeka provinces are divided into northern and southern areas by high or low Ti and Zr content. An intraformational disconformity is identified in both the Paraná and Etendeka provinces. Igneous activity in the Paraná province migrated NW-SE over 138-126 Ma. This timespan is close to the age of central igneous complexes in Namibia (137-124 Ma). The central igneous complexes have a roughly linear distribution because they exploited lithospheric weaknesses of the Damara Fold Belt.

d) The age of faulting onshore is poorly constrained except where they cut Karoo sediments or the Etendeka flood basalts. Activity of the Ambrosius Fault Zone mostly post-dates the flood basalts. The Waterberg Fault reactivated the Omaruru Lineament as a normal fault in early Karoo times. It was subsequently reactivated as a reverse fault but the timing is poorly constrained. The Autseib Lineament records reverse fault activity cutting the Otjohorongo Central Igneous Complex. This reverse faulting on both lineaments is interpreted to correlate with Early Cretaceous uplift and erosion on their extensions offshore.

4

REGIONAL INTERPRETATION OF THE NAMIBIAN PASSIVE MARGIN

4.1 Introduction

The regional interpretation was carried out to define a structural framework and history of the Namibian passive margin. Other regional studies have previously been undertaken but each had certain limitations. Early seismic data used by Emery *et al.* (1975) did not penetrate below the base of drift sediments. Later interpretations built up an image of the syn-rift morphology of the passive margin. Austin and Uchupi (1982) provided a broad structural picture. Gerrard and Smith (1982) carried out an excellent, more detailed seismo-stratigraphic interpretation of the passive margin from Cape Fria to the Cape of Good Hope. However, interpretation of the syn-rift sequence was limited and some transverse structures were noted but not examined in detail. A third generation of interpretations was carried out by Intera Information Technologies (Light *et al.* 1992, 1993; Maslanyj *et al.* 1992) with newly acquired speculative seismic data. These papers examined the "Atlantic" syn-rift history more comprehensively and interpreted continental break-up as simple shear. Transverse elements and the interaction of basement elements during rifting were not considered. Karoo rifting was superficially described but not presented in any detail. Much of the seismic data used in these papers was used in this regional interpretation.

It is significant that Dingle *et al.* (1983) noted that "the lack of large-scale faulting and basin development onshore in southwest Africa is quite remarkable." Offshore, there is also a lack of extensive large scale faulting during "Atlantic" rifting to account for the degree of crustal stretching often cited to precede final break-up. In addition to examining segmentation of this passive margin, this thesis also interprets the Karoo to determine whether Karoo stretching pre-weakened the lithosphere before "Atlantic" break-up.

4.2 Geophysical and geological database

4.2.1 Seismic and well database

This comprises 10,430 km (out of 14,300 km) of speculative data (Fig. 4.1) in the offshore waters of Namibia. This was acquired during 1989-1991 on behalf of Namcor by Intera

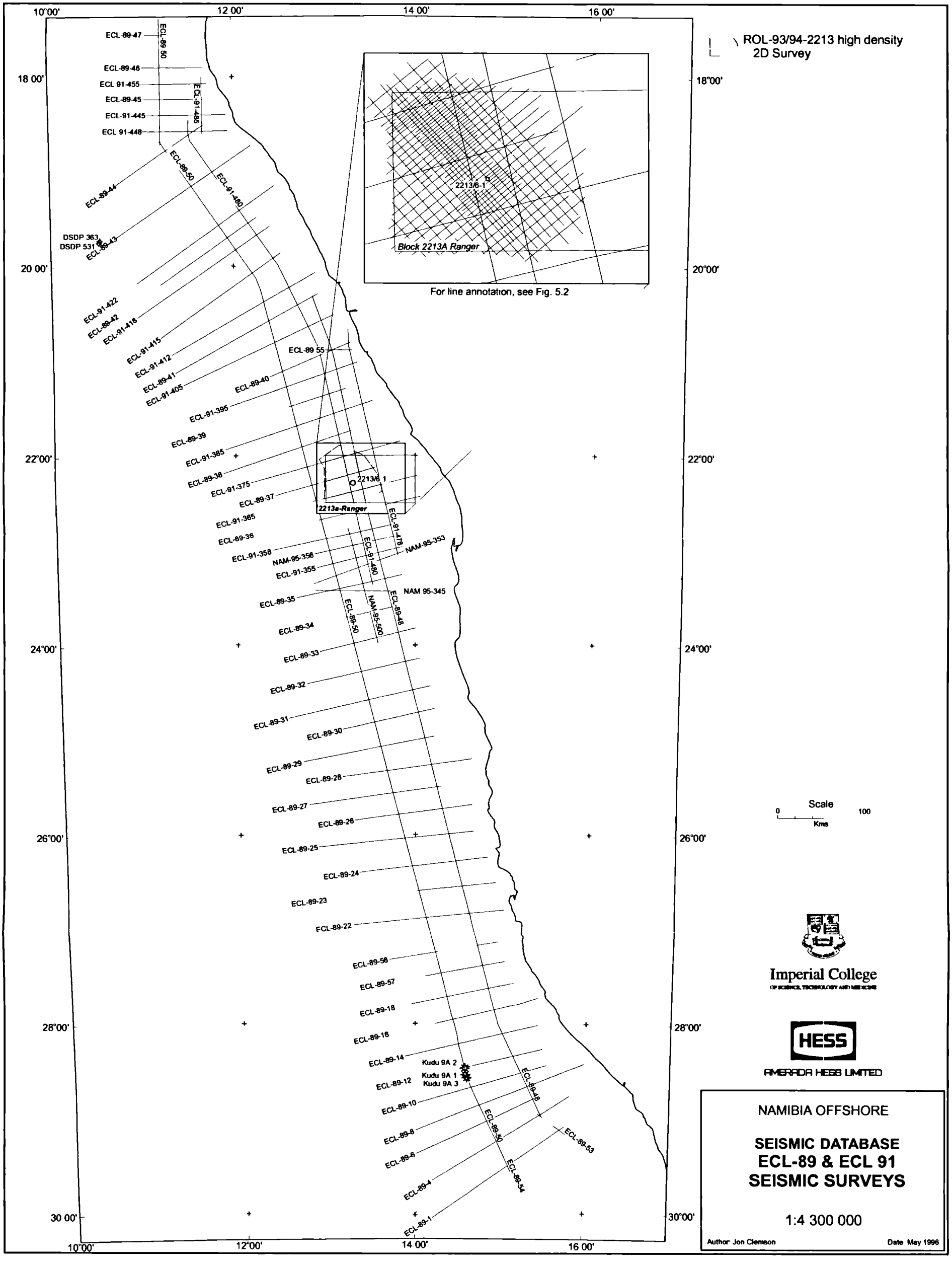


Figure 4.1 Seismic database of the ECL-89 and ECL-91 seismic surveys

Information Technologies/Halliburton Geophysical Services. The source was a sleeve airgun array at a depth of 6 metres and recorded with a 3600 metre cable. The 60-fold migrated data is displayed down to 7.0 or 8.0 seconds. Acquisition and processing parameters are shown in Figure 4.2. To the southwest of Walvis Bay, a further 425 km of data locally allows a more comprehensive structural interpretation. This data was acquired in 1995 by Intera Information Technologies to infill the pre-existing data. This was shot with a longer 4500m cable at a depth of 7m and is displayed down to 6.9 seconds (TWT).

Within the area studied, there are three commercial exploration wells openly available for seismic calibration. However, all are located in the Kudu gas accumulation, 140 km northwest of the Namibia/South Africa boundary. Results of the wells are summarised in Hoal (1990). Of these wells, Kudu 9a-1 to 3, only the final well has sufficient velocity information available to provide seismic calibration. General details of a further nine wells drilled on the continental shelf off South Africa are summarised in Gerrard and Smith (1982) and Dingle *et al.* (1983). These are located 300-450 km south of the Kudu wells. There are no seismic data available with which to tie in these wells to the Namibian dataset.

Limited data from well 2213/6-1, drilled offshore from Cape Cross, has also been incorporated into the thesis.

The Toscanini stratigraphic well is located north of Cape Cross near the mouth of the Huab River. It penetrated Cretaceous volcanics and terminated in Pan-African basement after encountering 431m of Permo-Triassic Karoo clastics (unpublished well summary sheet, Du Preez Exploration 1972).

There are several Deep Sea Drilling Project wells outwith the study area - DSDP 361-363 & 530-532. There are no seismic ties between these wells and the ECL datasets but some provide valuable geological information on a regional scale.

- DSDP 361. This is located over 600 km south of the study area above oceanic crust. The oldest sediments penetrated are of early Aptian age and estimated to be between 36-86 metres above oceanic crust from seismic profiles (Bolli *et al.* 1978). To the west of this well, seismic reflector AII pinches out on oceanic basement near

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OFFSHORE NAMIBIA

NON-EXCLUSIVE SURVEY

ECL

ECL-89-42B/42D/42E/42
S.P. 3001 TO 3954/5044 TO 6410
7411 TO 10347/1837 TO 1

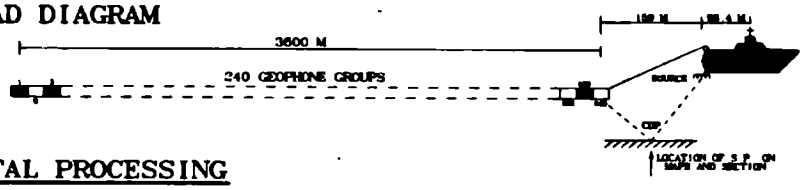
55 DEGREES → ← DIRECTION SHOT

FILTERED MIGRATION

FIELD DATA

DATA SHOT BY	- HGS PARTY 2930 M V PATRICK E HAGGERTY
DATE SHOT	- SEPT 1989 - FEB 1990
RECORDING INSTRUMENTS	TSR001,SPACE VARIANT RECORDING DELAYS APPLIED
RECORDING FILTERS	- HIGH FILTER AND SLOPE 180 HZ 72 DB/OCT
	LOW FILTER AND SLOPE 8 HZ 18 DB/OCT
RECORDING POLARITY	- A POSITIVE PRESSURE AT THE HYDROPHONE PRODUCES A NEGATIVE NUMBER ON TAPE AND A DOWNWARD DEFLECTION ON THE FIELD MONITOR RECORD
DIGITAL TAPE FORMAT	- SEGD DEMUX 6250 BPI 16 BIT QUAT
RECORD LENGTH / SAMPLE RATE	- 7 0 SEC OR 5 0 SEC OF DATA AT 2 MS SAMPLE RATE
ENERGY SOURCE	- 4 STRINGS OF 64 GUNS, 2180 CU IN SLEEVE AIRGUN ARRAY OPERATING AT 1900 PSI
GUN DELAY	- 51 2 MS
SOURCE DEPTH	- 6 0 METRES AVERAGE
SOURCE TO ANTENNA DISTANCE	- 96 4 METRES
FATHOMETER TO SOURCE DISTANCE	62 METRES
SHOTPOINT INTERVAL	- 30 METRES, 1 POP PER SHOTPOINT
SHOTPOINT ANNOTATION	- SHOTPOINTS ANNOTATED AT CDP POSITION
CABLE LENGTH	- 3600 METRES, 240 GROUPS
CABLE DEPTH	- 8 0 METRES AVERAGE
HYDROPHONES	- 40 PER GROUP
COVERAGE	- 60 FOLD, 240 TRACE
PRIMARY NAVIGATION SYSTEM	- ARGO / SYLEDIS
SECONDARY NAVIGATION SYSTEM	- TRANSIT SATELLITE
	- ALL NAVIGATION DATA REFERENCED TO CNP

SPREAD DIAGRAM



DIGITAL PROCESSING

POLARITY CONVENTION	- THE POLARITY OF THE FIELD RECORDING WAS MAINTAINED THROUGHOUT THE PROCESSING AND DISPLAY
RECORD LENGTH / SAMPLE RATE	- 7 0 SEC MAX / 4 MSEC
STATIC CORRECTIONS	- SHOT AND STREAMER STATIC 9 5 MS, AIRGUN DELAY 51 2 MS
ADJACENT TRACE MIX	- 2 - 1 TO YIELD 120 TR, 60 FOLD DATA
TRUE AMPLITUDE RECOVERY	- 6 0 DB PER SECOND FROM WB TO WB+4 0 SECONDS SPHERICAL DIVERGENCE CORRECTION APPLIED
PRE DECONVOLUTION MUTE	- USING A 100 MS RAMP, START TR/TIME 112/0 111/300 1/3200
DESIGNATURE	- OFFSET DEPENDENT DEMULTIPLEXED STREAMER WAVELET VERSION 6 FMIN=5 HZ FMAX=125 HZ HCSLOPE=72 DB/OCT LCSLOPE=24 DB/OCT
TIME VARIANT SCALING	- USING 1500 MS GATES,START TR 120 WB+1000 MS START TR 1 WB+2000 MS
VELOCITY ANALYSIS	- USING 9 DEPTH POINT VELSCAN ANALYSES, 1 EVERY 30KMS
VELOCITY ANALYSIS	- USING 15 DEPTH POINT VELSCAN ANALYSES, 1 EVERY 5 KMS
FK DEMULTIPLE	- VELNP=67000, VELPP=4
KIRCHHOFF DIP MOVEOUT	- DIP LIMITED TO 90 DEGREES ON 30 OFFSETS
VELOCITY ANALYSIS	- USING 15 DEPTH POINT VELSCAN ANALYSES, 1 EVERY 2 KMS
INNER TRACE MUTE	- USING A 100 MS RAMP,START TR 120 97 91 90 START TIME(+WB),1500 2500 3500 7000
NORMAL MOVEOUT CORRECTION	- USING ANNOTATED VELOCITIES
FIRST BREAK SUPPRESSION	- USING A 100 MS RAMP, START TR/TIME, 112/0 111/300 1/3200
COMMON DEPTH POINT STACK	- 30 FOLD CDP STACK
DECONVOLUTION	- 1 X ZW1 FILTER LENGTH + ZW GAP ZW=0 8 X TWO WAY WB TIMES, ZW1=0 3 X TWO WAY WB TIMES DESIGN GATE , WB-80 TO WB+4000 MSEC
TIME VARIANT FILTERING	- AS BELOW
FK MIGRATION	- 60 DEG WAVE EQUATION MIGRATION USING SMOOTHED STACKING VELOCITIES REDUCED AS FOLLOWS WB EQ 13, 85 PC , WB EQ 25, 92 5 PC , WB EQ 38, 90 PC - INTERVAL VELOCITIES LIMITED TO 6000 M/SEC
TIME VARIANT FILTERING	- FREQUENCY(HZ) TIMES+WB(MS) FREQUENCY(HZ) TIMES+WB(MS) 5-15 - 60-70 500 5-15 - 55-65 1000 5-15 - 50-60 2000 5-10 - 40-50 3000 5-10 - 40-50 3500 5-10 - 35-45 4500 5-10 - 30-40 5500
TIME VARIANT SCALING	- FLATTVS USING 1000 MS GATES, START TIME WB
TIME VARIANT SCALING	- FITLNTVS USING 100 MS GATES, START TIME WB

DISPLAY

HORIZONTAL SCALE	-	33.330 TR/CM 66.666 TR/KM
VERTICAL SCALE	-	8.00 CM/SEC
POLARITY	-	NORMAL
TRACE TYPE, BIAS	-	WTVAR, 10 PERCENT
DATUM	-	SEA LEVEL
DISPLAY UNIT	-	0.507936 CM

DISPLAY GAIN

INPUT	
CDP	ALL
GAIN DB	TIME MSEC
-60 5	0

The ECL-89 dataset has similar parameters

Figure 4.2 Acquisition and processing parameters of the ECL-91 dataset.

Table 4.1 Interval velocities applied to estimated sequence thicknesses and depth-converted figures (Figs 5.46 & 6.17)

		SEQUENCE	LITHOLOGY	VELOCITY (m/sec)
Drift Phase		Sequence E	Sandstone, siltstone, claystone.	2150-2725
Transitional Phase		Sequence D	Sandstone, claystone. & anhydrite (Hyena Back-Basin).	3000-3500 4100
'Atlantic' Rift Phase		Sequence CIII	Sandstone, siltstone, claystone.	3500-4000
		Sequence CII	Sandstone, siltstone, claystone, volcanics.	3700-5000
		Sequence CI	Sandstone, siltstone, claystone, volcanics.	3800-4500
Karoo Post-Rift & Drift Phases	Upper Karoo	Sequence B	Sandstone, siltstone, clayst; (volcs at top?)	4000-4700
	Lower Karoo	Sequence A	Sandstone, siltstone, claystone, limestone.	4000-5000
Pan-African Orogenic Phase		Crystalline Basement		5500-6000

Due to the paucity of well data on the Namibian passive margin, the interval velocities (above) are estimates based on expected lithologies and depth of burial

magnetic anomaly M0 (Bolli *et al.* 1978). Reflector AII is dated as Late Aptian (Bolli *et al.* 1978).

- DSDP 362 was drilled on the southeastern flank of the Walvis Ridge and just west of the seismic coverage. DSDP 532 is in the immediate proximity to this well. However DSDP 362 terminated in the Oligocene and DSDP 532 in the Eocene (Sibuet *et al.* 1984).
- DSDP 363 was drilled on the crest of the northern flank of the eastern Walvis Ridge. The well terminated in Late Aptian-Albian limestones (Sibuet *et al.* 1984). Its location on the ridge, well to the west of seismic coverage, renders this to be limited in value.
- DSDP 530 is located to the north of the Walvis Ridge in the Namibe Basin.
- DSDP 531 was drilled on top of a guyot-like feature located on the Walvis Ridge. Only samples from shallow water Cretaceous carbonates were recovered (Sibuet *et al.* 1984).

Kudu 9a-3 provides the only meaningful well-to-seismic calibration (**Table 4.2**). However, calibration data is limited to a simple checkshot survey. From this data, a depth-time curve has been interpolated so that post-Barremian horizons can be calibrated (Fig. 4.3).

4.2.2 Gravity and magnetic data

The 1:1 000 000 Geological Map of Southwest Africa/Namibia (1980) has offshore free-air gravity data, but is limited in its extent. Two more recent regional free-air gravity maps are found in Light *et al.* (1992) and Gladczenko *et al.* (1995). The map of Gladczenko *et al.* (1995) (Fig. 4.4) is more extensive, covering the continental margin and adjacent ocean basin. Offshore magnetic data is limited to the continental margin north of Walvis Bay. This is shown in Figure 4.5, which is taken from the Airborne Magnetic Anomaly Map, published by the Geological Survey of Namibia (1993).

Table 4.2 Calibration data for Kudu 9A-3

WELL CALIBRATION
KUDU 9A-3

Horizon	Depth (m) KB (Subsea)	Time (TWT in secs)
Sea Bed	191.5 (-165.5)	0.225
Purple Marker (not mapped) (Base Eocene)	722 (-696)	0.740
Crimson Marker (Base Palaeocene)	790 (-764)	0.785
Yellow Marker (intra-Turonian)	3490 (-3464)	2.805
Dark Blue Marker Mid Aptian	3842 (-3816)	2.985
Light Blue Marker (intra Lower Aptian)	3995 (-3969)	3.060
Dark Green Marker (Near Base Aptian)	4088 (-4062)	3.115
TD	4526 (-4500)	3.320

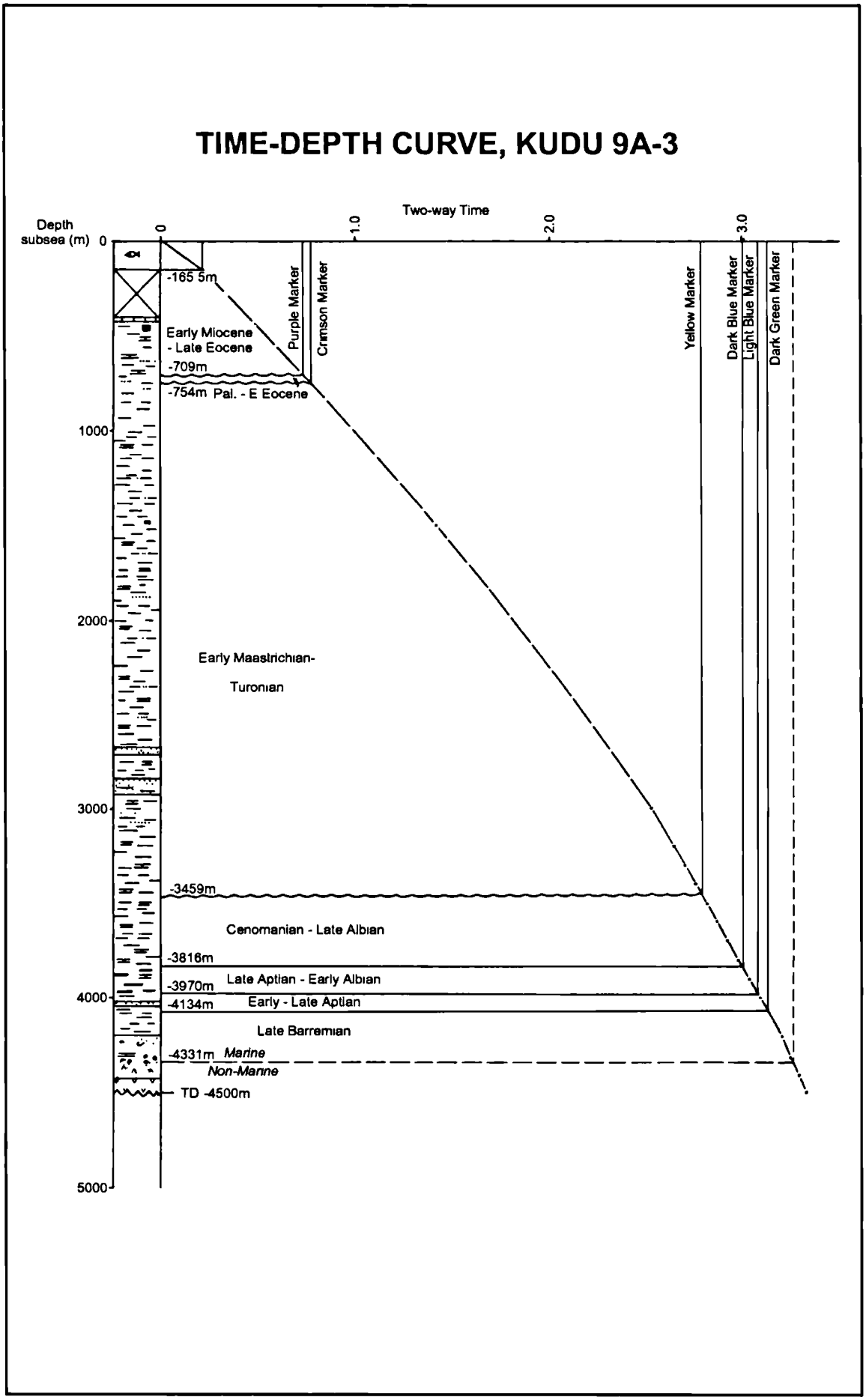
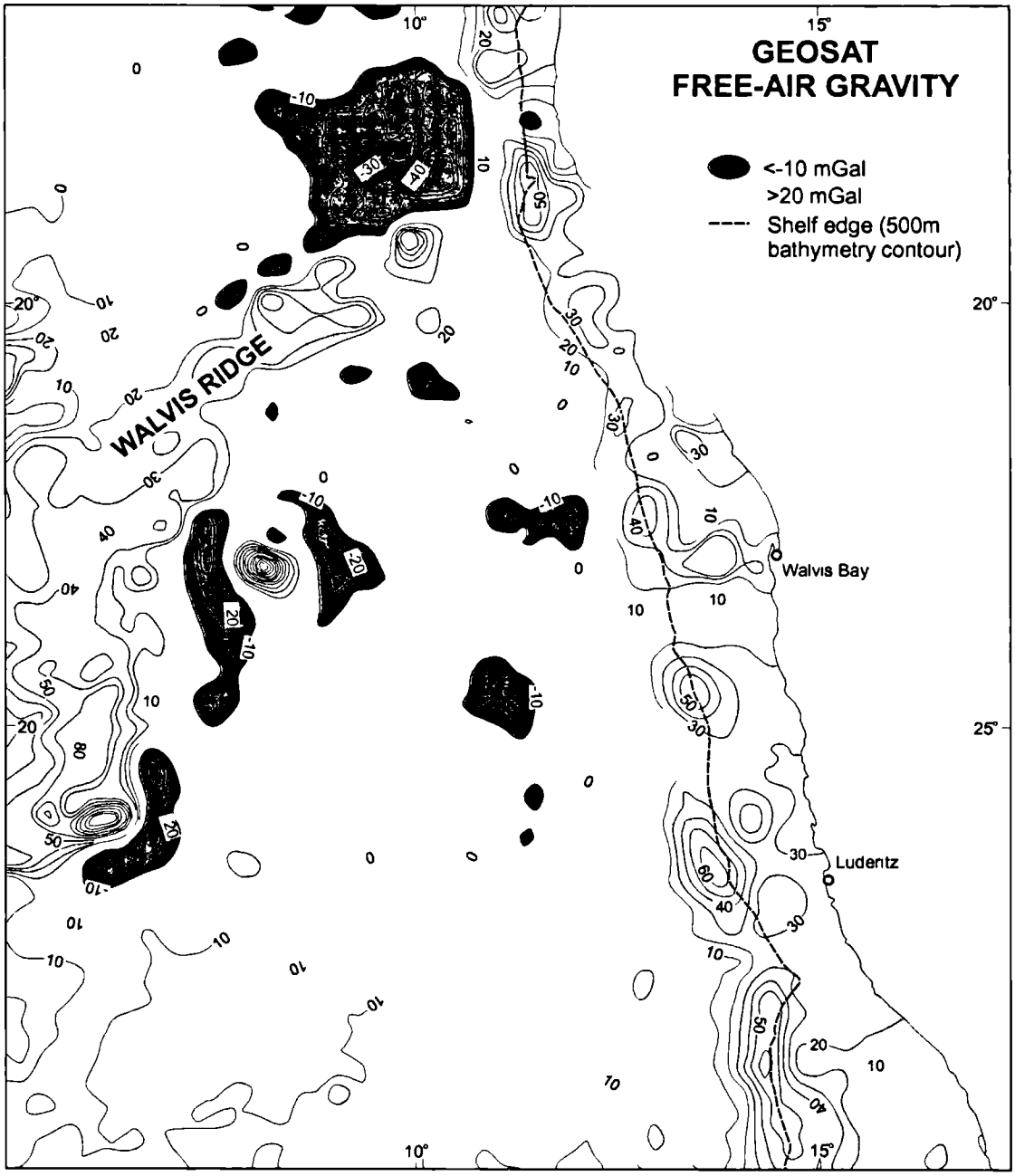


Figure 4.3 Time-depth curve, Kudu 9A-3



Free-air gravity anomaly map of the Namibian passive margin. Contoured from GEOSAT altimetry data gridded in 5'x5' grids, compiled by Haxby (1987). From Gladczenko (1995)

Figure 4.4 Free-air gravity anomaly map of the Namibian passive margin (from Gladczenko et al. *1995)*

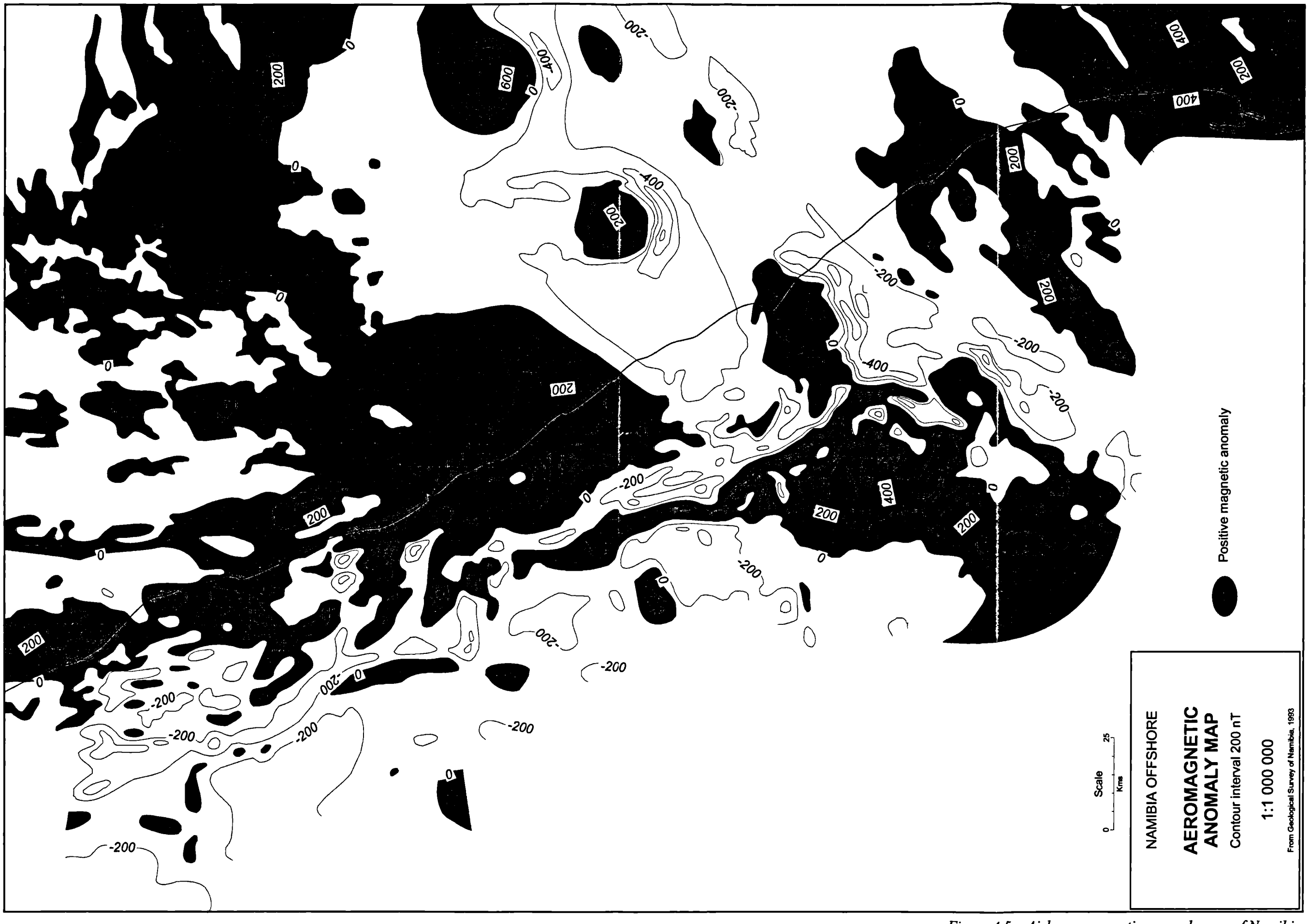


Figure 4.5 Airborne magnetic anomaly map of Namibia

4.3 Tectonic elements

The Namibian passive margin includes two major basins, the Lüderitz and Walvis Basin (Fig. 4.6). The Orange Basin lies off South Africa and falls outside the studied area. These basins were originally defined by post-rift sedimentary depocentres (Gerrard and Smith 1982). However, they are also discrete syn-rift tectonic units of the "Atlantic" Rift Phase separated by segment boundary zones. The Lüderitz Basin lies to the west of the Lüderitz Arch. The Walvis Ridge separates the Walvis Basin from the Namibe Basin. Most of this basin lies in offshore Angola, although its southern end extends into Namibian waters. It is not examined in any detail in this thesis.

Tectonic elements are grouped into crystalline basement and rift and drift features. Many of these are shown in the serial cross-sections of the Namibian passive margin (Fig. 4.7). The term 'crystalline basement' includes any formation or sequence subjected to orogenic deformation and regional metamorphism. The youngest basement is the Late Proterozoic to Early Cambrian Pan-African Fold Belt. On the Lüderitz Arch, older crystalline basement of the Namaqua-Natal metamorphic complex extends offshore (Fig. 4.6).

Basement features.

- The base of the Pan-African tectonic sequence is evident on and south of the Lüderitz Arch. Thrust nappes can be identified in the Namaqua-Natal metamorphic complex but the Pan-African tectonic sequence is almost seismically opaque and shows fewer thrust nappes. The various tectonic domains are outlined in *Chapter 3* and their influence on subsequent tectonic history is discussed in *Chapters 5* and *6.*

- Namibian Platform. This incorporates the area between the Hinge Line (see below) and coast. It is mostly featureless, having been almost peneplained at the end of the Transitional Phase. Most of the platform is underlain by crystalline basement, but there are also local elements such as the Swakop Basin and thrust-ramp graben (see below). In the Cape Cross area (Fig. 4.6), the Karoo rift sequence occurs on large areas of the platform.

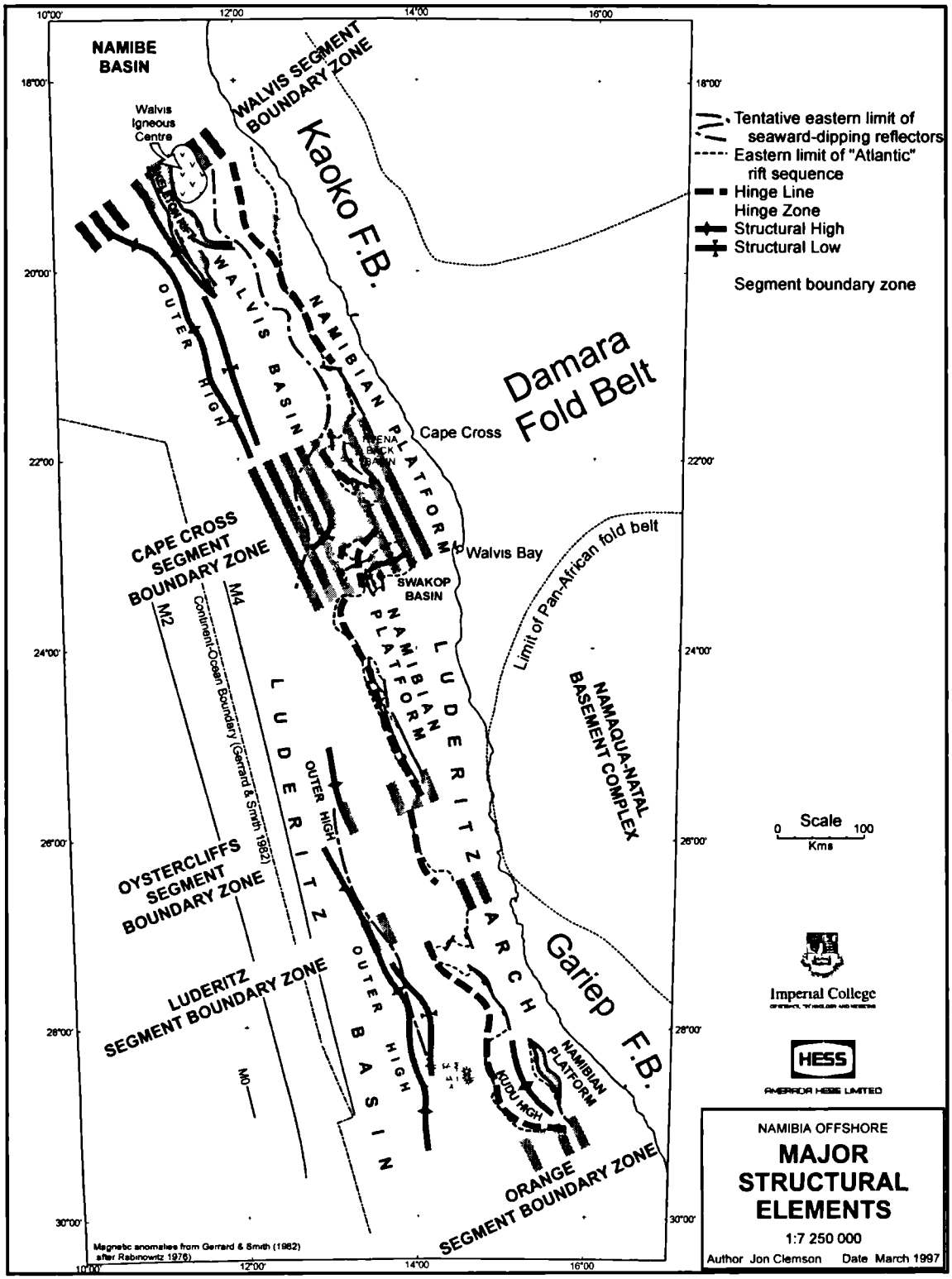


Figure 4.6 Offshore Namibia - major structural elements

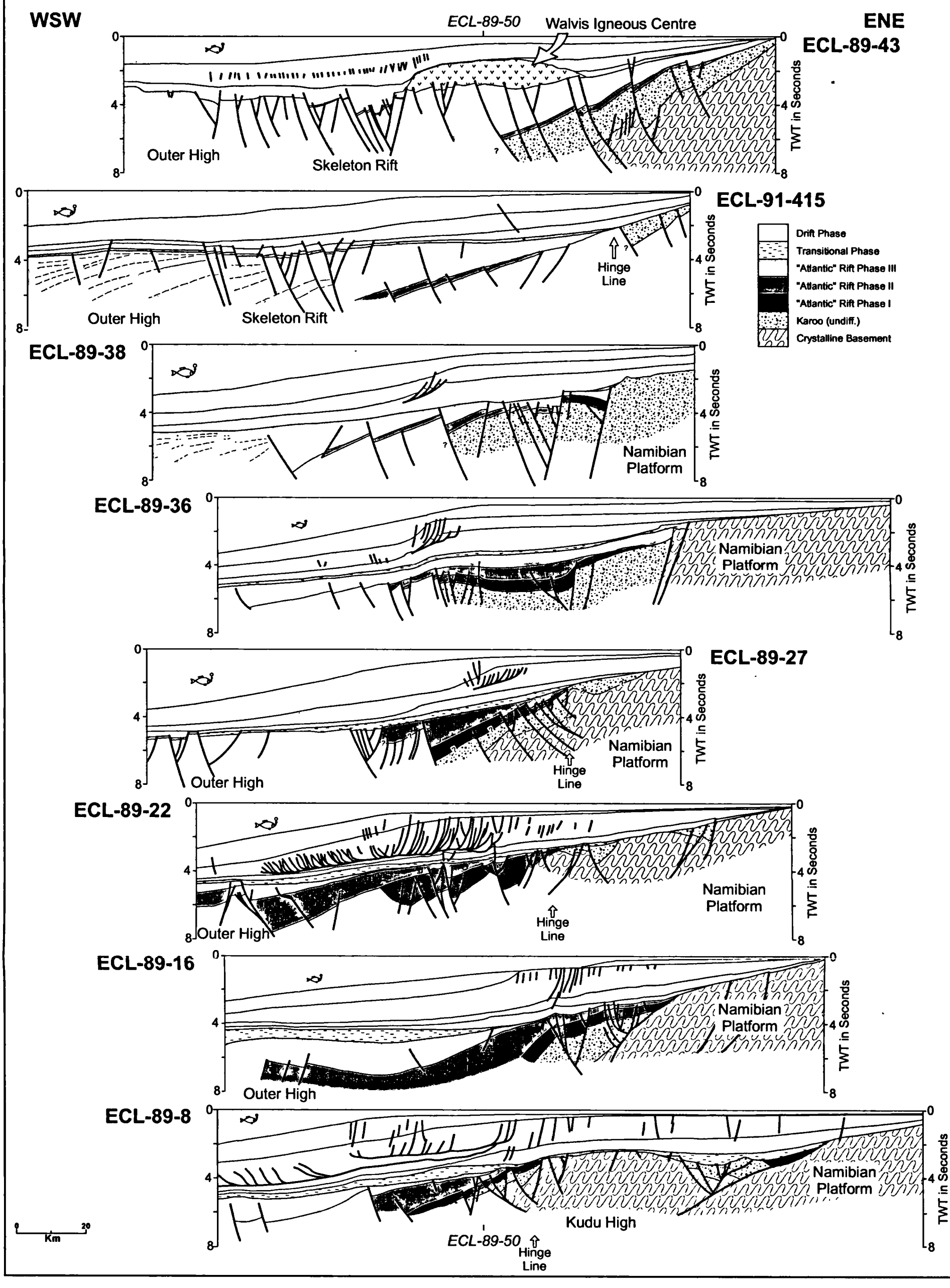


Figure 4.7 Serial cross-sections of the Namibian passive margin

Rift features.

Many major elements extend the entire length of the Namibian passive margin:

- Outer High. The Marginal High identified by Gerrard and Smith (1982) equates with the Outer High described here. It is so-called after the terminology of Schuepbach and Vail (1980). Its origin is discussed in *Chapter 4*. Gerrard and Smith (1982) have shown the Outer High to extend from the Walvis Ridge in the north to the Falklands-Agulhas fracture zone in the south. On the available seismic data, the relationship between the Outer High with the continent-ocean boundary cannot be seen. The ECL-89/91 datasets do not extend west to the continent-ocean boundary of Gerrard and Smith (1982). The Outer High is defined at the break-up unconformity but is only evident in their depth-converted map (Fig. 4.8). The Outer High west and south of the Lüderitz Arch is cored by a structural high often fault-bounded to the east. In the Walvis Basin, the Outer High is apparent in time sections and lies on the wedge of seaward-dipping reflectors. However, there is no evidence for any fault-bounded structures beneath the Outer High.

- Seaward-dipping reflector sequence. Seaward-dipping reflector sequences have been identified on the Namibian passive margin by Hinz (1981) and Austin and Uchupi (1982) and studied in detail by Gladczenko *et al.* (in press). Similar sequences were drilled on the Vøring Plateau off Norway and off southeast Greenland. They encountered subaerial and shallow submarine basalts interbedded with sediments.

- Hinge Line. Many syn-rift seismic reflections of the "Atlantic" rift sequence converge updip eastward to the Hinge Line (Gerrard and Smith 1982, Maslanyj *et al.* 1992) (Fig. 4.7). This feature was active since earliest rift times but largely ceased in influence after the break-up unconformity. It is primarily in the abrupt offsets and salients of the Hinge Line that the segmented structure of the margin is most obviously expressed (Fig. 4.6). Seismic coverage does not extend across the full width of the rifted margin, so the morphology of the Hinge Line is an important guide to the gross segmentation of the margin. Locally, flexure along the Hinge Line is associated with faulting and collapse of small half-grabens. This occurred on the north of the Lüderitz Arch, where dips to the west are steepest and this flexing is most acute.

- Central Half-Graben. A steeply-dipping sedimentary wedge thins east to the Hinge Line. In the Lüderitz Basin, faulting in the west defines the Central Half-Graben. Within the half-graben, most faults are downthrown to the east. This feature is offset along its

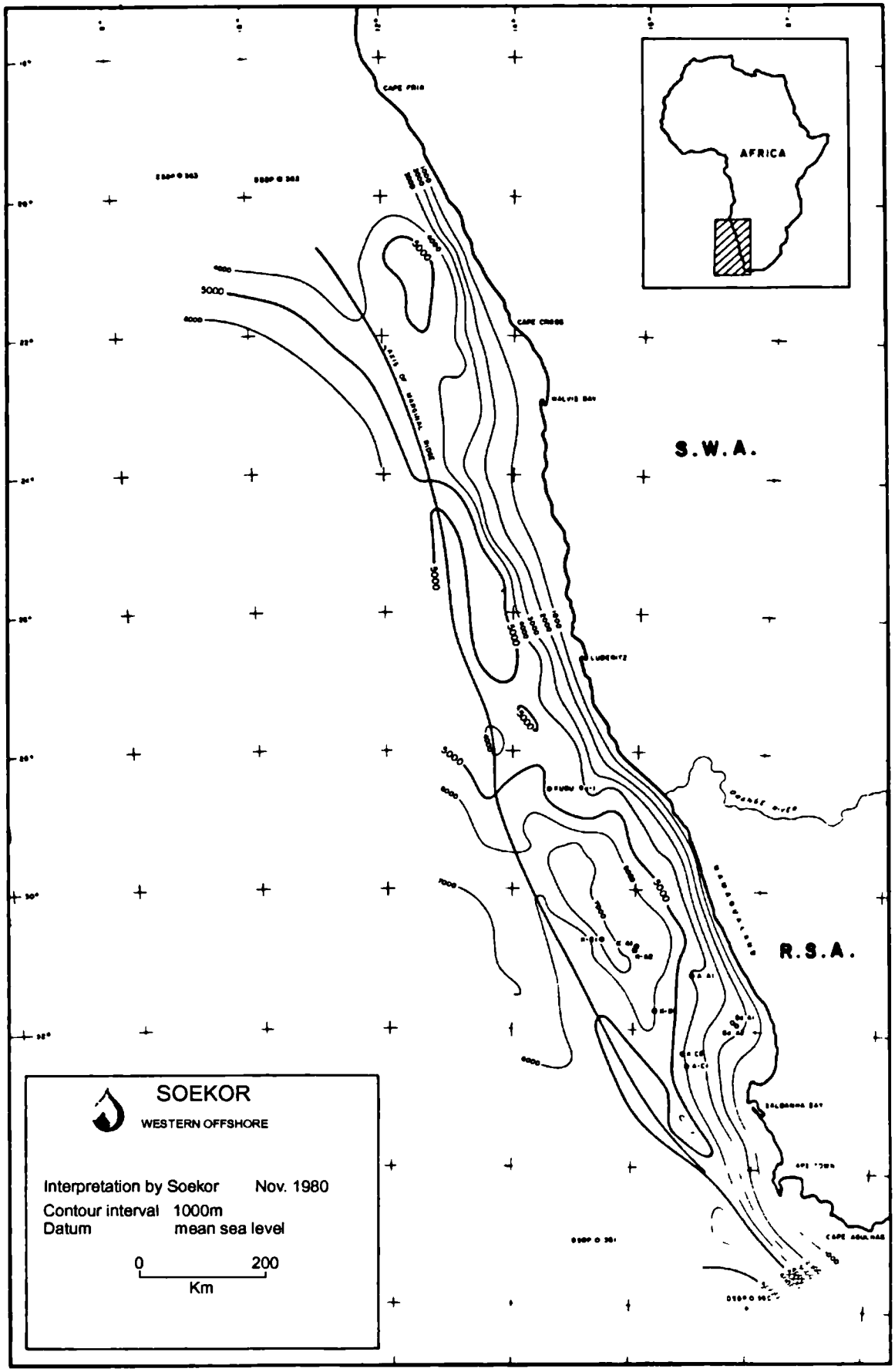


Figure 4.8 "Horizon R" of Gerrard & Smith (1982); equivalent to the Light Green Marker (break-up unconformity)

length by segment boundary zones. Although a thick sedimentary wedge is present in the Walvis Basin, the faulted western boundary is not seen.

More localised features include:

- The here-named "Namib Rift" is a large, early Karoo rift beneath the Walvis Basin. It extends from the Cape Cross Segment Boundary Zone to the Walvis Ridge. It generally thins to the east although the eastern margin is fault-bounded in part. Its western margin is too deep to be identified.

- Thrust-ramp graben (Light *et al.* 1993) are reactivated Pan-African low angle thrust-ramps east of the Hinge Line.

- The Kudu High is located in the south of the Namibian passive margin and lies west of a major reactivated thrust fault.

- The Hyena Back-basin is a small NNW-SSE-oriented half-graben on the Namibian Platform in the Cape Cross Segment Boundary Zone.

- The Swakop Basin is a small ENE-WSW-oriented Karoo basin in the Cape Cross Segment Boundary Zone. It is the preserved remnants of the larger Namib Rift rather than a syn-sedimentary basin

- Segment boundary zones. These subdivide the continental margin into a series of segments of varying length and are discussed in depth in *Chapter 6.*

- The here-named "Skeleton Rift" is a mid-Aptian NNW-SSE-oriented graben system superimposed on the larger "Atlantic" rift system. The Skeleton Rift splays into two major arms in the south.

Drift features.

- Hinge Zone. This zone 25-50 km across (Fig. 4.6) flanks the west of the largely undisturbed Namibian Platform. The Transitional Phase and lower Drift Phase sequences dip west from the platform across the Hinge Zone, before levelling out in the Lüderitz and Walvis Basins. There is some onlap of post-rift reflections onto this Hinge Zone. It is a warped zone developed in the early thermal cooling stage between the stable platform and subsiding basins. Its location generally but not always conforms to the Hinge Line.

4.4 Geophysical interpretation

Previous studies of the Namibian passive margin have identified some of the seismic markers. The earliest work (Emery *et al.* 1975, Austin and Upuchi 1982) named the most significant markers 'Atlantis' or 'AII' and Davie' or 'D'. Other, later work used letters for significant horizons (Gerrard and Smith 1982, Light *et al.* 1992,1993 and Maslanyj *et al.* 1992) or a combination of letters and numbers (Muntingh and Brown 1993). This thesis addresses seismic markers as colours to avoid confusion with earlier work and provide ready identification of illustrations with the text. The seismic character of each interpreted horizon is described below and examples are shown in Figure 4.9. The basis for the age of seismic markers below the base of Kudu 9A-3 are discussed in the text of this chapter.

Puce Marker. This lowest pickable marker is poorly defined and is best seen in the Walvis Basin and Cape Cross Segment Boundary Zone. It is the lowest identifiable reflection of a semi-continuous, low frequency and amplitude package. This Permian marker is interpreted as representing the base of the Karoo megasequence.

Red Marker. This marker is identified in the Cape Cross area only. The tight seismic grid in Block 2213A allows it to be interpreted here and in adjacent areas. It is a low to high amplitude, positive reflector that separates a poorly reflective sequence above, from a more reflective sequence below. In some areas, it truncates underlying reflections at moderate to high angle. This distinctive Mid-Triassic unconformity separates the Karoo Rift Megasequence A from the Karoo Post-Rift Megasequence B.

Brown Marker. This marker is also poorly defined but has been mapped along most of the Namibian passive margin. It exhibits both onlap and truncation just west of the Hinge Line. It is usually a positive trough, but due to the variable acoustic impedance contrast in this dipping zone it can be of variable polarity. The marker is the base of Sequence C_1 and represents the ?Oxfordian/Kimmeridgian onset of the "Atlantic" Rift Phase I in the Lüderitz Basin. It is absent in the Walvis Basin except in the extreme south.

Orange Marker. This marker also displays both onlap and truncation, especially where dips increase eastward as it climbs towards the Hinge Line. Here also, polarity may vary but

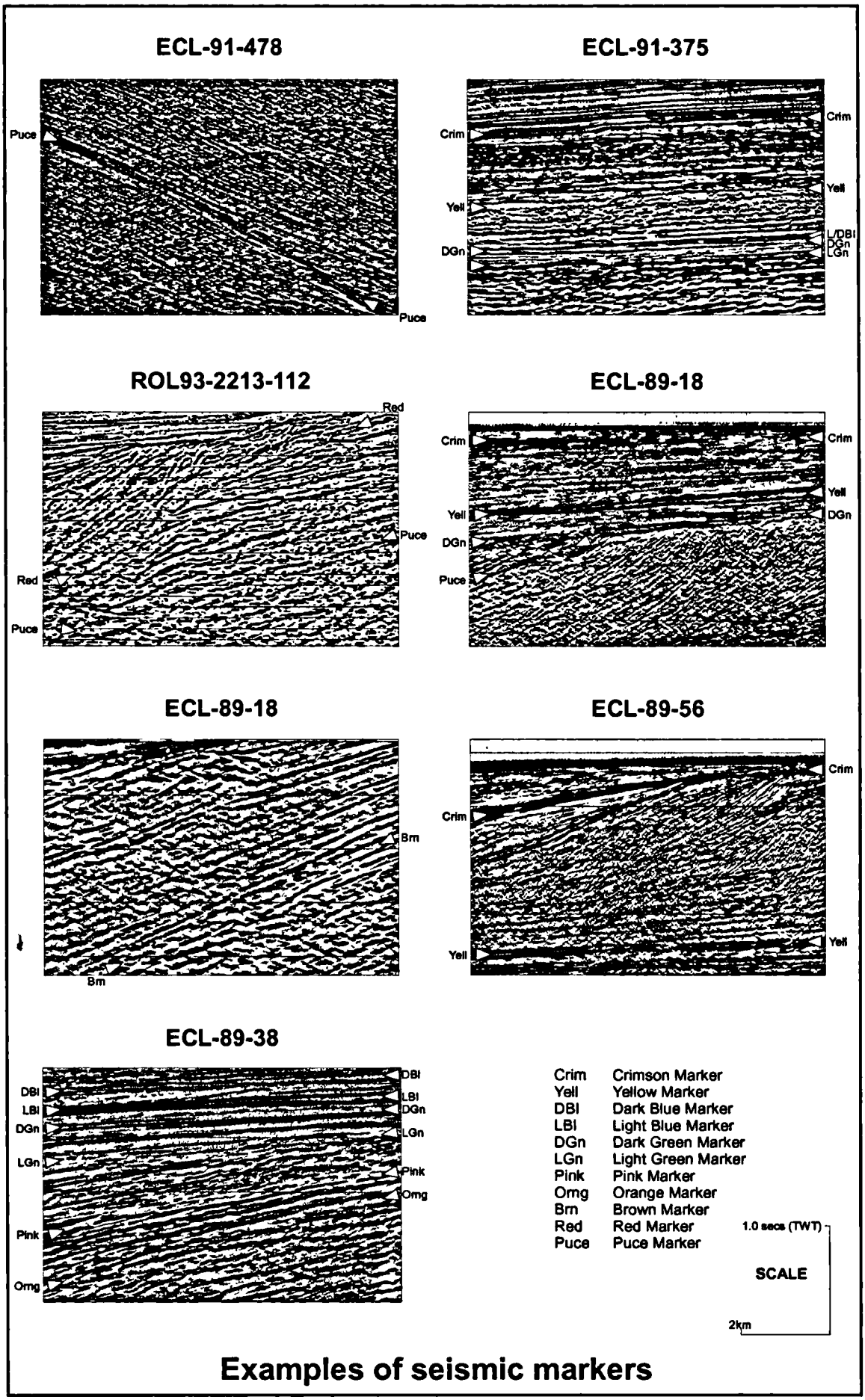


Figure 4.9 Examples of seismic markers

again it is usually a positive event. Further to the west in the Lüderitz Basin, the reflector is more often disconformable, with a strong, generally continuous black peak beneath a weaker white trough. This mid-Valanginian horizon is the base of the Sequence C_2 ("Atlantic" Rift Phase II) and marks the onset of rifting in the Walvis Basin.

Pink Marker. This positive reflector separates generally conformable seismic packages although locally, especially towards the Hinge Line, onlap and truncation are evident. In the Walvis Basin it defines the top of a strongly reflective package interpreted to be the lateral equivalent of the Etendeka flood basalts. In the Lüderitz Basin the reflection is weaker but still separates similar packages, although with less contrast in reflectivity. It marks the base of Sequence C_3 ("Atlantic" Rift Phase III) and is Early Hauterivian in age.

Light Green Marker. Like the preceding horizons, this also displays onlap and truncation. To the west it is a well-defined white trough with an underlying black peak. There is a marked change in seismic character above and below this horizon. Below, reflections are lower in frequency and amplitude and are generally discontinuous in the east, but more continuous in the west. Above, reflections are higher frequency and continuous particularly in the west. Unlike preceding horizons, the Light Green Marker is not confined to areas west of the Hinge Line. This is particularly so in the Lüderitz Basin. The marker truncates other reflectors though it is itself often truncated by the Dark Green Marker. It extends west beyond the seismic data coverage and does not reach the boundary defining thickened and normal oceanic crust. The abrupt difference in seismic character above this marker is interpreted as the initial marine transgression of a restricted Atlantic Ocean occurring at final break-up (Falvey 1974). It is regarded as the break-up unconformity south of the Walvis Ridge. There is indirect evidence that it may be younger in the Walvis Basin (see *Chapter 6*). Its age ranges from Late Hauterivian in the Orange Basin to early Barremian to late Barremian in the Lüderitz and Walvis Basins respectively.

Dark Green Marker. This generally strong white trough is continuous except where it approaches the Hinge Line. It truncates underlying markers eastwards to become the top basement reflector on the Namibian Platform. It is the deepest calibrated horizon in Kudu 9A- 3. There is no significant log break but it lies close to a change in sedimentary environment that may be linked to a major transgressive event. This heralds a change from

outer shelf to deeper, poorly oxygenated waters (McMillan 1990). The Dark Green Marker is Early Aptian in age and marks the end of the Transitional Phase.

Light Blue Marker. A strong, high amplitude, positive event characterises this horizon on shelf areas, but it becomes weaker to the west and appears to downlap onto the Dark Green Marker. In Kudu 9A-3 there is a significant downhole sonic velocity increase at this level. This marker is also Early Aptian in age and lies in the lower part of the Drift Phase megasequence.

Dark Blue Marker. This moderate amplitude, continuous reflector is a negative seismic event in basinal areas but updip from a shelf break it becomes a positive event. There is a mid-Aptian downhole decrease in sonic velocity in Kudu 9A-3. Here, restricted marine shales pass up into more open marine, abyssal/base of slope shales (McMillan 1990). Earlier studies have identified this as a significant seismic reflector and in the past it has been called the 'Atlantis II' or 'AII' by Emery *et al.* (1975). This has been tied to DSDP borehole 361 where anoxic sediments rich in terrestrial organic matter pass up into more oxygenated marine shales (Dingle *et al.* 1983). In the north of the Walvis Basin it becomes indistinguishable from the Light Blue Marker. This horizon is the break-up unconformity north of the Walvis Ridge (Light *et al.*, 1993) but is low in the Drift Phase succession on the Namibian passive margin. Late rifting just south of the Walvis Ridge that produced the Skeleton Rift became significant at this time. The Dark Blue Marker also represents the change from a restricted marine to open ocean setting. Continental break-up north of the Walvis Ridge may have radically altered marine circulation patterns and led to flushing of the restricted marine basin south of the Ridge. This marker probably represents a major transgression breaching the Rio Grande Rise - Walvis Ridge.

Yellow Marker. On platform areas this is sometimes a very strong, continuous positive trough at the top of a prograding sequence. In proximal slope areas it is often broken up by slumping and channelling and further west into the basin, it becomes a much weaker, poorly defined positive event. It is poorly defined in the Walvis Basin. This horizon correlates with the Turonian condensed section in the Kudu wells and is recognised as a major flooding event (Muntingh and Brown 1993) in the south of the area. This marker defines the top of Sequence E_1.

Crimson Marker. A strong, high amplitude positive trough at the base of the Palaeocene in Kudu 9a-3 marks a hiatus at the top of a thick prograding sequence. This horizon is disrupted in proximal slope areas by slumping and channelling on and north of the Lüderitz Arch. In basinal areas where a full section is probably present, it is not clear whether this marker is late Cretaceous or early Palaeocene in age. It defines the top of Sequence E_2.

4.5 Stratigraphic sequences

The post-Pan-African sedimentary pile can be subdivided into megasequences or 'tectono-stratigraphic units' related to regional tectonic events - the Karoo Rift and Post-Rift phases, the "Atlantic" Rift Phase and subsequent Transitional and Drift Phases. Their offshore - onshore relationship is shown in Fig. 4.10 and their relationship to seismic markers in Table 4.3.

The terms 'sequence or 'megasequence' do not refer to sequences *sensu* Vail *et al.* (1977) or Galloway (1989). The seismic packages of interpretations in this thesis are bound by unconformities or correlative disconformities (Van Wagoner *et al.* 1988) but 'sequence or 'megasequence' is applied informally, and often on a much larger scale where the unconformities bound tectono-stratigraphic seismic units.

4.5.1 Pan-African basement

The seismic character of the Pan-African basement is most evident in the Cape Cross area and on the Lüderitz Arch. The basement structure in the Cape Cross area is reviewed in *Chapters 5* and *6.* On the Lüderitz Arch, the Pan-African megasequence is readily identifiable as a thick but seismically opaque package. The top is planed by the break-up and Lower Aptian unconformities and draped by Transitional and Drift sediments. Its base is marked by an abrupt increase in reflectivity below which reflections are semi-continuous and moderate in frequency and amplitude (Fig. 4.11). This contact between basement suites of contrasting reflectivity is believed to be a shear zone separating the Pan-African (above) and Namaqua-Natal (below) basement domains. It has been mapped on the Namibian Platform in the north of the Lüderitz Arch (Fig. 4.21). In the Walvis Basin where the Kaoko

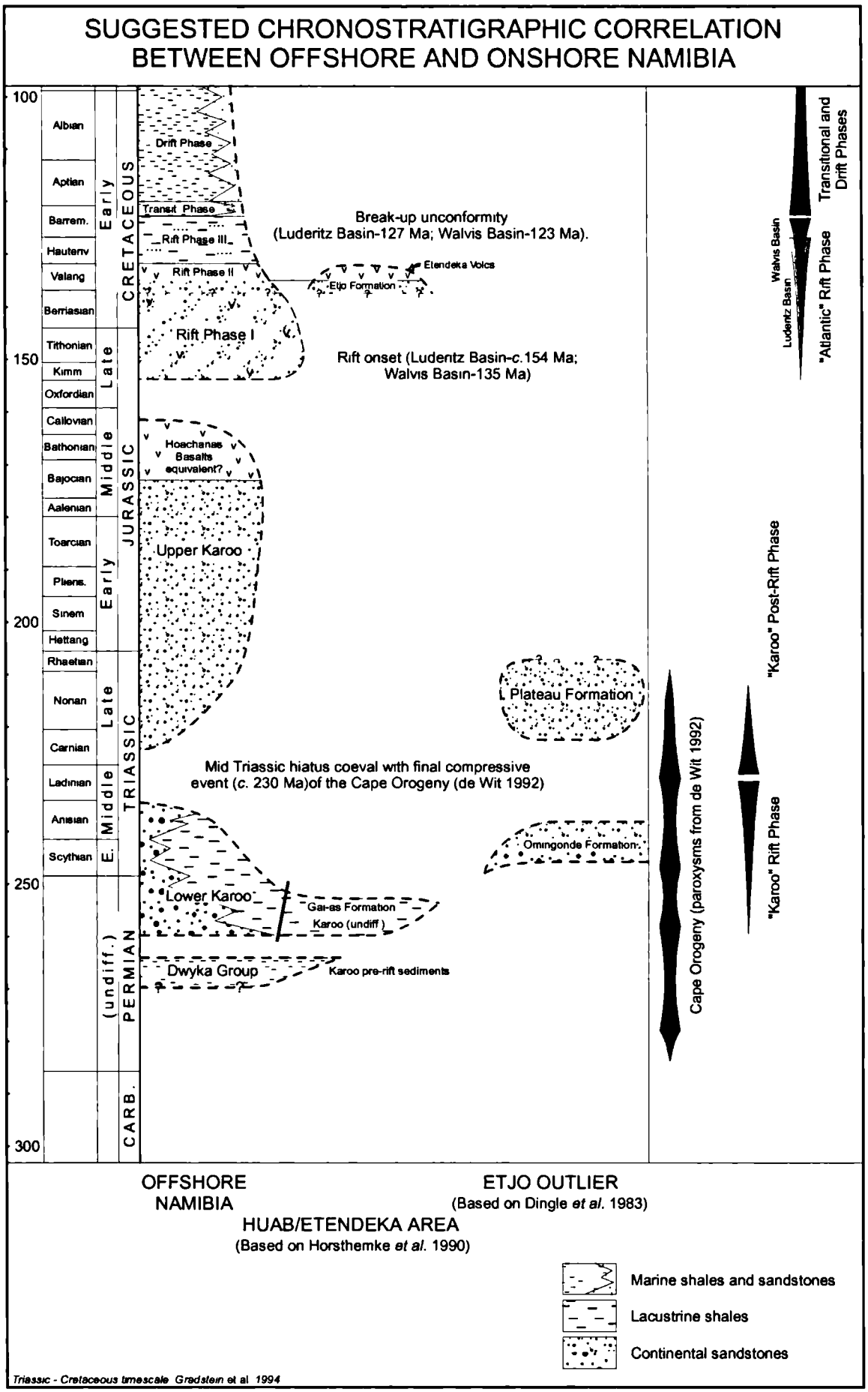


Figure 4.10 Chronostratigraphic correlation between offshore and onshore Namibia

Table 4.3 Stratigraphy of the Walvis and Lüderitz Basins

Sequence	Age	
	Walvis Basin	**Lüderitz Basin**
Drift Phase- Megasequence E		
Crimson Marker - Sea Floor	Palaeocene - Recent	
Yellow - Crimson Marker	Turonian - Maastrichtian	
Dark Green - Yellow Marker	Early Aptian - Cenomanian	
Transitional Phase- Megasequence D		
Light Green - Dark Green Marker	Early Aptian - Late Barremian	Early Aptian - Early Barremian
"Atlantic" Rift Phase - Megasequence C		
Rift Phase III: Pink - Light Green Marker	Late Barremian - Early Hauterivian	Early Barremian - Early Hauterivian
Rift Phase II: Orange - Pink Marker	Mid to latest Valanginian	
Rift Phase I: Brown - Orange Marker	absent	?Oxf./Kimm. - Mid Val.
Karoo Post-Rift Phase- Megasequence B		
Red-Brown Marker	Late Triassic - Middle Jurassic	
Karoo Rift Phase- Megasequence A		
Puce - Red Marker	?Permian - Early Triassic	
Pan-African basement		
Purple-Puce Marker	Late Proterozoic - Early Cambrian	

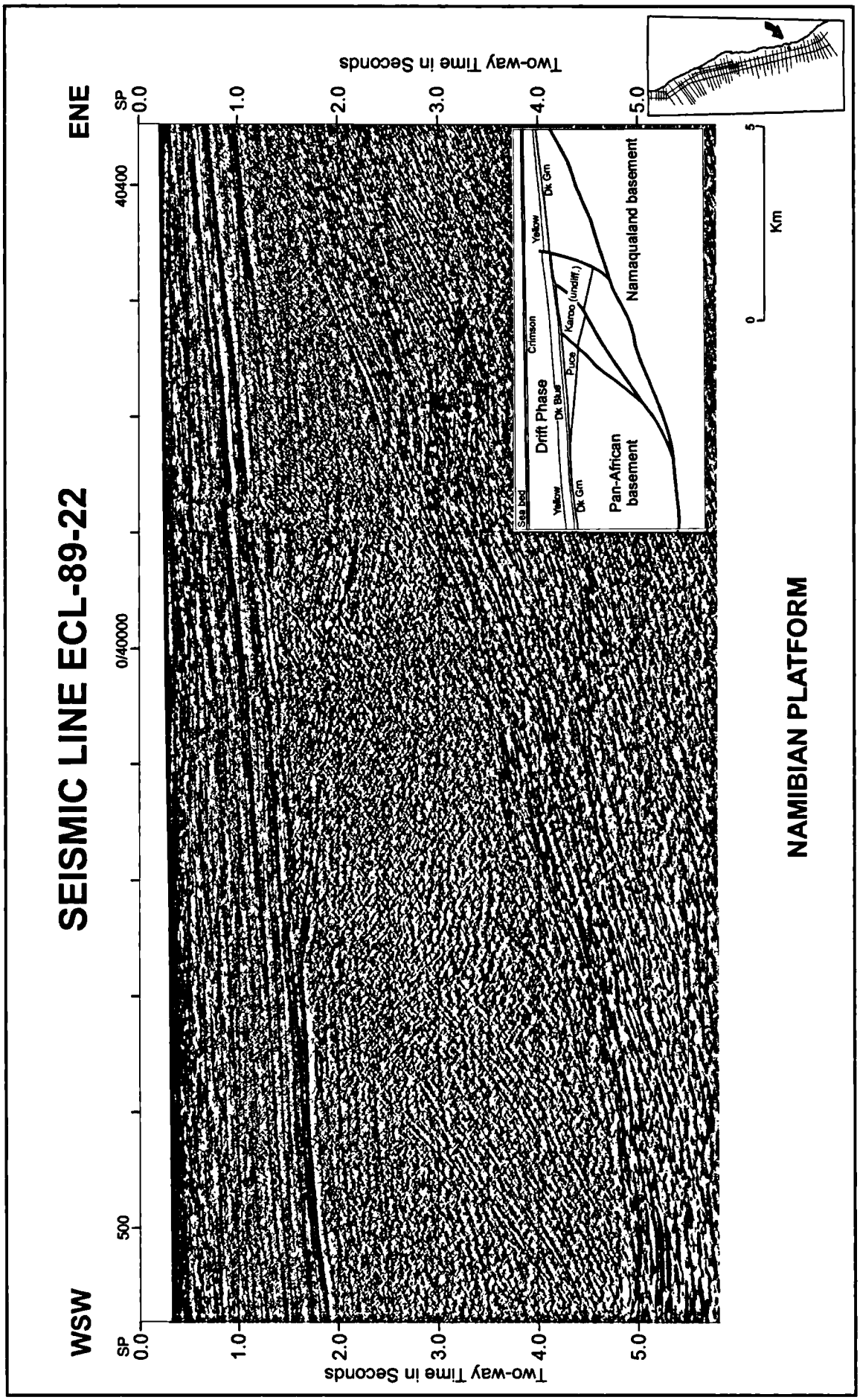


Figure 4.11 Seismic section of the Pan-African and Namaqualand basement

arm of the Pan-African Fold Belt comprises the basement, there are few identifiable basal reflections. Here, like onshore, much of the Kaoko basement terrane may have been removed by erosion.

4.5.2 Megasequences A and B (lower and upper Karoo)

These megasequences are best identified in the Cape Cross Segment Boundary Zone and adjacent areas. The base of Megasequence A, the Puce Marker (Fig. 4.12), is an angular unconformity truncating Pan-African basement. Where the basement is characterless, the deepest reflection of Megasequence A is interpreted as the base. This occurs over much of the mapped area and the Puce Marker is perhaps better termed the 'near base lower Karoo'.

Megasequence A is separated from Megasequence B by a marked angular unconformity (Fig. 4.13, shotpoints 600-4600). Megasequence B onlaps the flanks of uplifted areas of Megasequence A and is relatively undisturbed by faulting. This relationship, and their relative position between the crystalline basement and "Atlantic" rift sequences, suggest that Megasequences A and B correlate with the onshore lower and upper Karoo respectively. Offshore, a phase of inversion uplifted and eroded Megasequence A. This is suggested to correspond onshore with the Mid-Triassic hiatus (see *Chapter 3*). Megasequence A is regarded as a thick rift basin equivalent to the lower Karoo lacustrine and fluvial cratonic sediments in the Huab area (Horsthemke *et al.* 1990) and the Etjo Outlier. The upper Karoo Plateau Formation sandstones are a cratonic lateral equivalent of the post-rift Megasequence B.

Megasequence A comprises moderately continuous, moderately high frequency and amplitude reflections beneath Transitional and Drift Phase sediments on the Namibian Platform (Figs 4.14, 4.15). It is faulted and folded so that the composite unconformity is sometimes quite angular (Fig. 4.16). Another angular unconformity, the Red Marker, truncates Megasequence A on the southeastern eastern flank of the Walvis Basin. Here it is overlain by Megasequence B. Their relationship is discussed in *Chapters 5* and *6*.

Uplift and erosion associated with the unconformity between Megasequences A and B led to semi-isolated basins and bald structural highs in the Cape Cross - Walvis Bay area

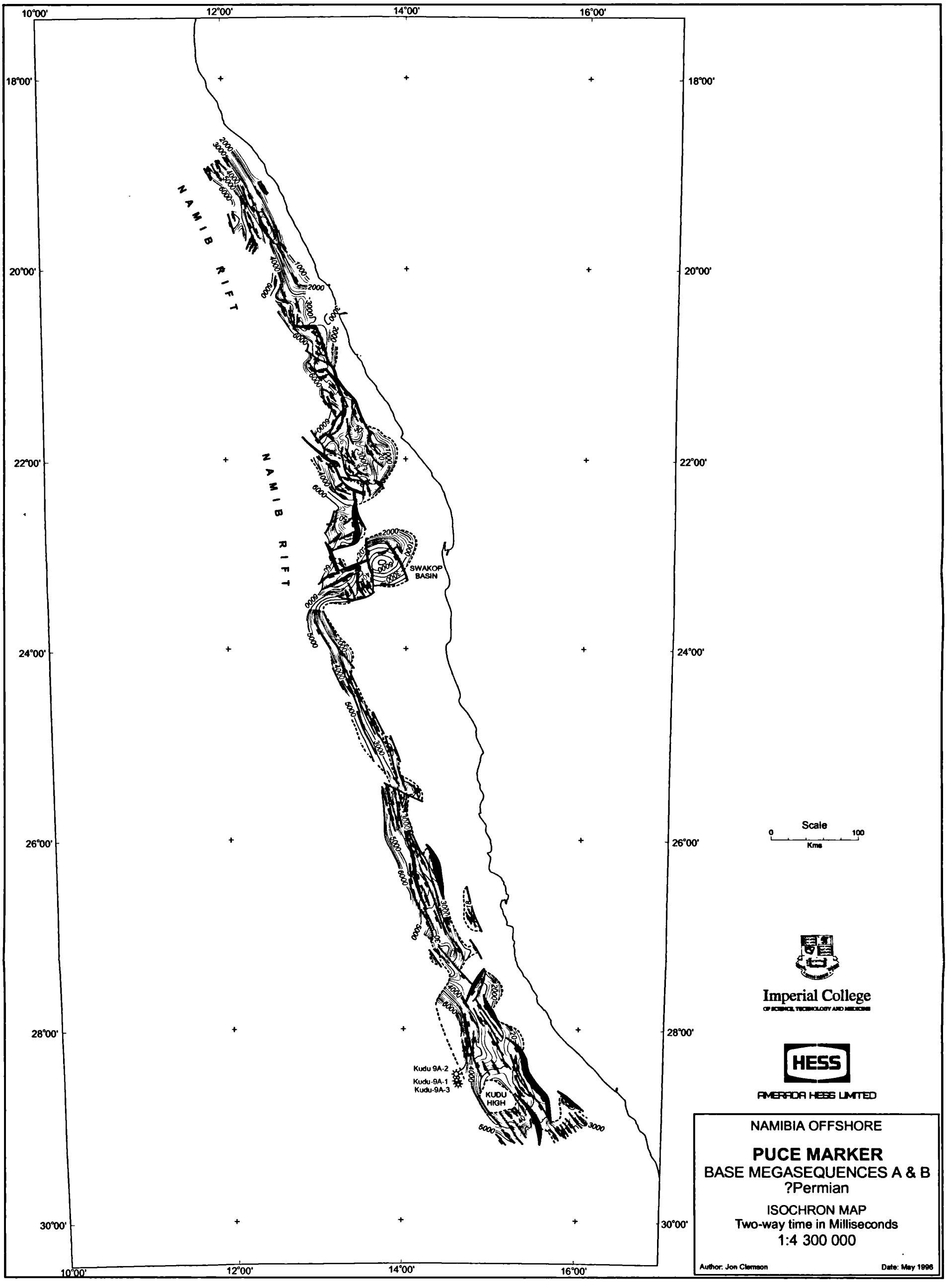


Figure 4.12 Offshore Namibia - isochron map of the base of Megasequences A & B (Puce Marker)

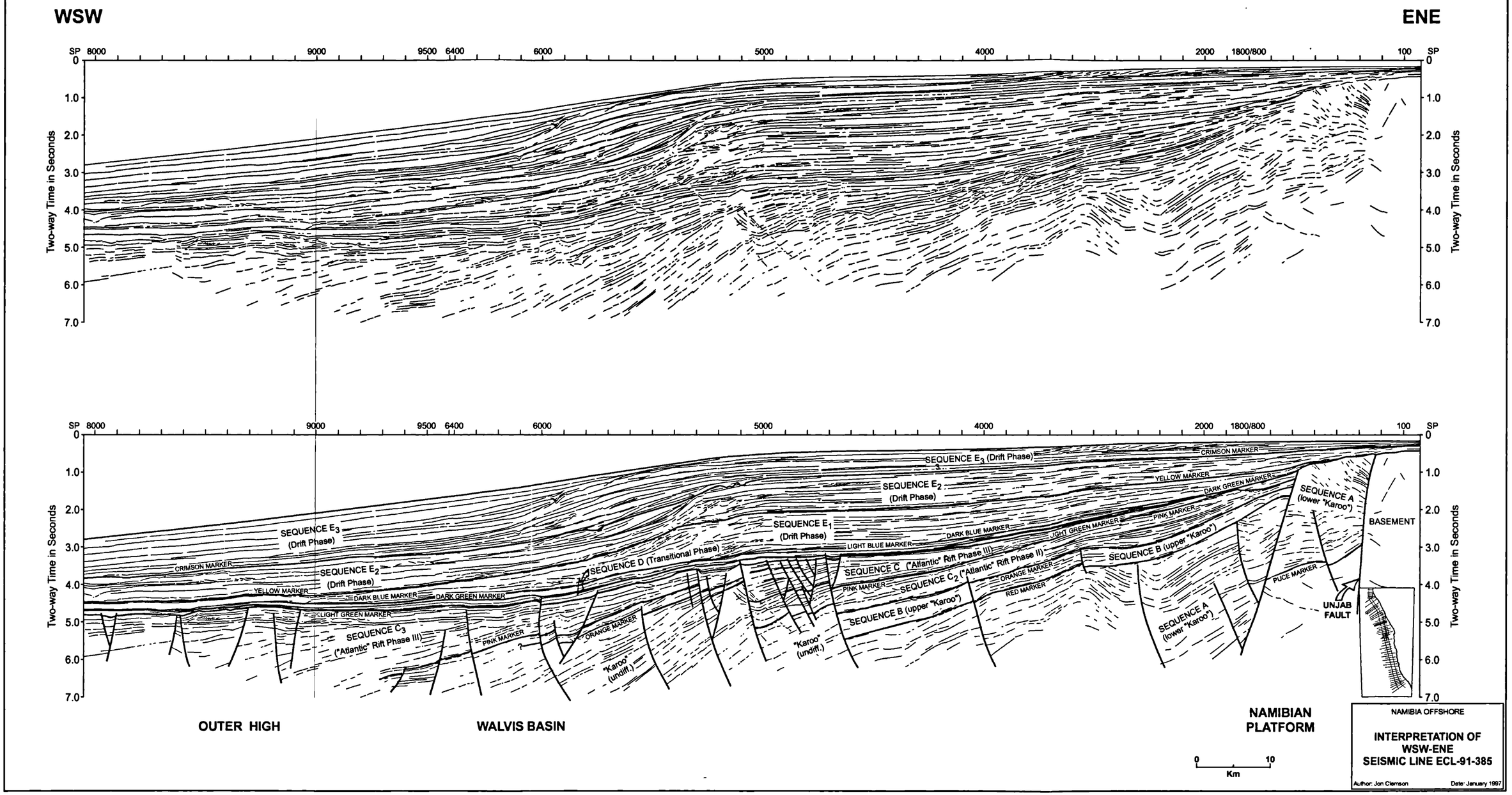


Figure 4.13 Interpreted line drawing of WSW-ENE oriented seismic line ECL-91-385

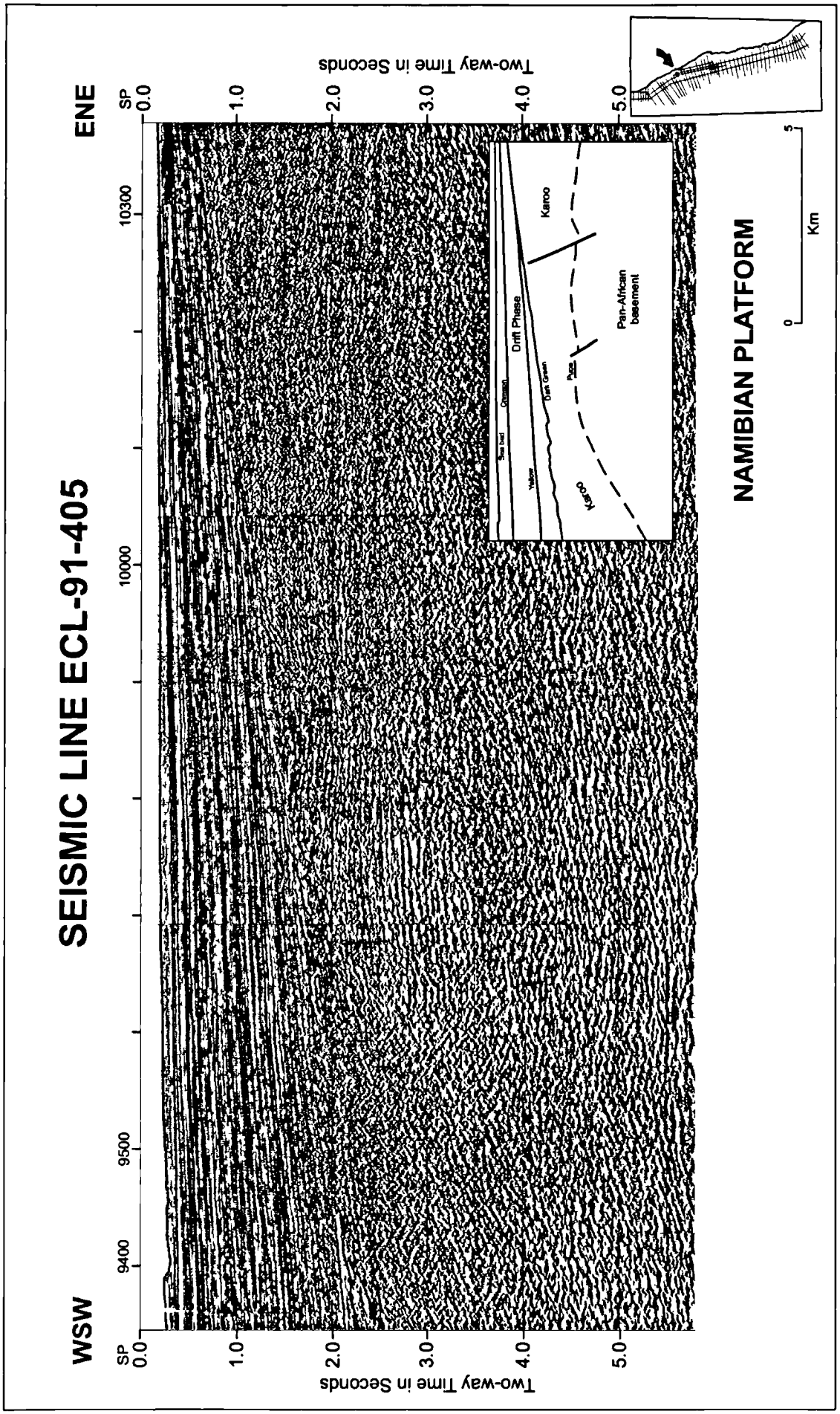


Figure 4.14 Seismic section of the Karoo in the Walvis Basin

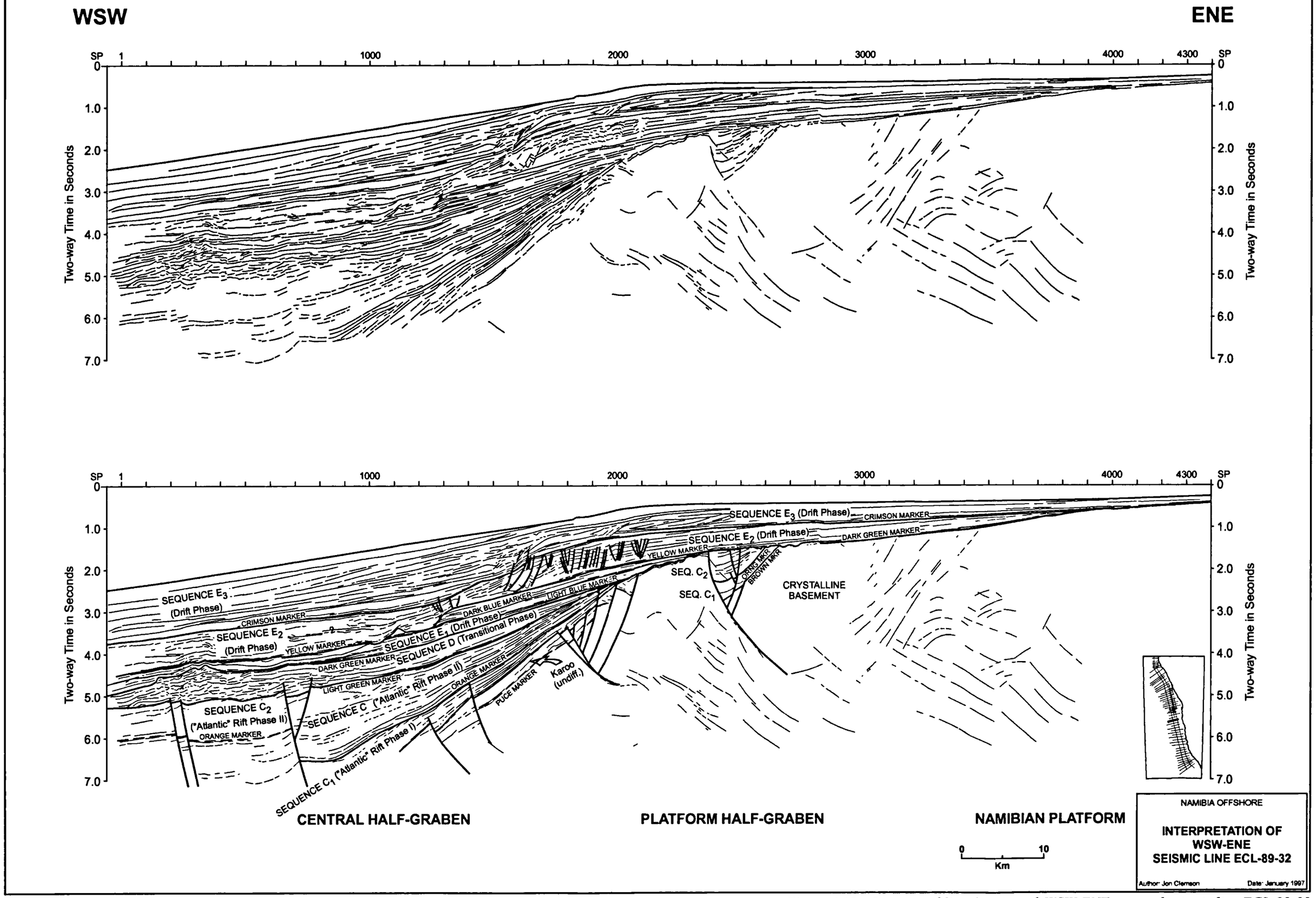


Figure 4.18 Interpreted line drawing of WSW-ENE oriented seismic line ECL-89-32

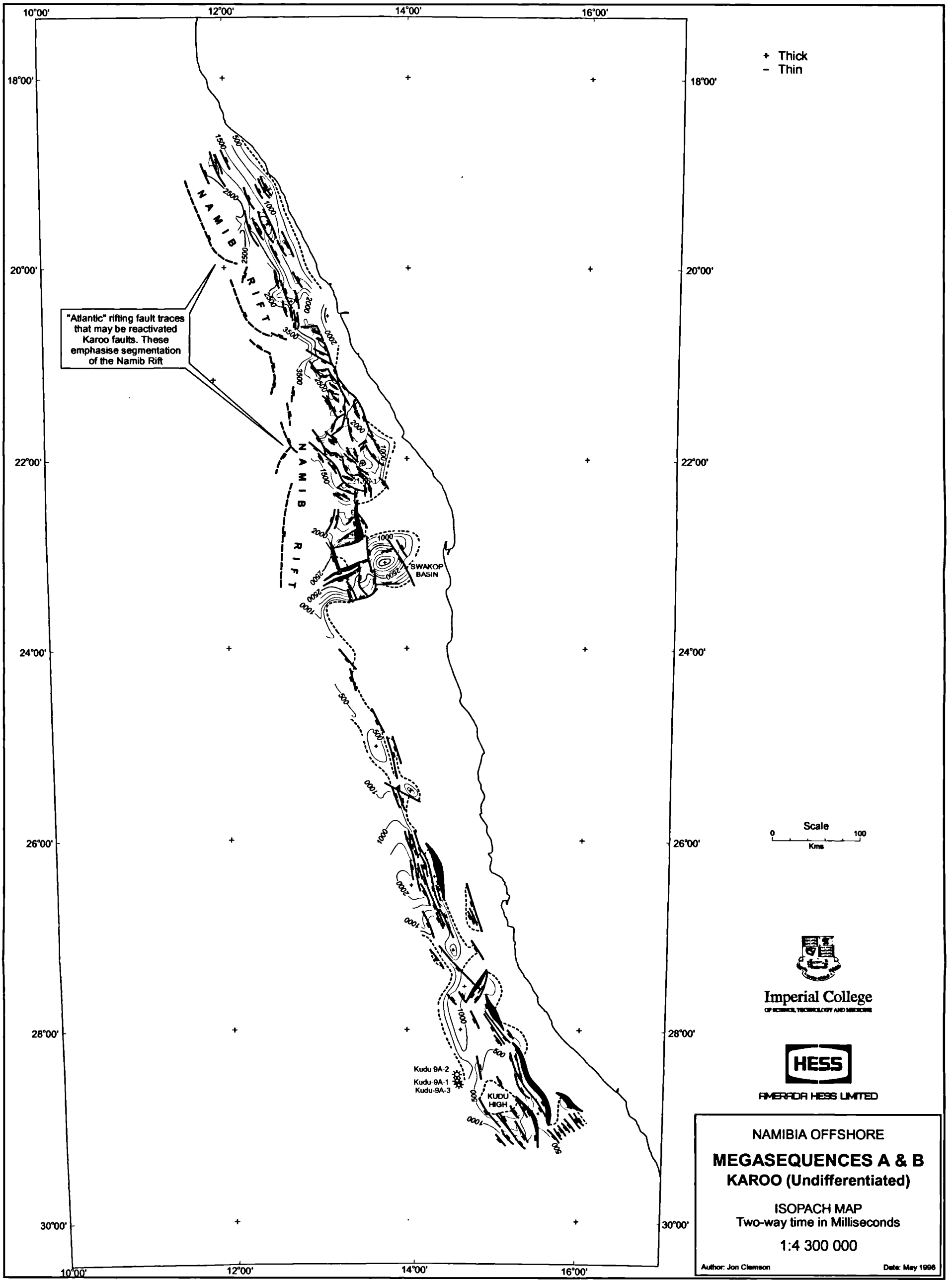


Figure 4.19 Offshore Namibia - isopach map of Megasequences A & B (undifferentiated Karoo)

Figure 4.20 Seismic section of the low-angle fault beneath the Kudu High

of continental rifting is poorly constrained and can only be inferred from regional events. The structural elements of "Atlantic" rifting are shown in Figure 4.21.

4.5.3.1 Sequence C_1 - (Rift Phase I)

This sequence consists of a westerly-diverging package of low to moderate amplitude, low frequency, fairly continuous reflections. Reflections are stronger at the top of the sequence; this may be syn-rift volcanics.

Sequence C_1 is only mapped along a narrow strip 40-60 km west of the Hinge Line due to increasingly steep dips deep in the "Atlantic" syn-rift sequence. It pinches out in the east, usually by erosion beneath the break-up and Lower Aptian unconformities. It is occasionally fault-bounded in the east, most notably in the Bogenfels area (Fig. 4.22), although these faults are small. The areal extent of Sequence C_1 is more complex in the Cape Cross Segment Boundary Zone where a salient extends 80 km east along the axis of the Swakop Basin. In the west in this area, it thins and is confined to a narrow half-graben (Fig. 4.23) before pinching out just north of the Cape Cross Segment Boundary Zone. In the south of the Lüderitz Basin (Fig. 4.22) it is up to 2.0 seconds (TWT) thick (4-5 km).

This sequence is also found in small fault-bounded basins on the Lüderitz Arch (Figs 4.18, 4.24). A strong positive event separates a gently divergent package from a more divergent package above. The strong reflection could be the Orange Marker and if so, these basins were active in both Rift Phases I and II. Angular truncation beneath the Lower Aptian unconformity suggests that these half-grabens were originally broader and that erosion on the Arch has been significant.

Pan-African thrust ramps east of the Kudu High have been reactivated as low-angle normal faults during extension (Figs 4.20, 4.25). A thrust-ramp graben (Light *et al.* 1993) extends for almost 100 km along this fault (Fig. 4.26). In the hangingwall to the fault, a sequence of parallel reflections is interpreted to be preserved Karoo. The seismic character resembles that of the Karoo in the Cape Cross area. This relationship suggests that faulting post-dated the Karoo sequence. The deflection of isopachs around the west of the Kudu High (Fig. 4.22) suggests that the high existed during deposition of Sequence C_1. This low-angle

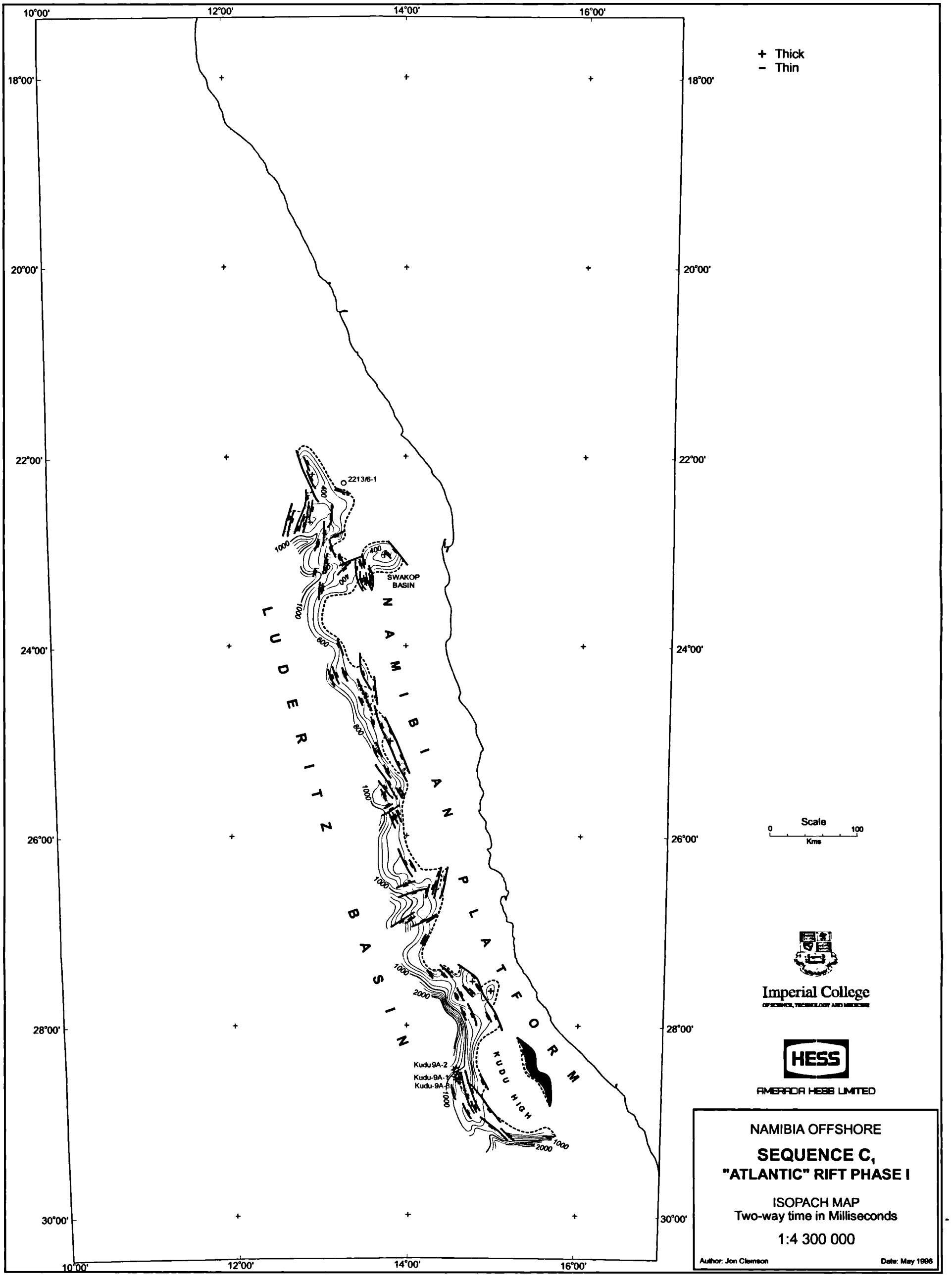


Figure 4.22 Offshore Namibia - isopach map of Sequence C_1 ("Atlantic" Rift Phase 1)

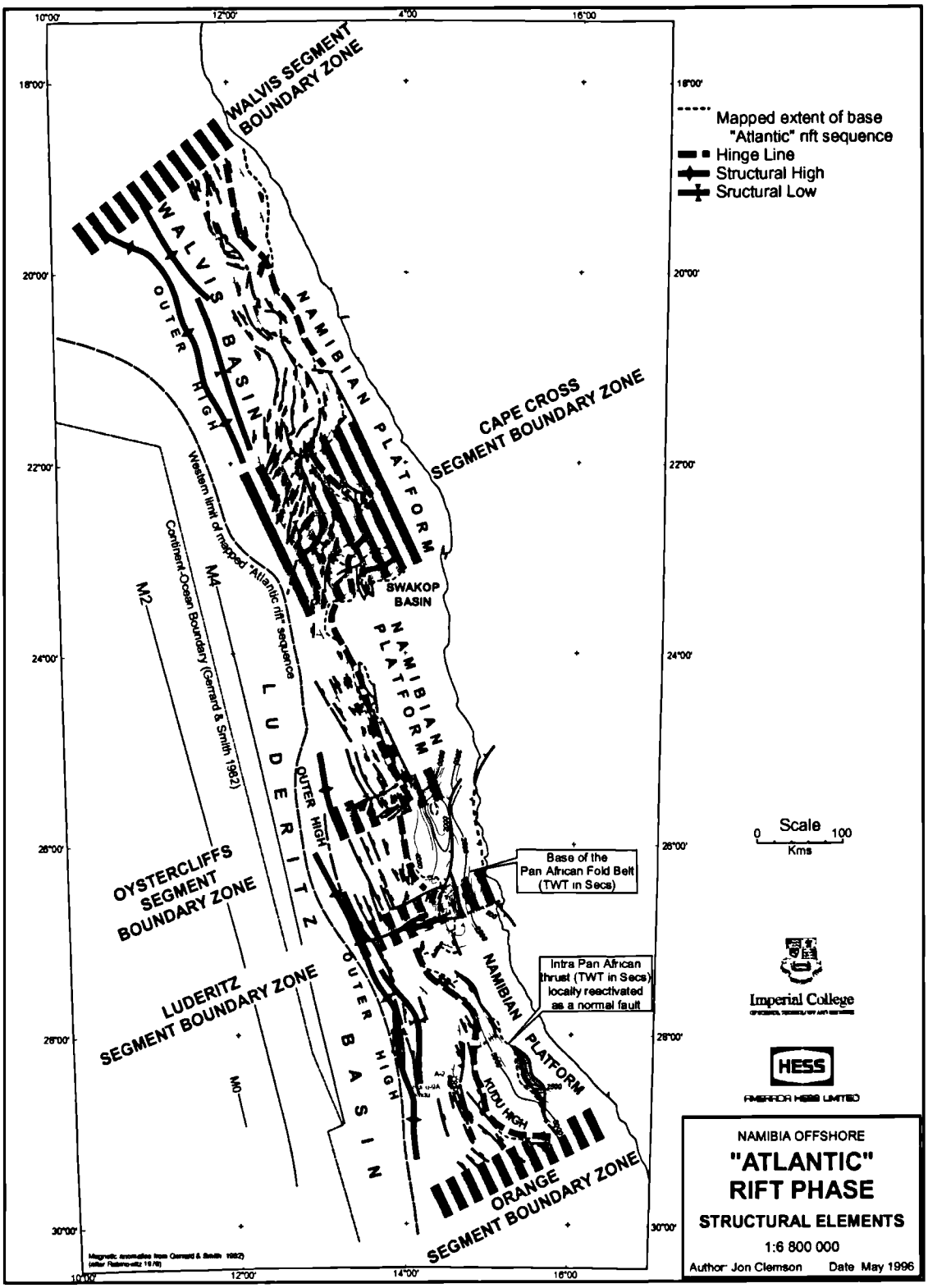


Figure 4.21 Offshore Namibia - structural elements of the "Atlantic"Rift Phase

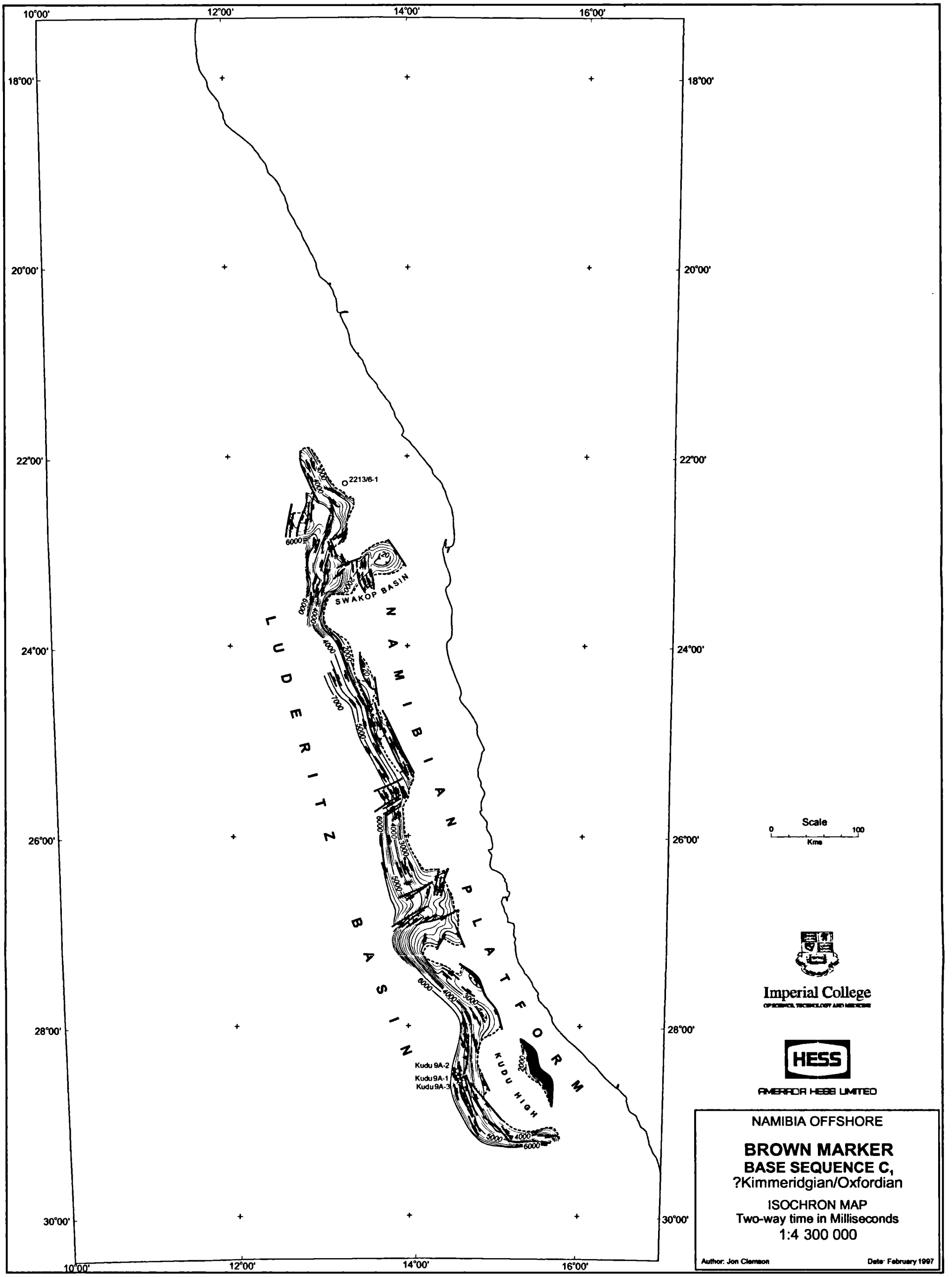


Figure 4.26 Offshore Namibia - isochron map of the base of Sequence C_1 (Brown Marker)

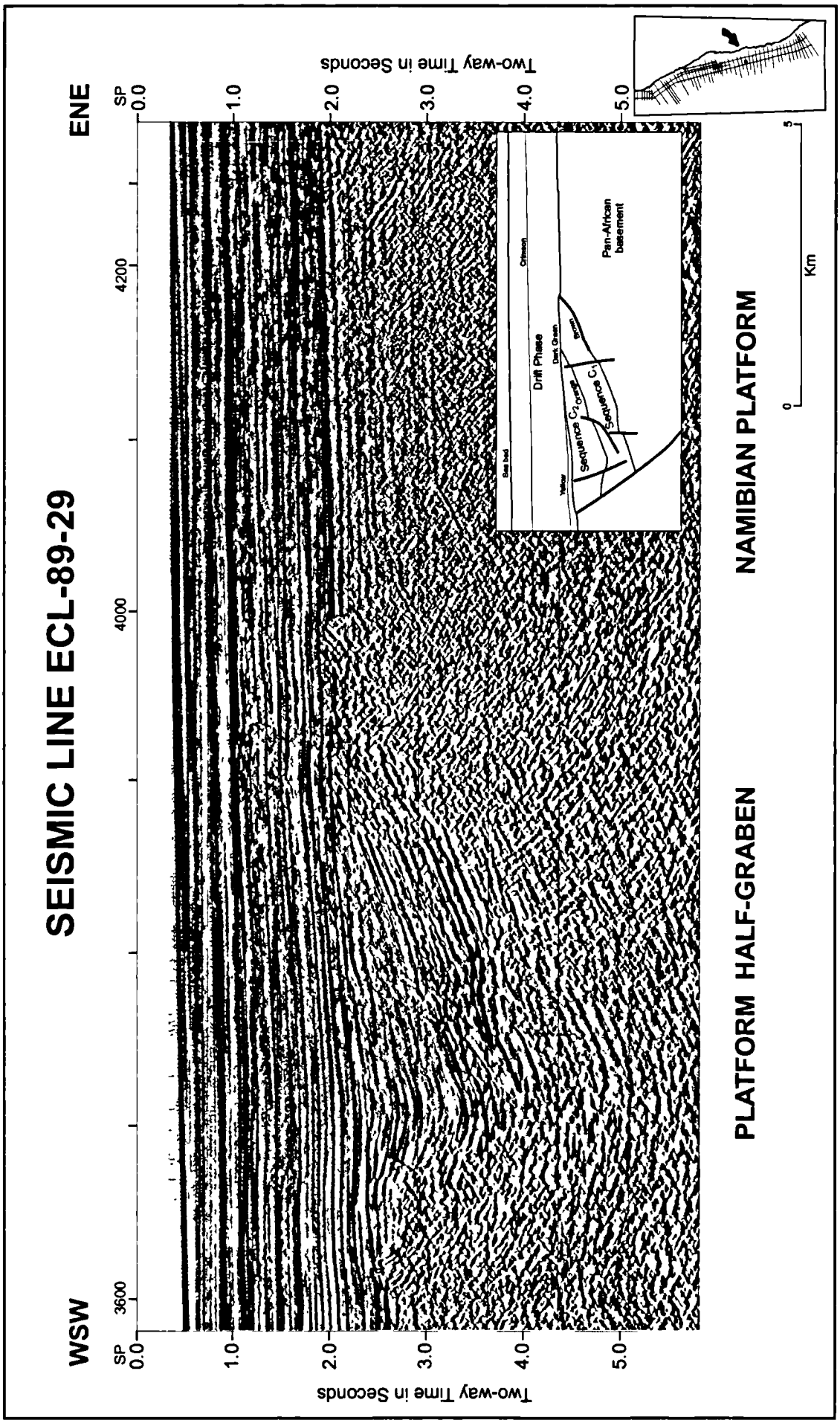


Figure 4.24 Seismic section of a half-graben on the Namibian Platform

faulting is therefore thought to have occurred in Rift Phase I. Any Karoo sediments were removed from the footwall by subsequent erosion. The Rift Phase I fill in the hangingwall passes upwards and away from the fault from chaotic to more coherent reflections (Fig. 4.20). This may be a subaerial proximal-distal sedimentary fan system.

The complete removal of the Karoo from the footwall of this major low-angle fault ensures that only the minimum lateral translation of the hangingwall can be determined. This is up to 13 km, and in the same order of minimum displacements of low-angle faults in the West Orkney Basin (Enfield and Coward 1987). There, regional crustal extension reactivated Caledonian thrusts. The timespan between the end of Caledonian deformation (end-Silurian) and basin rifting (early Devonian) is much shorter than the end of Pan-African deformation (early Cambrian, see *Chapter 3*) and "Atlantic" rifting (Late Jurassic).

Light *et al.* (1993) estimate 1 km of uplift in the region of the Great Escarpment at this time. However, up to 1.8 seconds (TWT) of Karoo sediments are preserved in the thrust-ramp graben. If all of this was deposited before faulting, then approximately 3.6-4.5 km of sediments have been removed from the footwall. It is expected that uplift and erosion was greater adjacent to the rift system. Not all this erosion may have occurred during rifting. A significant proportion may have been removed during early post-rift times when the Namibian Platform was peneplaned. Rust and Summerfield (1990) estimate 1.6-3.2 km of erosion had occurred by the end of rifting, based on sediment volumes. These maximum values for syn- and post-rift erosion concur with estimates of 3-4 km of Cretaceous erosion determined by apatite fission track analysis (Brown 1992).

The close spatial and temporal relationship between this elongate fault-controlled basin and the Kudu High to the west suggest a common genesis. Low-angle faulting at this scale during the "Atlantic" Rift Phase is seen nowhere else on the Namibian passive margin. The Kudu High is also a prominent structure extending west into the rift basin. Its structural origin is discussed in *Chapter 6* as it is close to the Orange Segment Boundary Zone.

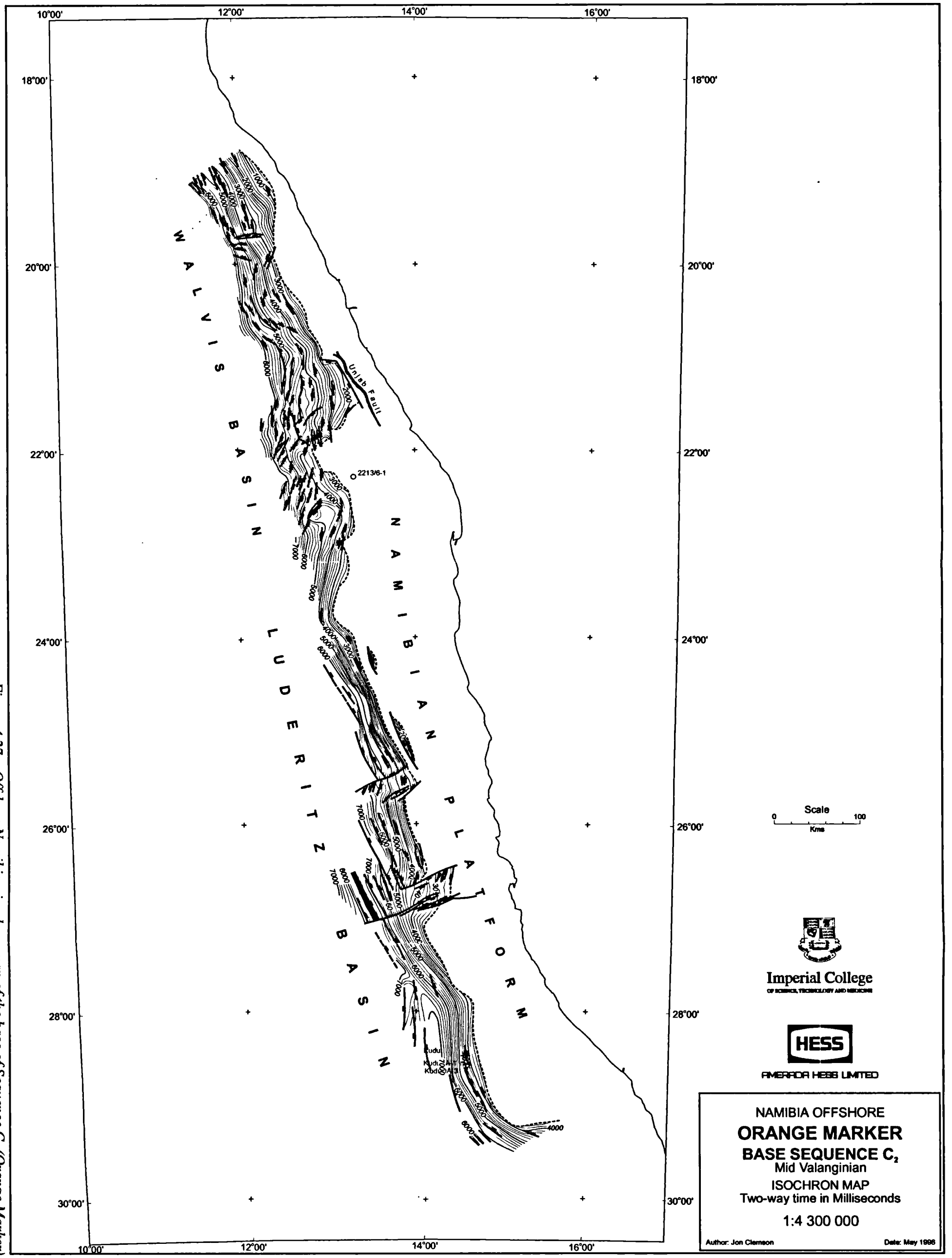


Figure 4.27 Offshore Namibia - isochron map of the base of Sequence C_2 (Orange Marker)

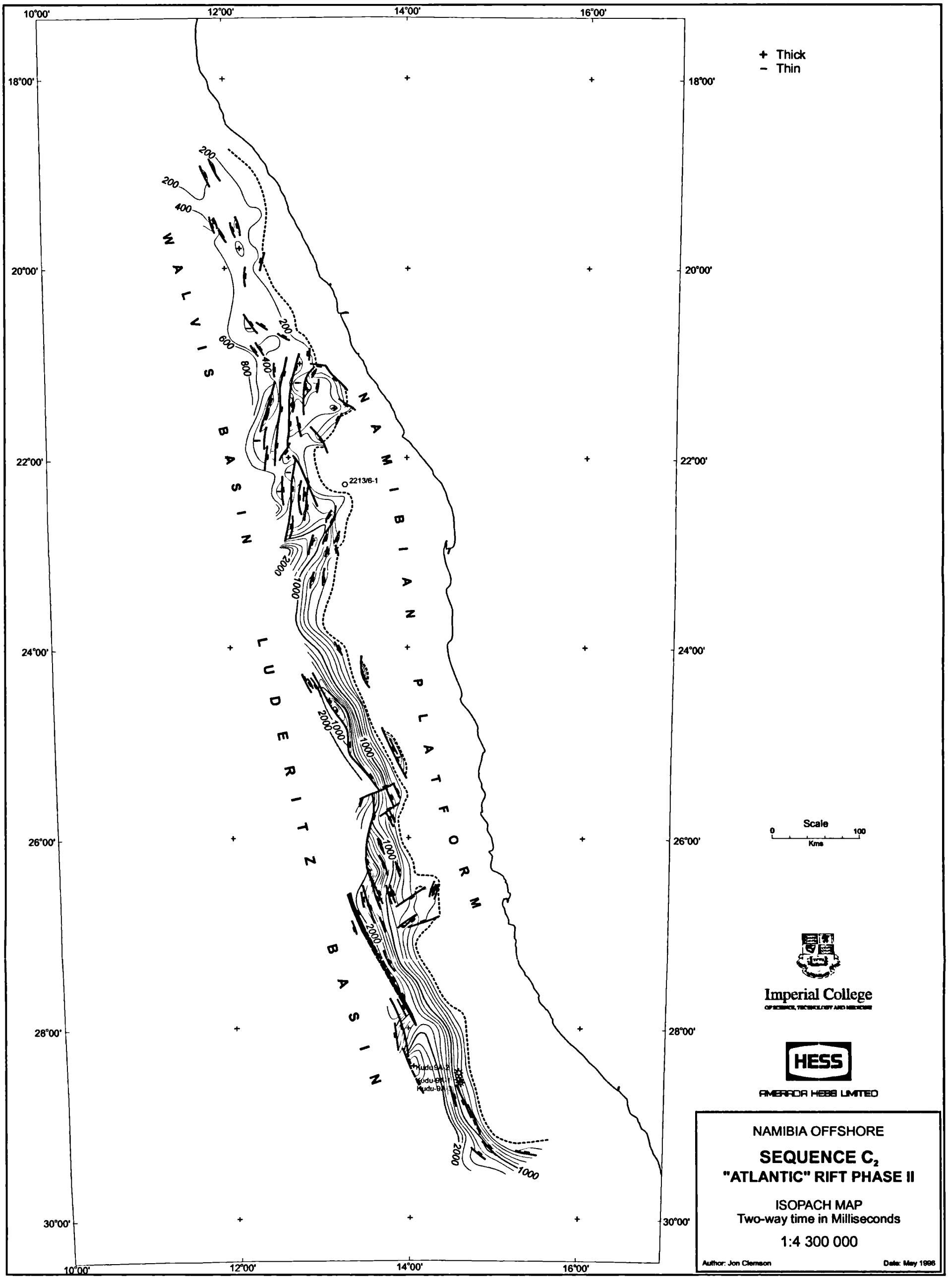


Figure 4.28 Offshore Namibia - isopach map of Sequence C_2 ("Atlantic" Rift Phase II)

4.5.3.2 Sequence C_2 - (Rift Phase II)

Sequence C_2 is well defined and most important in delineating the syn-rift structural configuration and its relationship to the segment boundary zones. It is a sequence of moderate to high amplitude, low to moderate frequency, often continuous reflections extending across much of the Central Half-Graben. In the Walvis Basin, any western bounding faults are not identified as this sequence passes off the base of the seismic sections.

Sequence C_2 converges east to the Hinge Line and pinches out by erosion beneath the break-up unconformity. Only a small section of the eastern margin is fault-bounded (Fig. 4.13, shotpoint 600). This occurs just north of the Cape Cross Segment Boundary Zone (Fig. 4.21). The fault is parallel to the Unjab Fault bounding the Karoo rift sequence, but lies up to 10 km west (Fig. 4.27).

Distinct breaks in the north-south continuity of the eastern margin to this sequence correspond to breaks in the Hinge Line. These, from south to north, occur at Lüderitz (26°45'), Oystercliffs (25°30'), Walvis Bay (23°00') and Cape Cross (21°45'). All these offsets of the pinch-out and Hinge Line are right-stepping (Fig. 4.21). Their significance is discussed in *Chapter 6*.

In the Central Half-Graben of the Lüderitz Basin and the southernmost Walvis Basin in the Cape Cross Segment Boundary Zone, this sequence is well developed (Fig. 4.28). It always exceeds 1.0 seconds (TWT) (*c*. 2 km) in basinal areas, often exceeds 2.0 seconds (TWT) (*c*. 4 km) and reaches 2.4 seconds (TWT) (*c*. 5 km). Conversely, in the Walvis Basin it barely reaches 1.0 seconds (TWT) (*c*. 2 km).

Reflections at the base of this sequence are usually conformable in the Lüderitz Basin, though as the wedge thins and climbs eastward, it may onlap onto the Orange Marker. Some lines display a truncational relationship at the base (Figs 4.18 and 4.29, shotpoints 800-1400) deep in the Central Half-Graben. This interval also thins west over the Outer High where it is fault-bounded in central parts of the Lüderitz Basin (Fig. 4.30, shotpoints 4300-4900). The top of this sequence, the Pink Marker, (Fig. 4.31) cannot be picked west

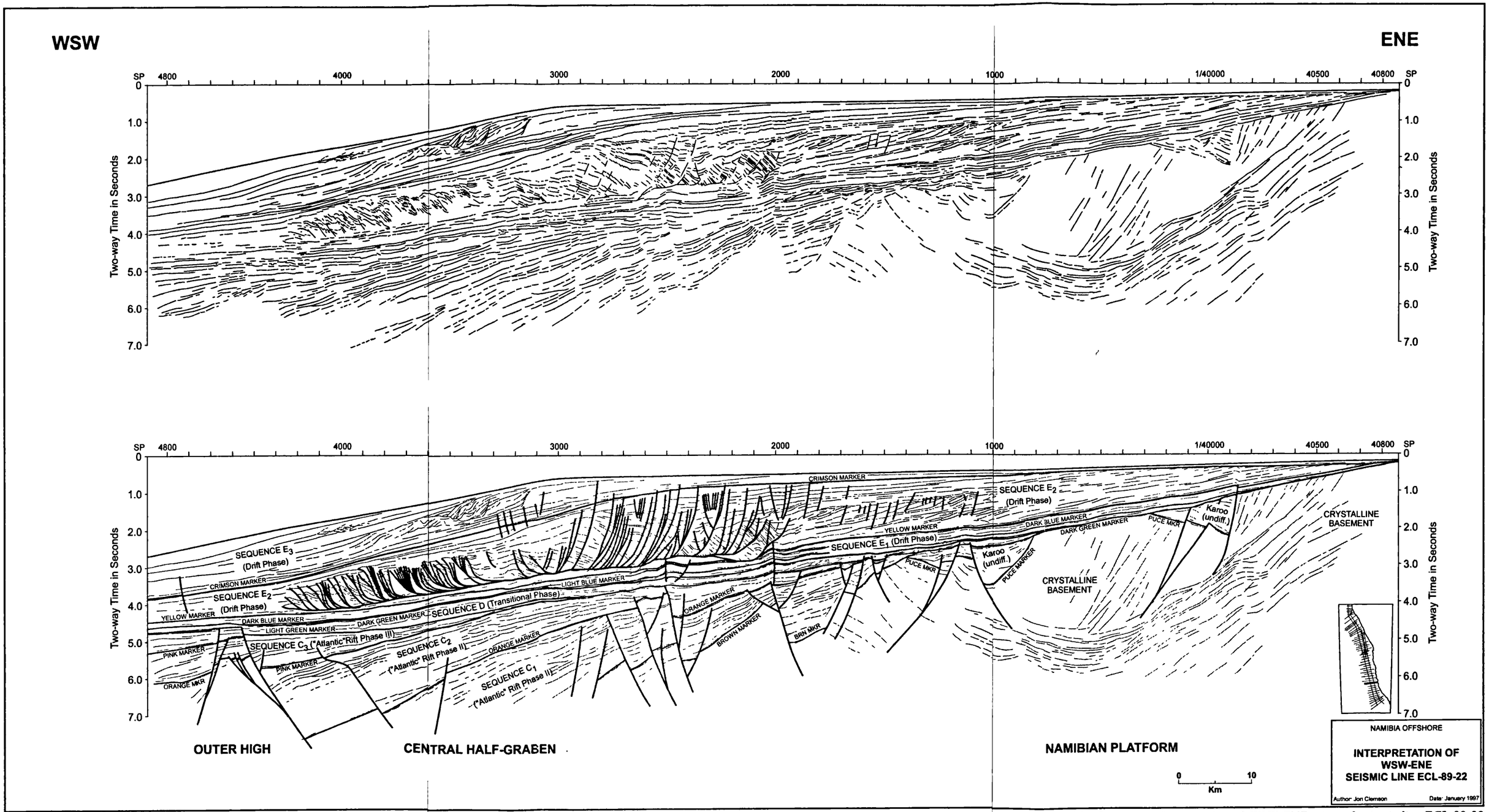


Figure 4.30 Interpreted line drawing of WSW-ENE oriented seismic line ECL-89-22

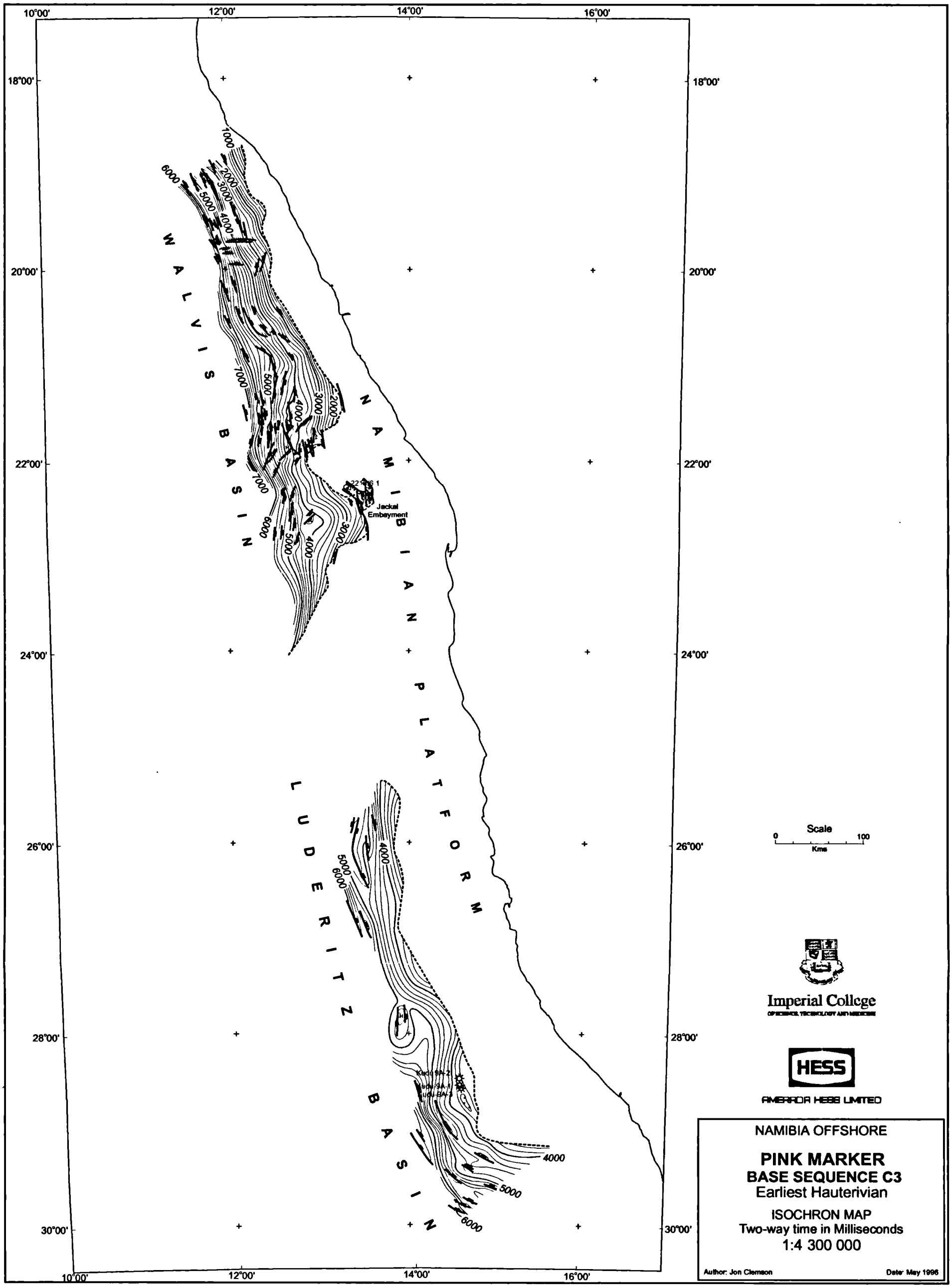


Figure 4.31 Offshore Namibia - isochron map of the base of Sequence C_3 (Pink Marker)

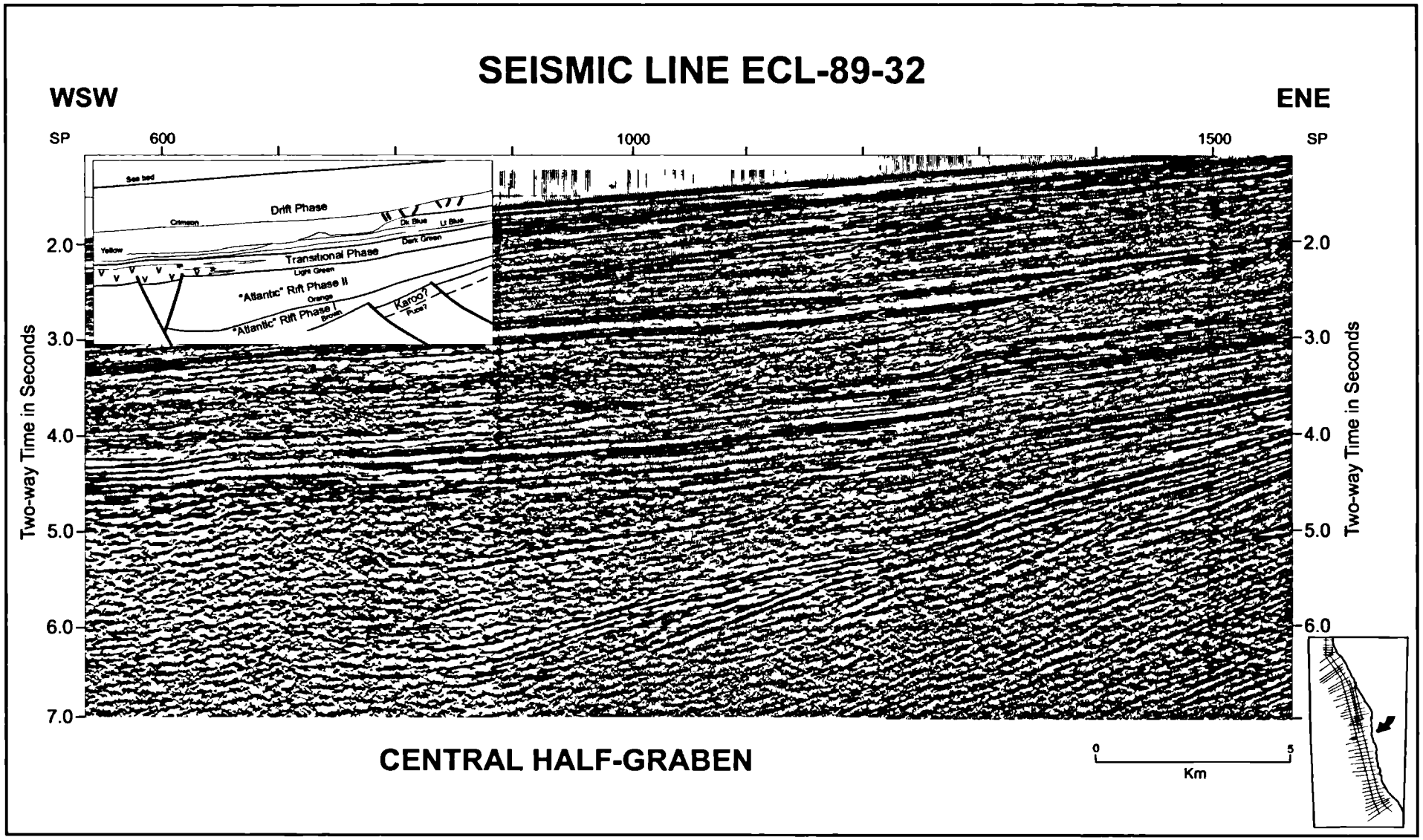


Figure 4.29 Seismic section in the Central Half-Graben

of the northern Lüderitz Arch where seismic control is poor. No line is available to tie along this section of the margin. The overlying Sequence C_3, if present, is believed to be thin. The isopach of Sequence C_2 (Fig. 4.28) includes any possible Sequence C_3 where the Pink Marker is not interpreted.

4.5.3.3 Sequence C_3 - (Rift Phase III)

This sequence is typified by poorly reflective, low amplitude, discontinuous reflections, both lower in the sequence and in eastern part of the Walvis and Lüderitz Basins. There is a change to the west and higher in the sequence where reflections become higher in frequency and continuity. There is no definable horizon separating these two seismic characters. There are also local changes in seismic quality with degradation westwards towards faults in the west of the Lüderitz Basin (Fig. 4.32, shotpoints 2200-2500). This suggests that footwall erosion of fault blocks may have occurred in the west of the basin.

The base of this sequence, the Pink Marker (Fig. 4.31), is often conformable with Sequence C_2 but locally shows onlap and truncation. It is usually cut out updip by the break-up unconformity in the Lüderitz Basin (Figs 4.30, 4.33) but occasionally it onlaps the Orange Marker. In the Walvis Basin, the Pink Marker is truncated in the east by the break-up and Lower Aptian unconformities. The east of Sequence C_3 is locally fault-bounded in the Cape Cross Segment Boundary Zone. This is associated with chaotic reflections and local depocentres.

At the top of this sequence the break-up unconformity, the Light Green Marker (Fig. 4.34), marks a distinct change in seismic character. In the east where Sequence C_3 is poorly reflective, it is overlain by higher amplitude reflections of the Transitional Phase sequence. In contrast, the more reflective seismic character in the western, upper part of Sequence C_3 is succeeded by continuous but lower amplitude, higher frequency reflections. Although this character change at the Green Marker occurs in both the Lüderitz and Walvis Basins, the absence of a NNW-SSE tie line directly linking the basins precludes clarifying whether this marker is synchronous or diachronous between the basins.

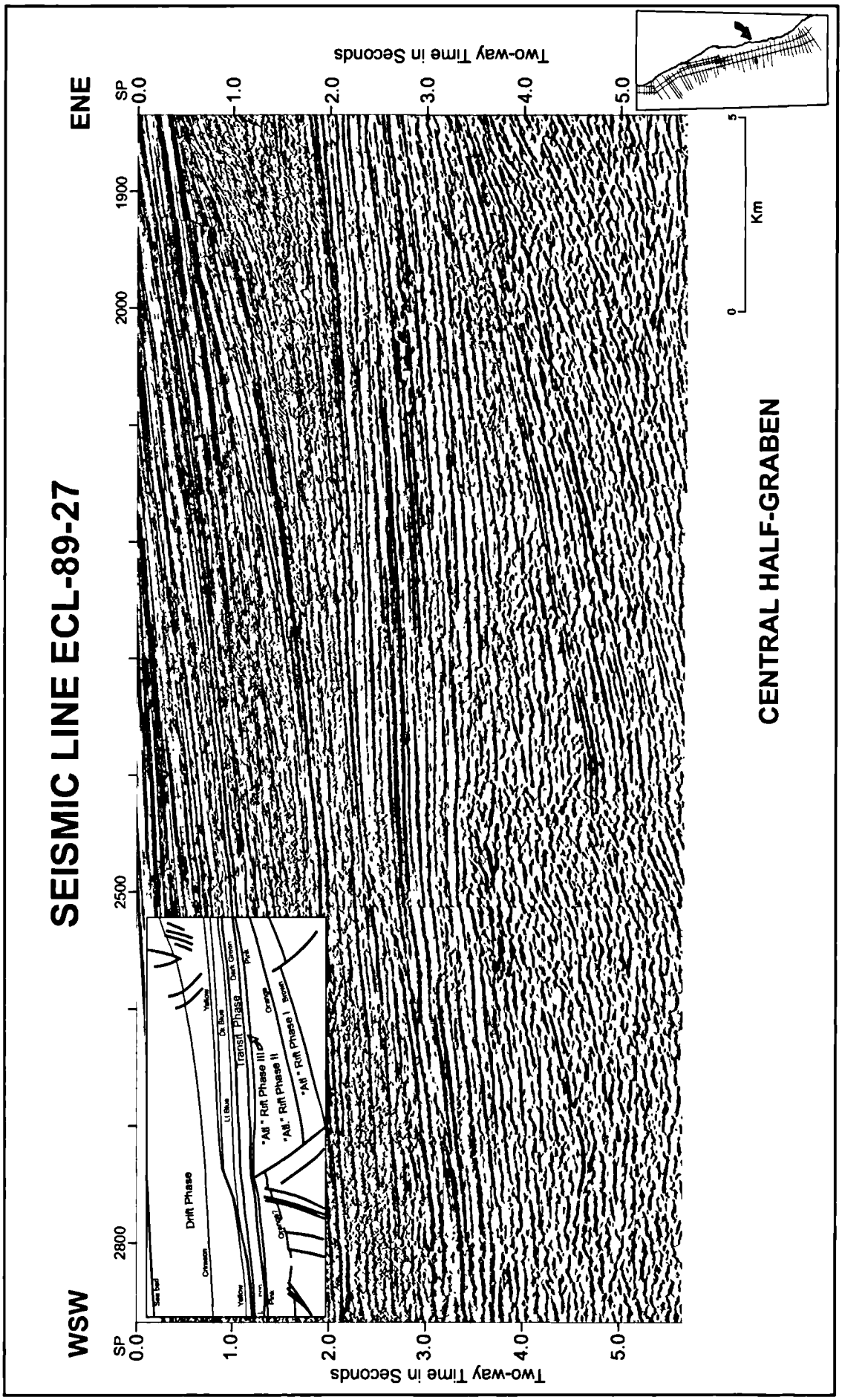


Figure 4.32 Seismic section of the fault-bounded western margin of the Central Half-Graben

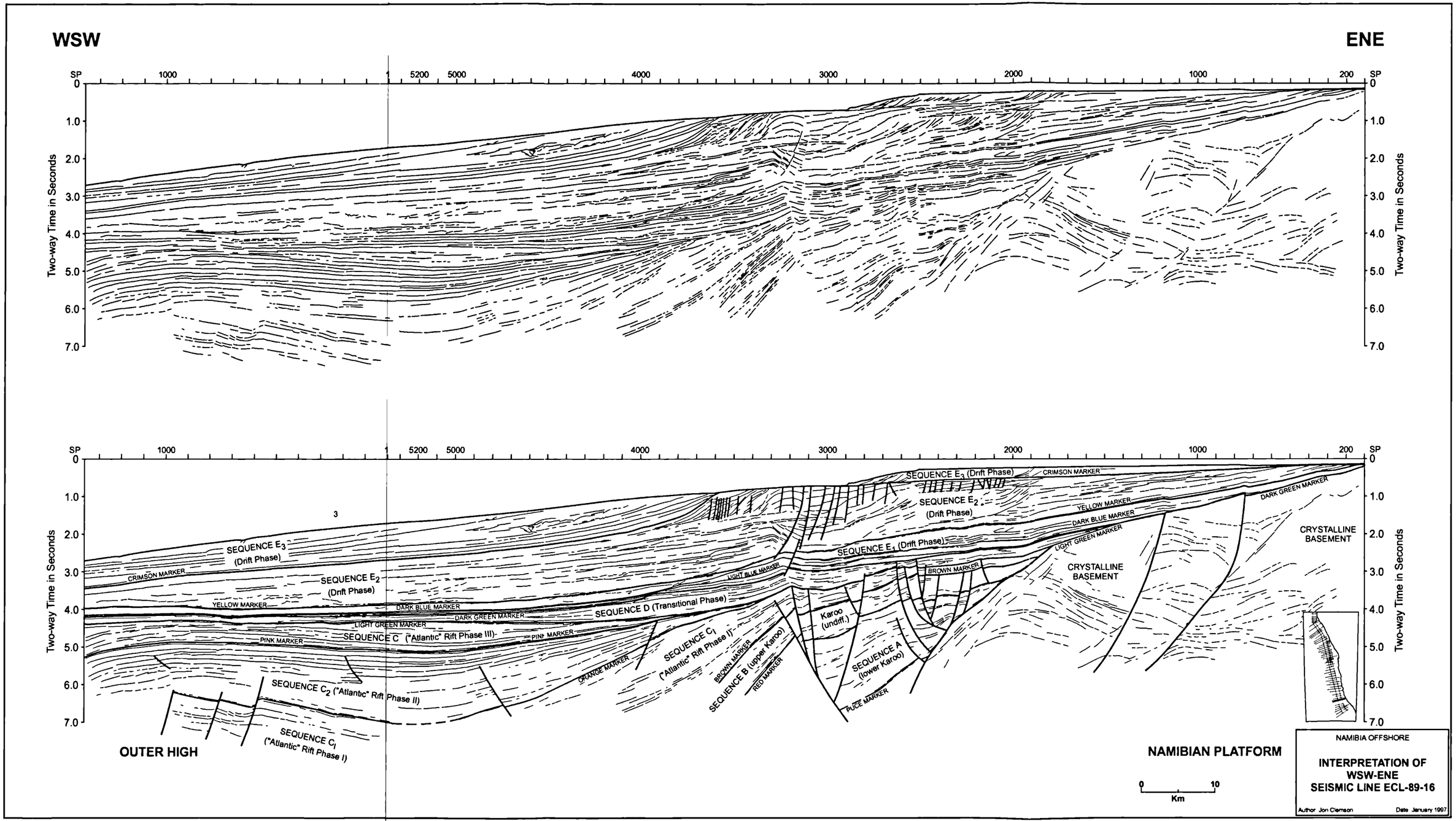


Figure 4.33 Interpreted line drawing of WSW-ENE oriented seismic line ECL-89-16

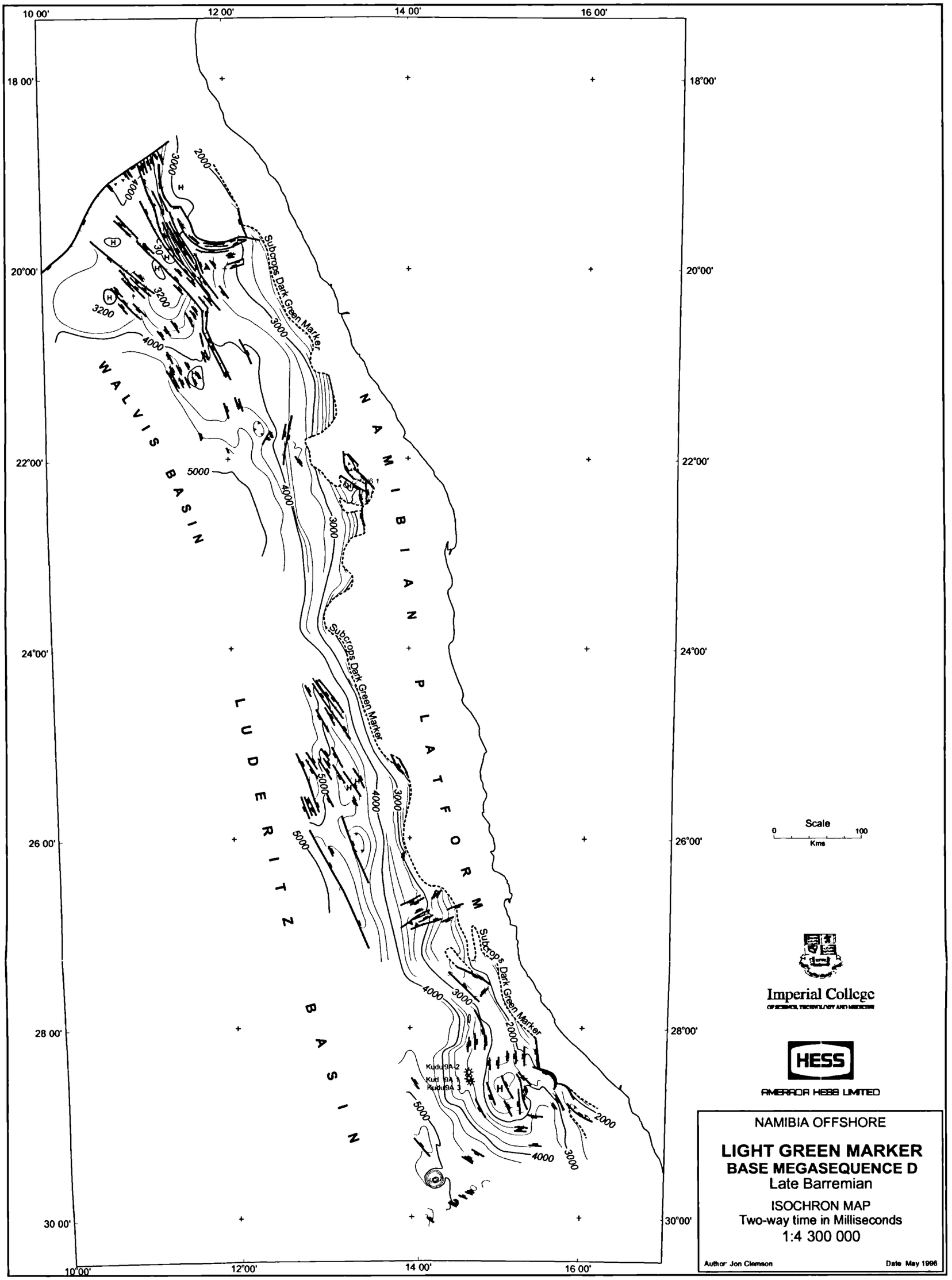


Figure 4.34 Offshore Namibia - isochron map of the base of Megasequence D (Light Green Marker)

The distribution of this sequence is similar to that of Sequence C_2, i.e. it is found entirely west of the Hinge Line. Isopach mapping (Fig. 4.35) can only be carried out in the east where the Pink Marker is present on the seismic data. Sequence C_2 is not interpreted west of the northern Lüderitz Arch, but is likely to be thin or absent in this area. It is a west-thickening sequence in general, but significant differences in thickness occur in the Lüderitz and Walvis Basins. It reaches 1.4 seconds (TWT) (*c.* 2.8 km) in the extreme southwest of the Lüderitz Basin. In this basin, it does not always thicken to the west. It may be draped over structural highs in the west of the basin (Fig. 4.33, shotpoints 500-1300) or thin on fault footwalls (Fig. 4.30, shotpoints 4400-4700). In the Walvis Basin however, it universally thickens westward to 2.0 seconds (TWT) (*c.* 4 km) or more where the base is present on seismic. In the extreme west it is up to twice as thick, but the base is not defined. The differing thicknesses in the Lüderitz and Walvis Basins contrast with Sequence C_2, which was much thicker in the Lüderitz Basin.

The Outer High, a swell along the west of the Namibian passive margin, was originally defined by Gerrard and Smith (1982) (Fig. 4.8). This high is located beneath the present continental slope. The increasing water depths insert a west-thickening, slow velocity water envelope. On time sections this pushes down reflections to obscure the presence of the Outer High (Fig. 4.15). Reflections above the break-up unconformity apparently downlap on time sections but in depth this can be regarded as onlap. This relationship indicates that the Outer High had probably formed by the time of break-up.

4.5.4 Megasequence D (Transitional Phase)

There is an abrupt change in the seismic character above the Light Green Marker. Reflections are more continuous, higher frequency and lower amplitude. In the south, frequencies are lower where the faulted and slumped section of the Upper Cretaceous prograding wedge reduces the signal-to-noise ratio at depth.

This sequence attains maximum thickness between the Outer High and the Hinge Zone. In the Walvis Basin it is thin and barely exceeds 0.1 seconds (TWT) except locally in the Cape Cross Segment Boundary Zone (Fig. 4.36). Where a shelf break has developed, it builds up to 0.35 seconds (TWT). It thins westwards and may become seismically unresolvable in the

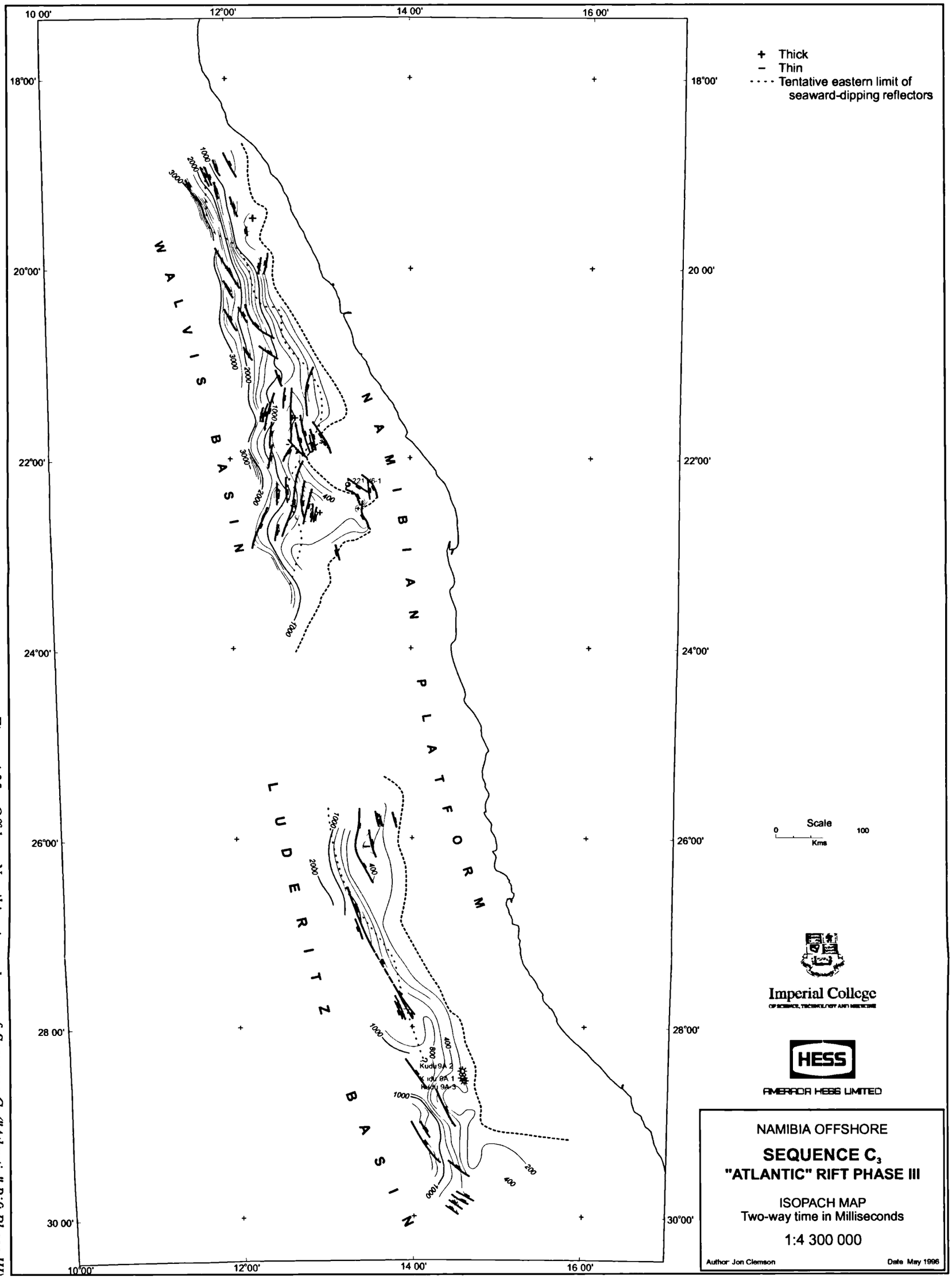


Figure 4.35 Offshore Namibia - isopach map of Sequence C_3 ("Atlantic" Rift Phase III)

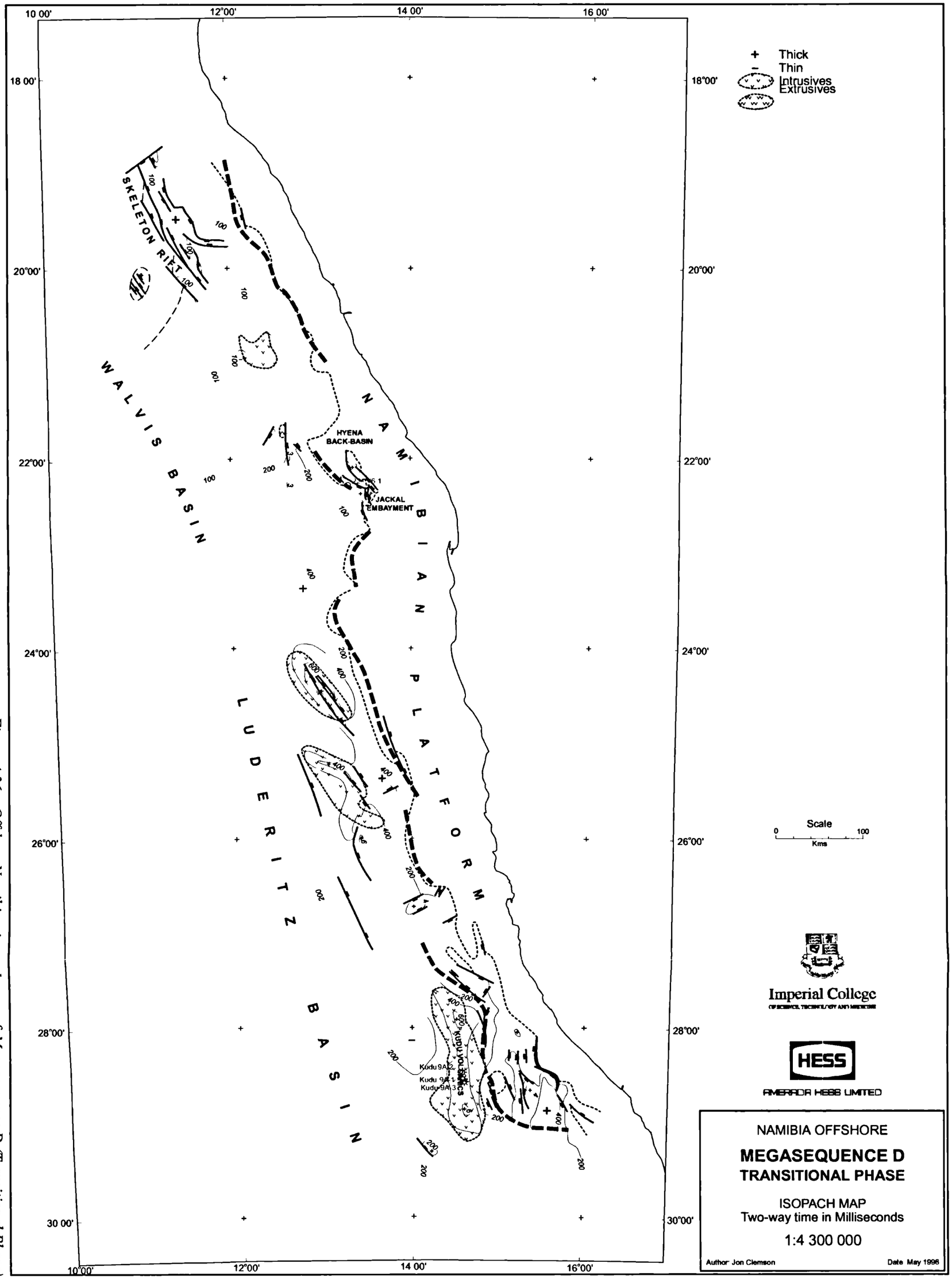


Figure 4.36 Offshore Namibia - isopach map of Megasequence D (Transitional Phase)

basin. To the east it pinches out at the base of the Hinge Zone. On the Namibian Platform this sequence is absent east of the Hinge Line. In the Lüderitz Basin it exceeds 0.8 seconds (TWT) in thickness. The thickest intervals east of the Lüderitz Arch have high amplitude chaotic reflections that are probably volcanics (Fig. 4.29, shotpoints 550-900). Eastward, these interfinger with semi-continuous, moderate amplitude reflections. Over the northern Lüderitz Arch the Dark Green Marker truncates this sequence along the Hinge Line (Fig. 4.37, shotpoint 1000) but on the southern flank of the Arch, a veneer extends 30-70 km east across the platform to pinch out onto the basement (Figs 4.25, 4.30). Low angle, west-directed shingling of reflections is evident in the south of the Lüderitz Basin.

Volcanics may also be present on the platform in the Cape Cross Segment Boundary Zone (Fig. 4.38), where an interval of semi-continuous to chaotic markers is evident. Unlike the basinal extrusives, the top has been eroded to leave relict topography with relief up to 0.1 seconds TWT (*c.* 150 metres).

Continuous reflections onlapping the Light Green Marker as it climbs up to the Hinge Line give little indication of active sedimentary input from platform areas. Locally however, more discontinuous, wavy, higher amplitude reflections downlap to the west just basinwards of the Hinge Line (Fig. 4.37, shotpoints 1000-1300). This may represent a fan shed from the eroding platform.

In the Lüderitz Basin, thick Megasequence D with an apparent shelf break lies west of the Hinge Line and Kudu High. This shelf-break, unlike the case in the Walvis Basin, does not appear to be constructional (Fig. 4.39, shotpoints 32,800-33,100). There are three possible reasons for this anomalous shelf-break:

a) Some increased thickness may be due to the Kudu volcanics in the lower part of Megasequence D (Fig. 4.38). However, most of the thickened section appears to fall in the sedimentary sequence *above* the volcanics.

b) Submarine erosion early in the Drift Phase.

c) Tectonic erosion in the west of the interval, caused by the detachment at the base of the Upper Cretaceous listric fault system. The position of this detachment is controlled by the presence of prodelta shales (see *Section 4.6.5.2*). The detachment does not appear

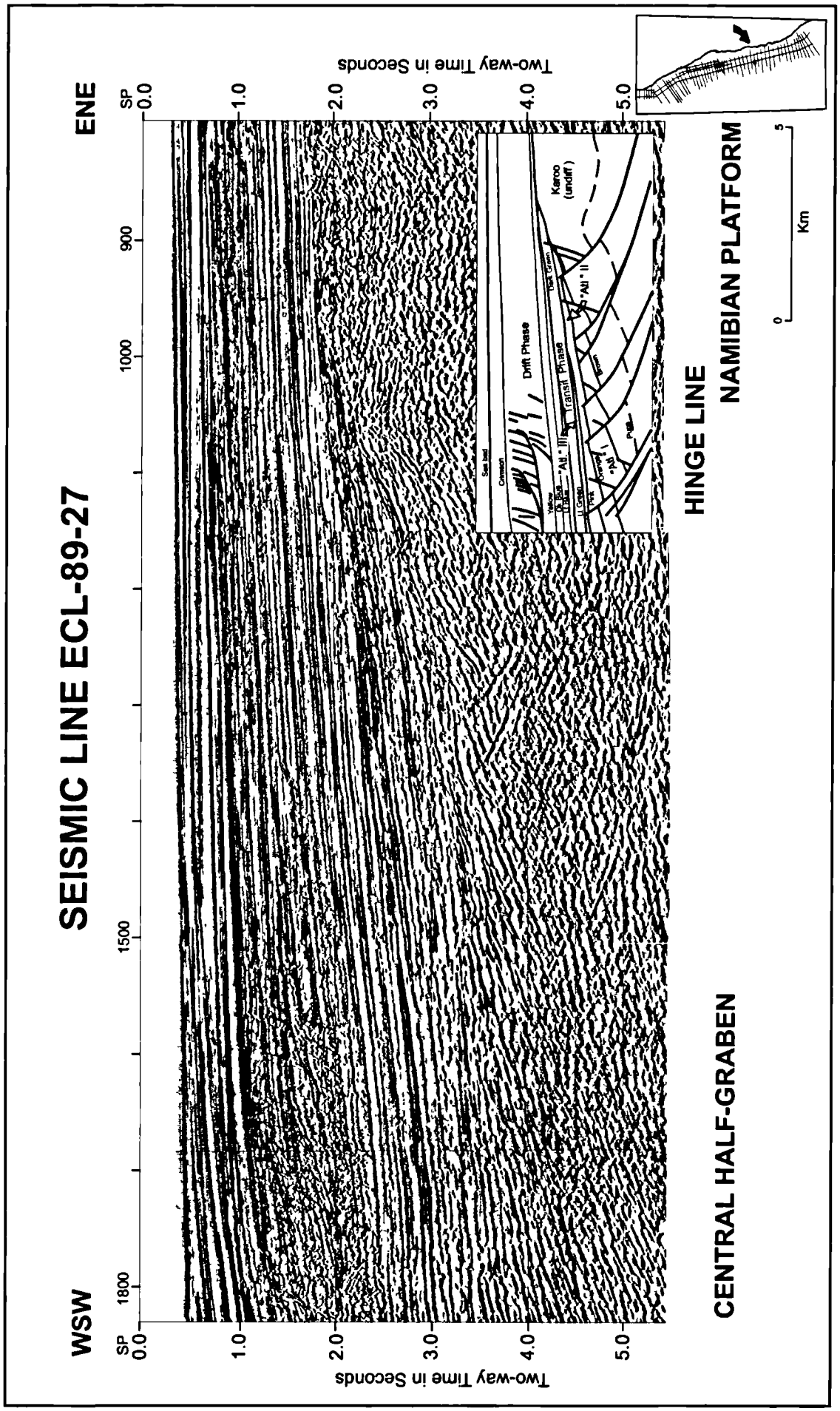


Figure 4.37 Seismic section of the Hinge Line and east of the Central Half-Graben

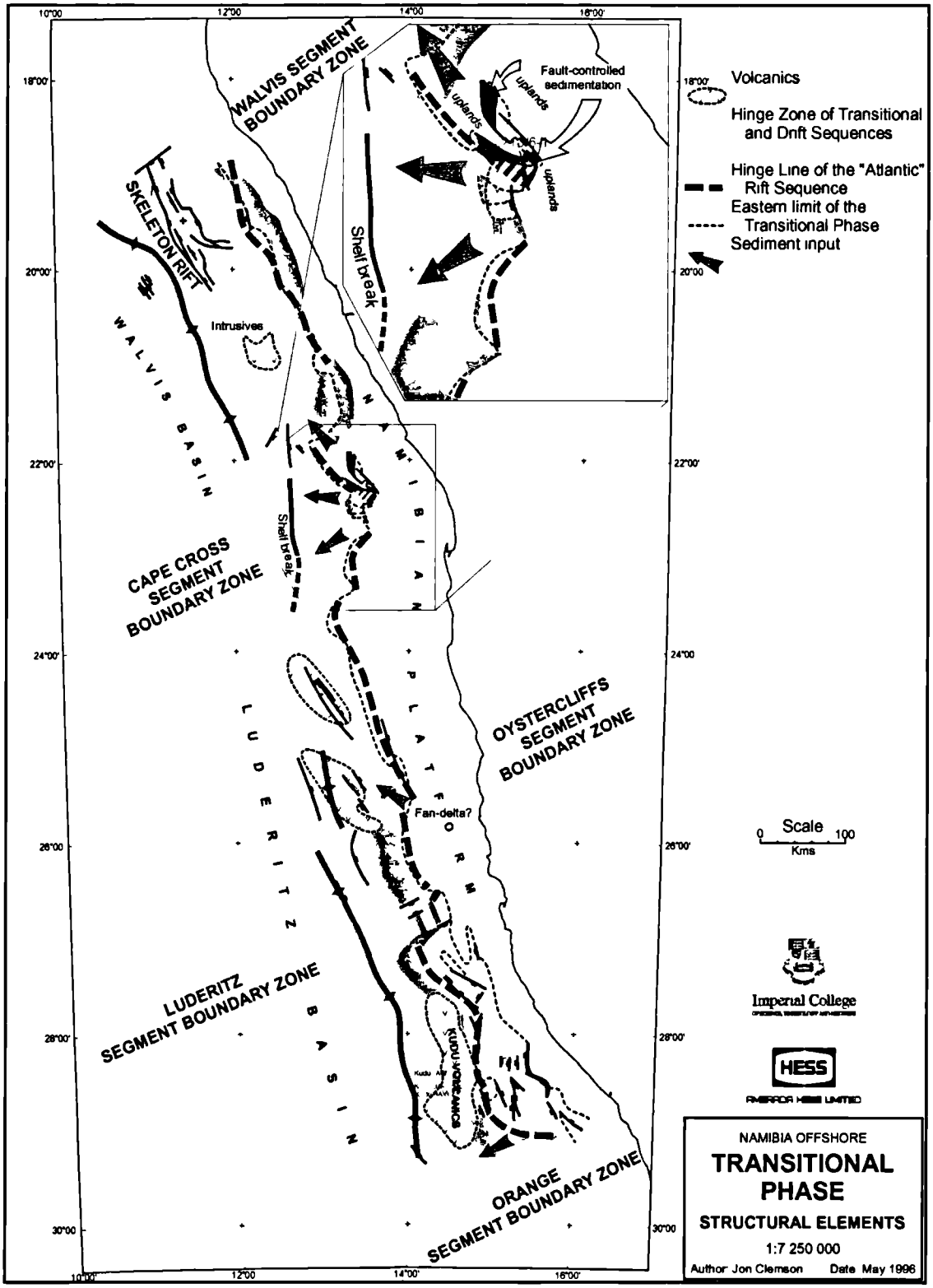


Figure 4.38 Offshore Namibia - structural elements of the Transitional Phase

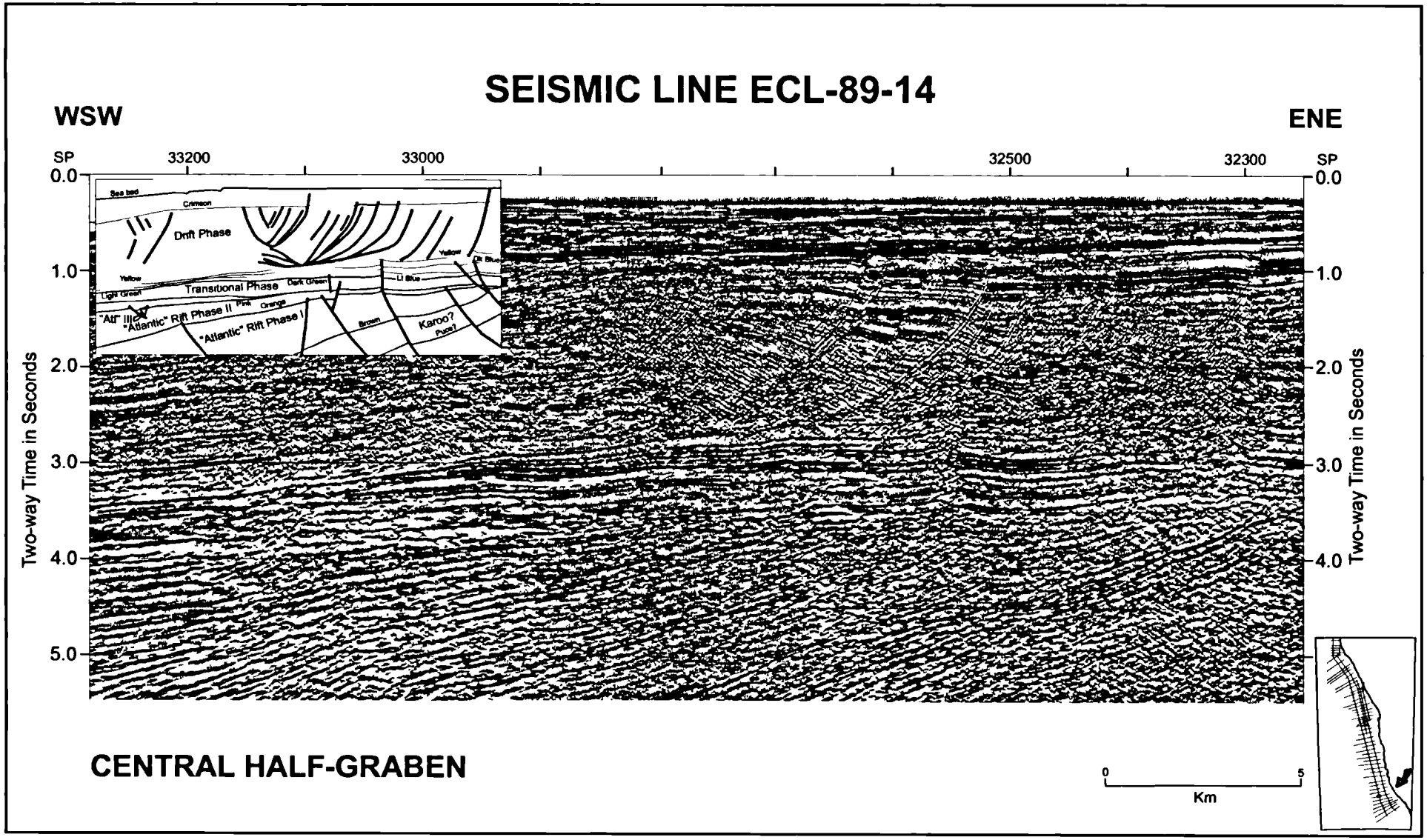


Figure 4.39 Seismic section in the Central Half-Graben

to cut down below the Dark Green, or even the Dark Blue Horizon. Furthermore, the anomalous shelf break is still evident where there is little listric faulting.

It is difficult to be certain of any one of these causes, but a) & c) are less likely. Thus, it may be due to submarine erosion.

There is evidence for syn-sedimentary faulting on the rift margin in the Jackal Embayment and Hyena Back-basin (see *Chapter 5*). In the far north of the Walvis Basin, the outline of the Skeleton Rift apparently became defined at this time (Fig. 4.36). Most other faulting is minor except block-faulting in the north of the Lüderitz Basin.

4.5.5 Megasequence E (Drift Phase)

The Drift Phase is dominated by subsidence, with stacked prograding sedimentary wedges building out along the passive margin. This allows the Drift Phase to be divided into three major sequences.

4.5.5.1 Sequence E_1

The Dark Green Marker (Fig. 4.40) defines the base of this sequence. Its top is defined by the Yellow Marker (Fig. 4.41) which correlates with the Turonian condensed section (McMillan 1990) in the Kudu wells. This relates to the worldwide Turonian highstand (Haq *et al.* 1988). This is the first post-rift sequence along the entire Namibian margin to extend beyond the Hinge Line and across the Namibian Platform.

Sequence E_1 includes the first major prograding sequences to develop on the subsiding passive margin (Fig. 4.42, shotpoints 1000-3400). Two distinctive flooding surfaces, the Light and Dark Blue Markers (Figs 4.43, 4.44), drape two of these prograding wedges in the lower part of Sequence E_1. These two markers become indistinguishable in the north of the Walvis Basin. They are respectively Early and mid-Aptian in age in the Kudu wells. The Dark Blue Marker is the same age as continental breakup north of the Walvis Ridge (Light *et al.* 1993).

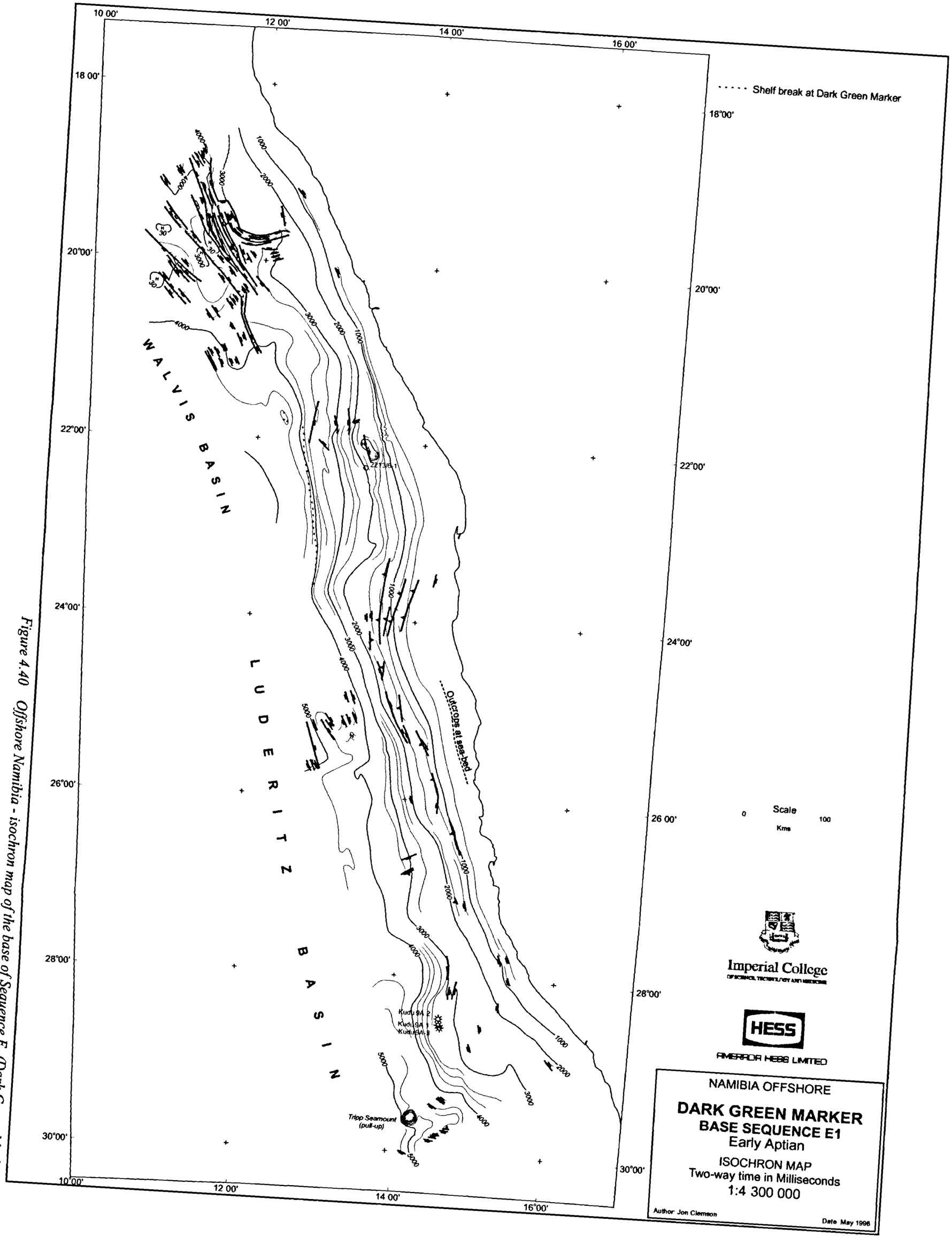


Figure 4.40 Offshore Namibia - isochron map of the base of Sequence E, (Dark Green Marker)

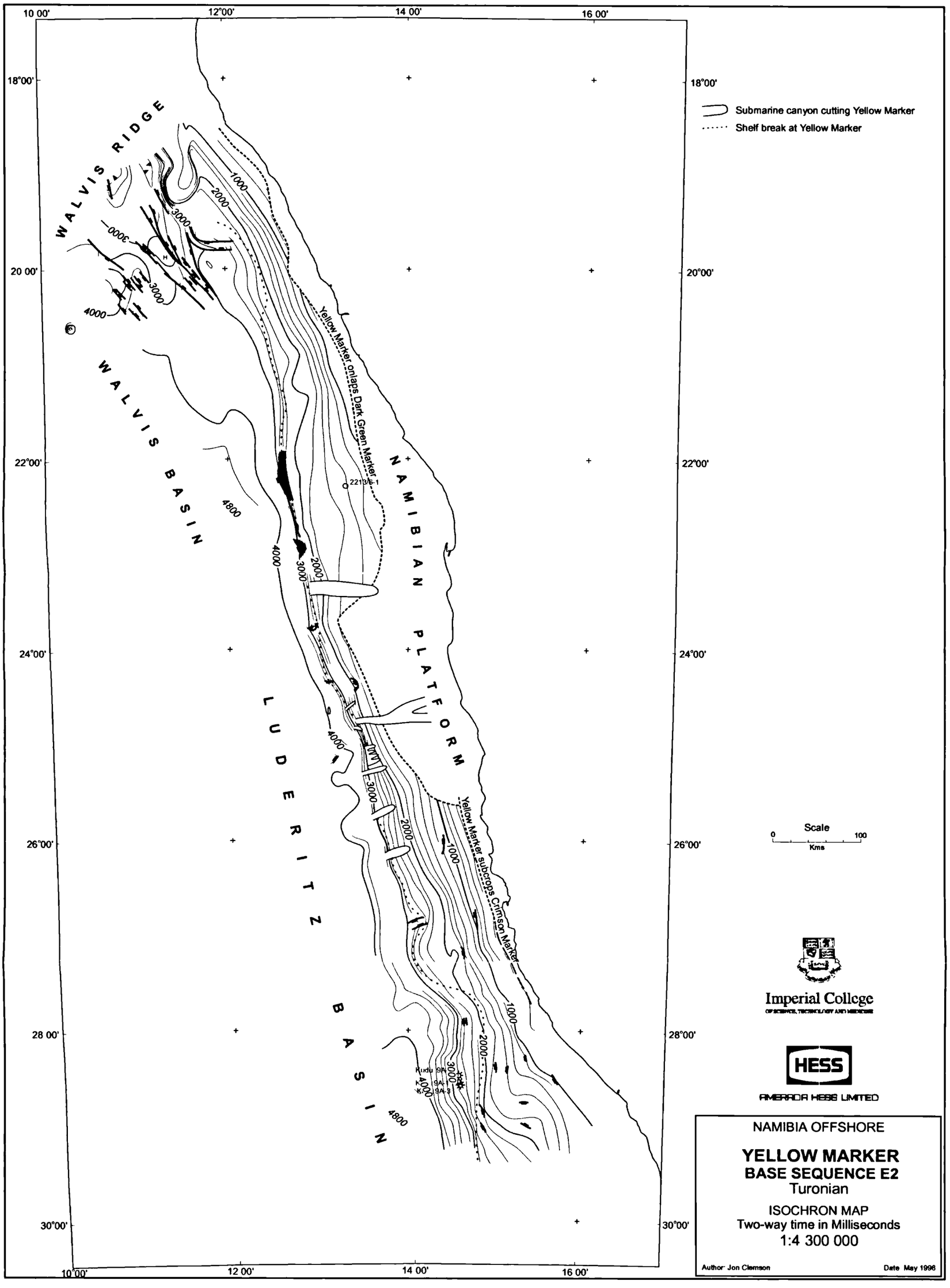


Figure 4.41 Offshore Namibia - isochron map of the base of Sequence E_2 (Yellow Marker)

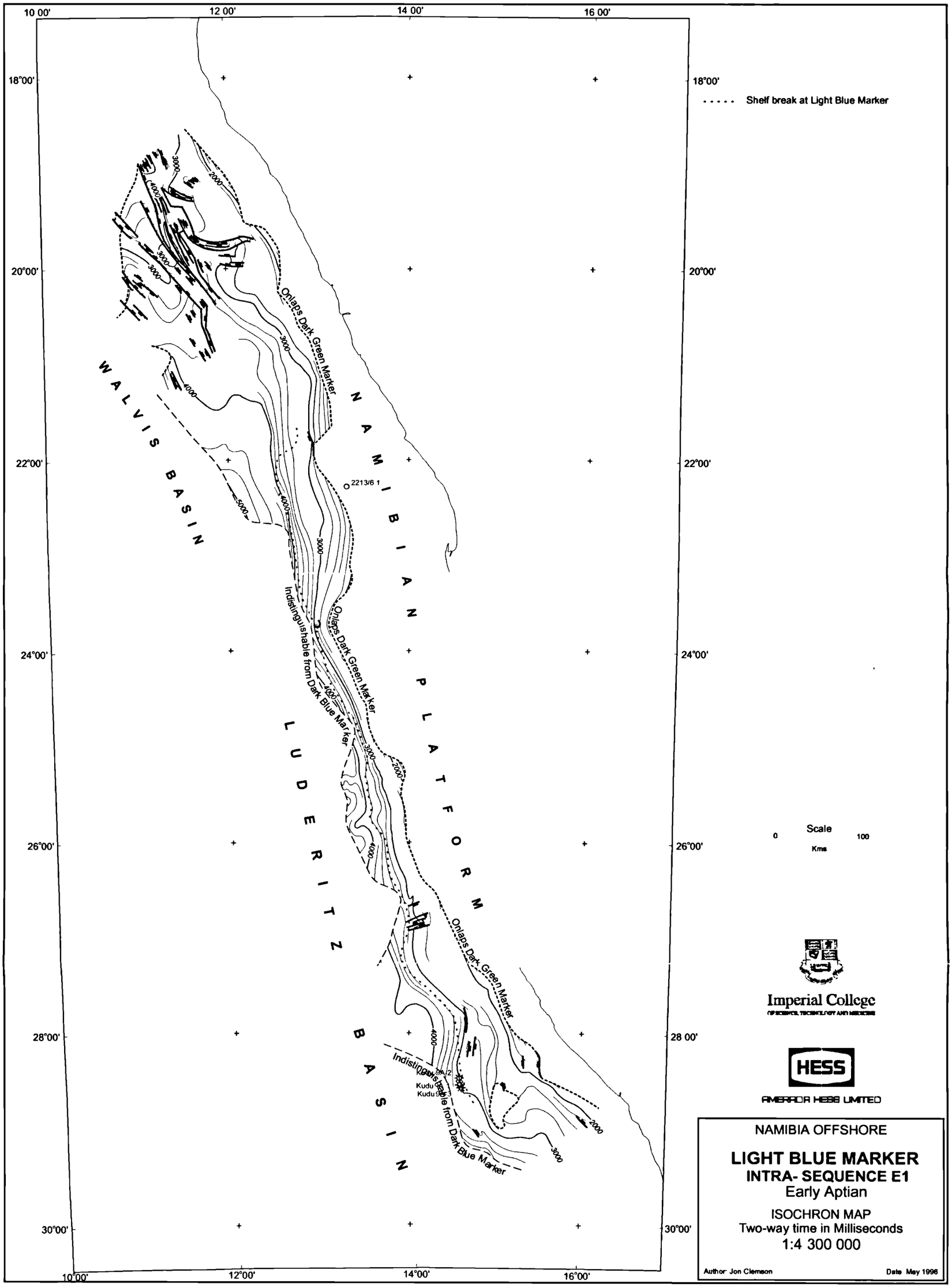


Figure 4.43 Offshore Namibia - isochron map of intra-Sequence E, horizon (Light Blue Marker)

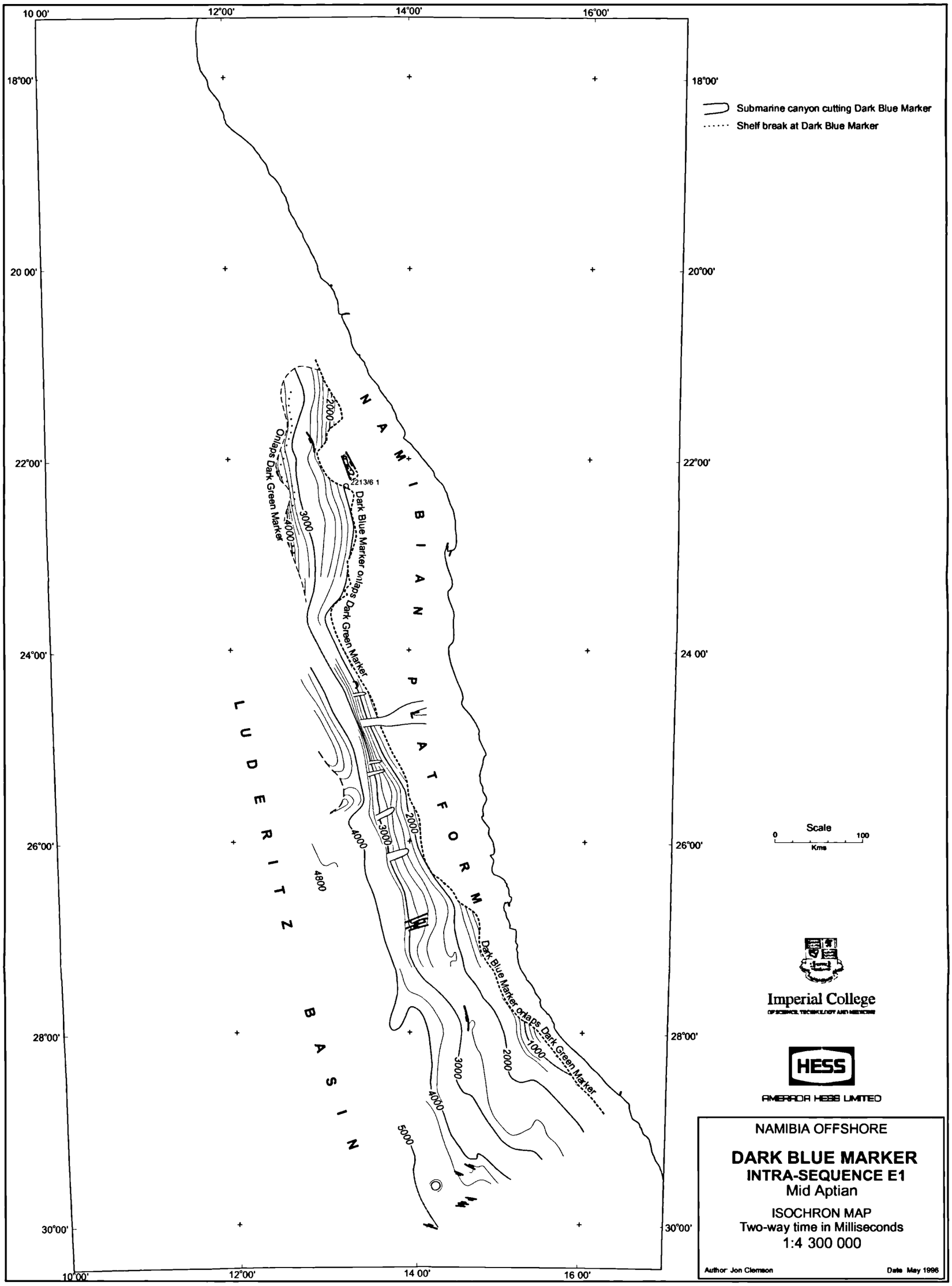


Figure 4.44 Offshore Namibia - isochron map of intra-Sequence E, horizon (Dark Blue Marker)

Both of these intermediate markers drape sedimentary wedges that thin and pinch out to the east onto the Namibian Platform. The Dark Blue-Yellow interval is the first to extend across most of the platform area. On the south of the Lüderitz Arch, the Yellow Marker subcrops the Crimson Marker (Figs 4.33, 4.41). It onlaps the basement on the northern Lüderitz Arch and in the Walvis Basin.

This sequence thickens seawards to the Hinge Line but thins west beyond the Hinge Zone. It reaches 1.4 seconds (TWT) in the Walvis Basin and thickens to 1.8 seconds (TWT) in the south of the Lüderitz Basin (Fig. 4.45). This depocentre heralds the build-up of an important delta system, the Orange Cone.

Seismic reflections on shelf areas are generally semi-continuous. Higher amplitude reflections may bound intervals showing westwards-prograding low-angle shingled reflections. The seismic character of the delta top facies is relatively featureless with little evidence of mouth bar sands or channels, and few indications of lowstand erosion surfaces. The shelf break is well developed in cross section except in the northern part of the Walvis Basin. Along the margin the shelf break is gently curvilinear in plan. This and the featureless delta top facies suggest a shelf edge, wave-influenced delta system with sediments worked laterally along the passive margin.

In the basin, the Dark and Light Blue Markers often downlap onto the Dark Green Marker. Significant basinal deposition only became established within the Dark Blue-Yellow interval (mid-Aptian - Turonian). In the Kudu wells this interval comprises prodelta to base of slope mudstones. Reflections within the basin are low amplitude, discontinuous and often wavy and sometimes chaotic. Evidence of slope fan progradation and mounding is also seen.

On shelf areas on the west of the Lüderitz Arch, reflections are more continuous and higher in amplitude. Small lenticular bodies with discontinuous reflections below the Dark Blue Marker occur. The shelf break here is atypical of prograding clastics sequences - it is steep and there are no foresets. Topset reflections end abruptly and there are no downlapping reflections (Figs 4.18 and 4.29, shotpoints 900-1400). The truncational geometry indicates that the shelf break was modified by submarine erosion.



Figure 4.45 Offshore Namibia - isopach map of Sequence E_1 (Drift Phase)

A north-south elongate volcanic dome 100x50 km in size is present on platform areas near the eastern end of the Walvis Ridge (Figs 4.46, 4.47). This dome, the Walvis Igneous Centre is built on the composite Light/Dark Blue Markers and draped by the Yellow Marker. It is discussed in detail in *Chapter 6* as it lies in the Walvis Segment Boundary Zone.

The NNW-SSE oriented Skeleton Rift in the north of the Walvis Basin developed early in the Drift Phase. Reflections below the composite Light/Dark Blue marker show minor divergence towards major faults (Fig. 4.48). Sub-horizontal, semi-parallel reflections above this marker show strong onlap at the base of the rift. Southwards, this rift system splays into two major arms. The relationship between the Skeleton Rift and Walvis Igneous Centre are discussed in *Chapter 6*.

4.5.5.2 Sequence E_2

This Late Cretaceous prograding sequence has three major sediment lobes: the Orange Cone in the south, the central Lüderitz Basin and the southern Walvis Basin. It is thinnest adjacent to the northern part of the Lüderitz Arch (Fig. 4.49).

The delta top seismic character is similar to the underlying sequence - that is, generally featureless, with parallel, fairly continuous, low to moderate amplitude reflections. In the Orange and Lüderitz sedimentary lobes, reflections are continuous on the delta top but become less so when passing landwards onto the flood plain. This regressive sequence progrades across the Turonian flooding surface and starts up to 60 km landwards of the end Cretaceous shelf break. The gradient of foresets varies with small sequences alternatively wedging out or thickening updip. These are apparently third order highstand lowstand systems tracts, but it is difficult to identify individual sequences over any distance. Along the entire passive margin, all sediment lobes including the major Orange Cone are gently curvilinear in plan (Fig. 4.47). The deepening waters along the subsiding passive margin precluded the growth of large sediment lobes beyond a mature shelf break.

The seismic character is similar in the Walvis Basin but the Turonian flooding across the shelf is not evident. The Yellow Marker lacks the very high amplitude it possesses in the

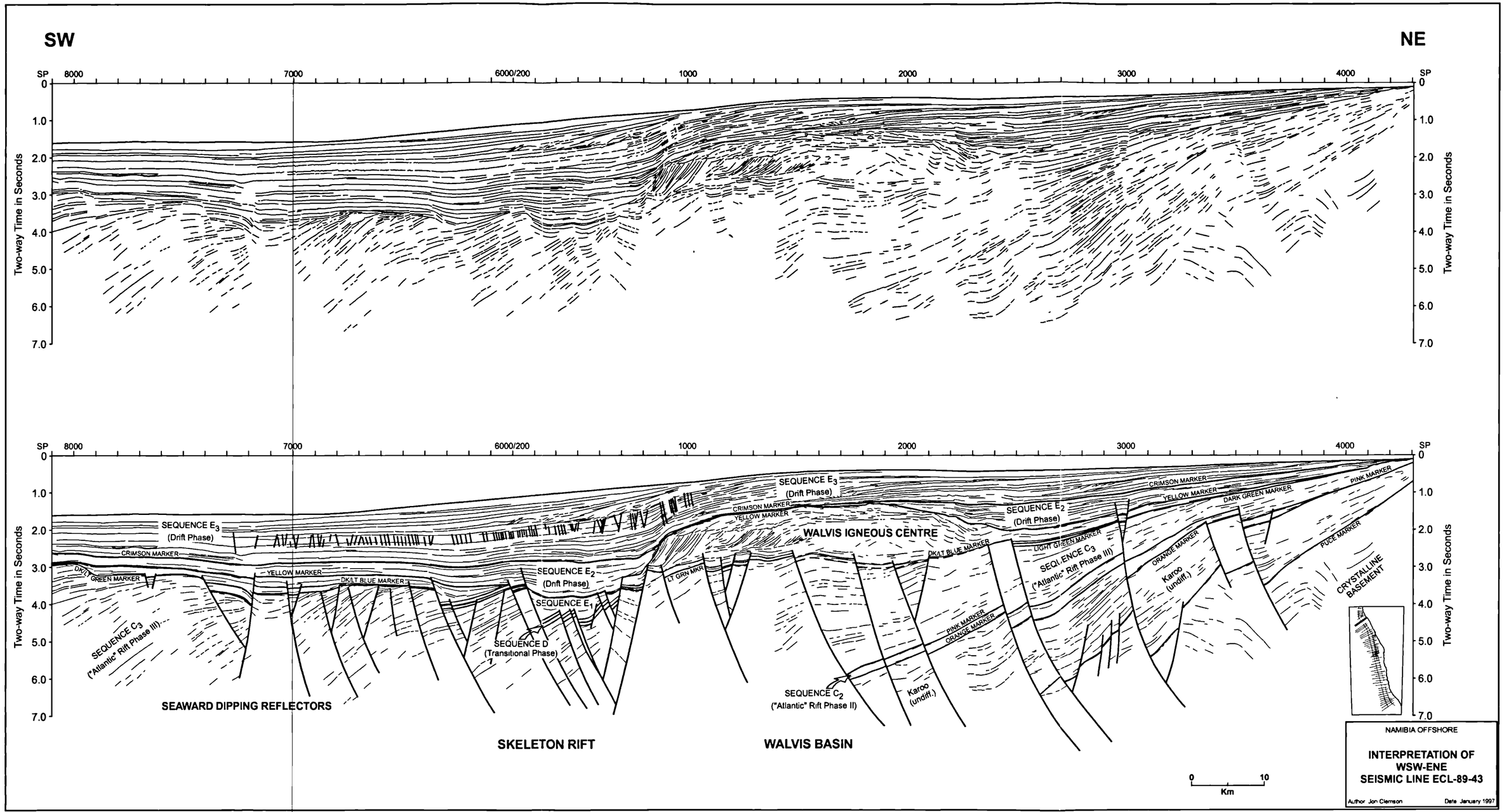


Figure 4.46 Interpreted line drawing of WSW-ENE oriented seismic line ECL-89-43

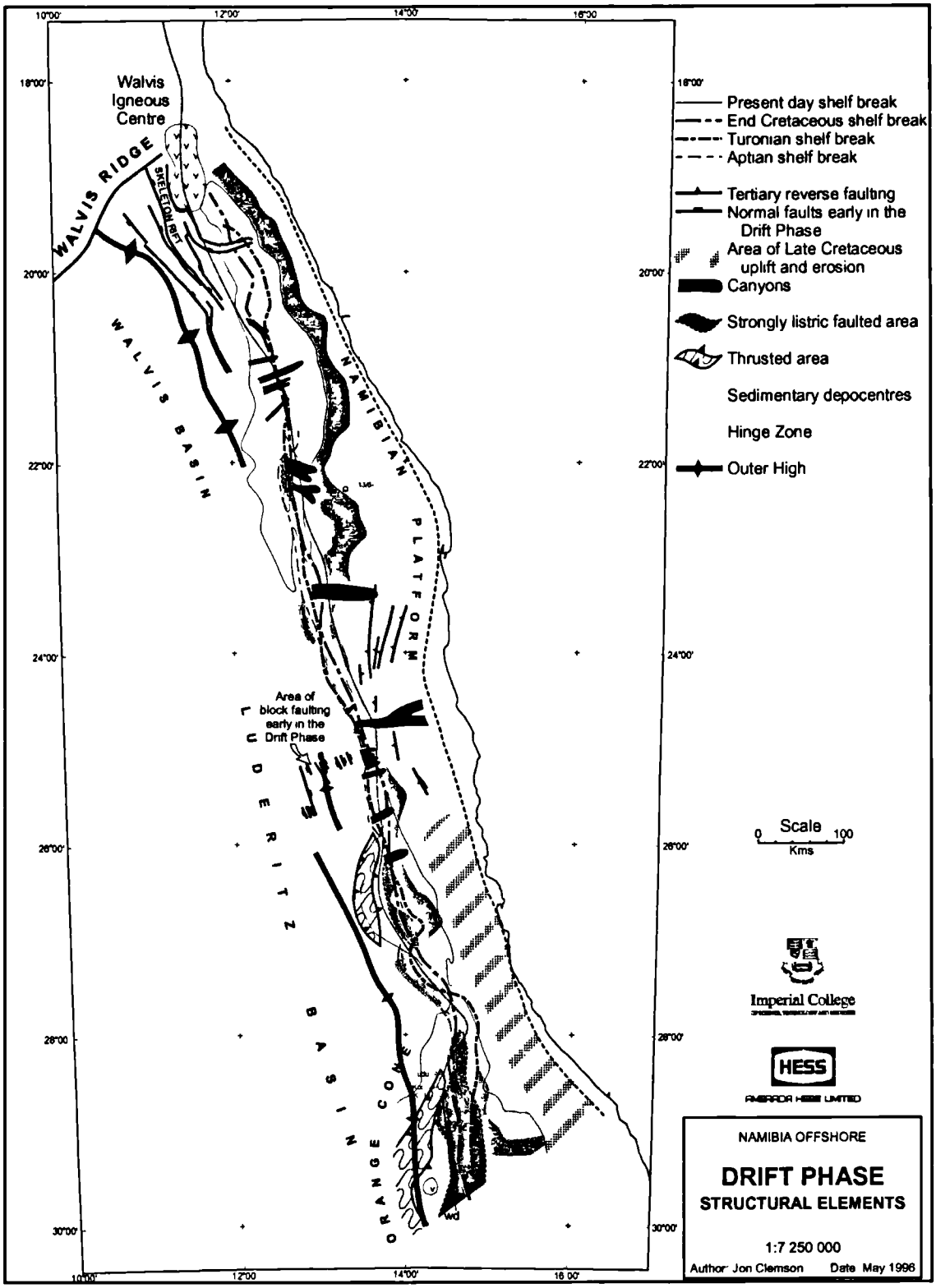


Figure 4.47 Offshore Namibia - structural elements of the Drift Phase

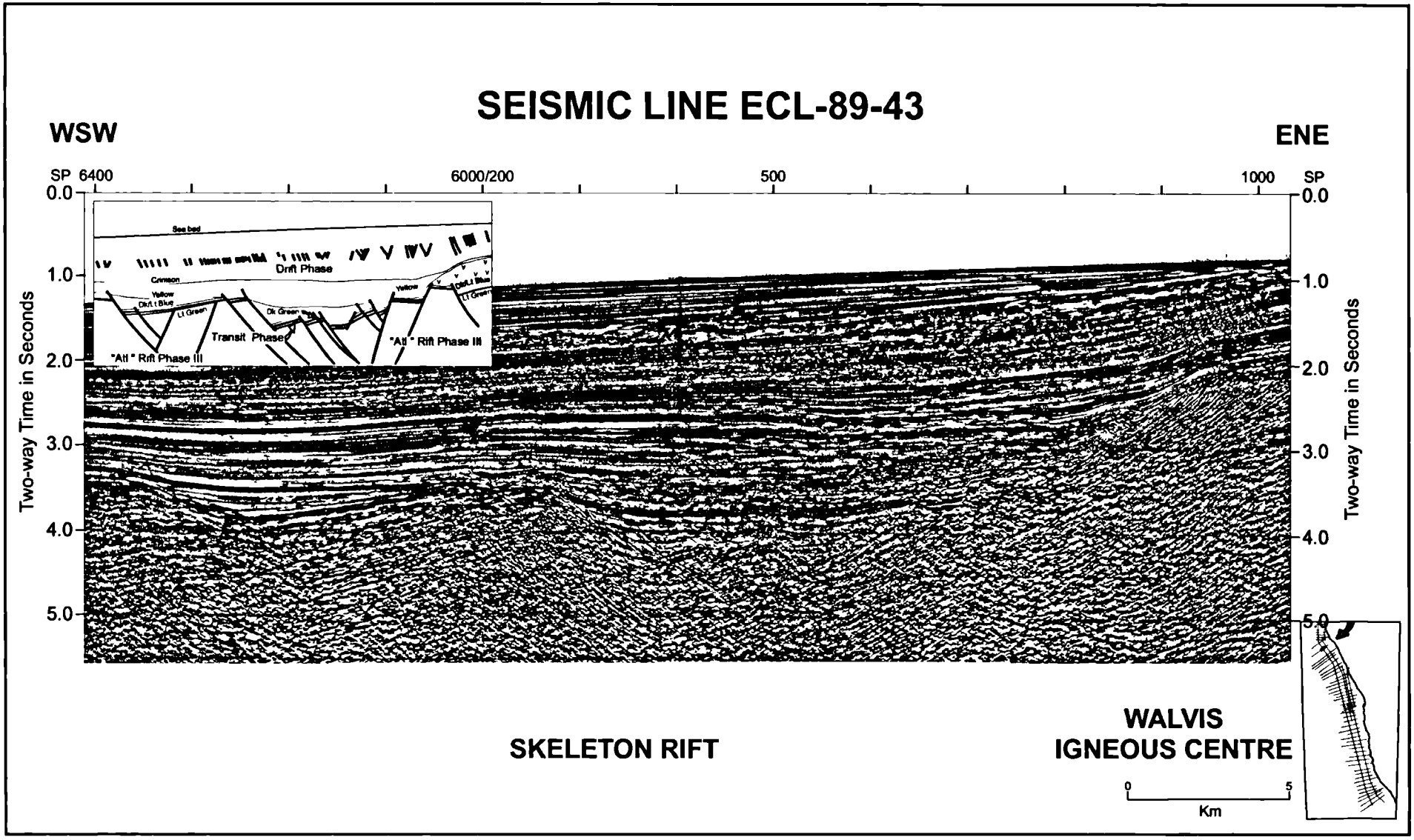


Figure 4.48 Seismic section across the Skeleton Rift

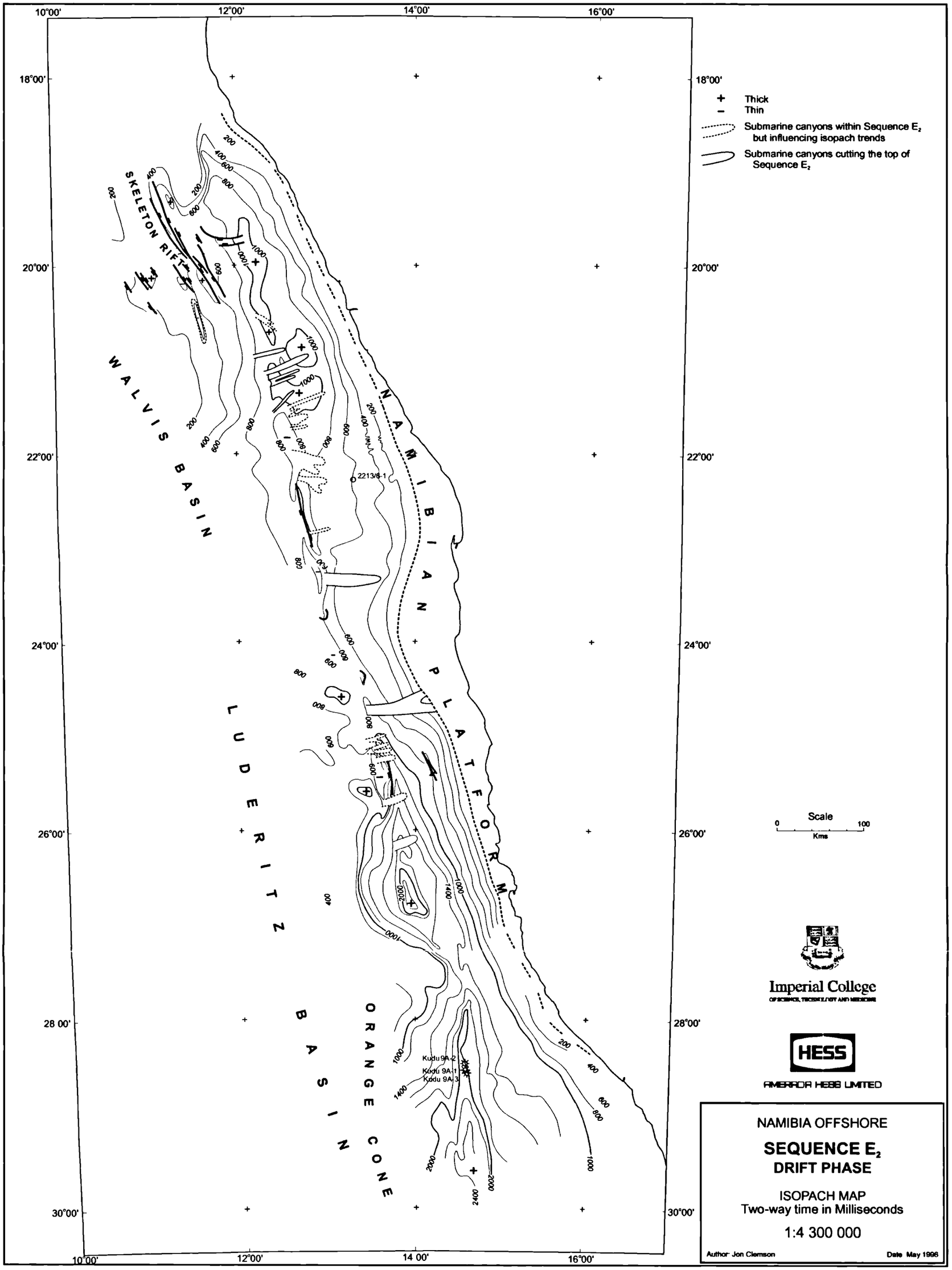


Figure 4.49 Offshore Namibia - isopach map of Sequence E_2 (Drift Phase)

Lüderitz Basin. The stacked aggrading sequences dominating the upper part of Sequence E_2 continue into Sequence E_3. Third order sequences are stacked with little shift in the shelf break away from the end Cretaceous shelf break. In the north there is a much greater lateral shift of sequences across the platform This shift is up to 30 km and may account for the subdued slope gradients in the north of the Basin.

Prodelta reflections are discontinuous to semi-continuous and sometimes show mounding. Further west, reflections converge and become continuous where pelagic sedimentation dominated over the Outer High.

Significant listric faulting close to the shelf break occurs in the Orange Cone and Lüderitz Basin sediment lobe. The faults often pass down into one and sometimes two detachment surfaces close to or above the Yellow Marker (Figs 4.25, 4.30, 4.42). Listric faulting is much reduced where the Upper Cretaceous shelf break has not prograded beyond the Turonian shelf break (Fig. 4.47). Where this has occurred, the faults may translate into toe thrusts immediately basinward of the listric fault (Fig. 4.39, shotpoint 32,800) or more commonly, movement was translated along the detachment to the leading toe thrust (Fig. 4.30). This detachment system may extend up to 90 km across the continental slope. The thrust-ramps are stacked into imbricate fans; each ramp was progressively jacked up by a new basal thrust-ramp until the fan locked. A new fan then developed basinwards until that in turn locked, and the frozen thrust-ramp fans were progressively carried along the detachment. Between the listric and thrust faulting, there is often a neutral zone some 3-8 km wide resting on the detachment. This combined faulting and thrusting is absent in the Walvis Basin. Listric faulting is also much reduced.

Within the sequence, large canyons incise the delta slope and outer shelf near the shelf break. They occur in the south of the Walvis Basin and the northern part of the Lüderitz Basin. Channels are cut within the Upper Cretaceous, and Tertiary channels cut down into the Upper Cretaceous. These are differentiated on Figure 4.49. The most extensive canyon systems cut deeply into the top of the Upper Cretaceous and extend back from the shelf break by *c.* 50 km. Landwards of these canyons, there is no evidence of any fluvial channels of comparable size. Many small gullies 1-2 km across are seen on the delta slope and also larger canyons cutting down even to the Yellow Marker. The deepest canyon is 8 km across

and appears to have been overdeepened and widened to 15 km by collapse and slumping. This canyon is at least 80 km long and even on the shelf it is 0.8 seconds (TWT) (7-800 metres) deep. The scale of this canyon is much greater than any feature on the delta-top, but there is no evidence of any sediment build-up downslope from its mouth. The reworked sediments have either been carried out beyond the database or redistributed along the continental slope as contourites.

Sequence E_4 is truncated beneath Sequence E_3 along inshore areas south of the Oystercliffs Segment Boundary Zone (Fig. 4.47). The Crimson Marker (Figs 4.33, 4.41) is a well-defined angular unconformity in this area.

4.5.5.3 Sequence E_3

This is a period of waning sedimentation with prograding sedimentary systems declining in scale and generally being deposited more landwards than in the Upper Cretaceous. Some sediments prograde across the Upper Cretaceous shelf break. Other sedimentary lobes are superimposed upon the Upper Cretaceous shelf in the Walvis Basin. Their flanks may sometimes face landwards as well as towards deeper waters. Internally these lobes have short to semi-continuous, moderate amplitude reflections showing progradation. They may be sand-dominated, although the presence of carbonate build-ups is a possibility. High amplitude continuous reflections in interlobe areas are probably a mud-dominated facies. Over the Lüderitz Arch reflections are medium to high amplitude, high frequency and continuous. Here, small reversed normal faults have created small flexures in the Tertiary section.

Sequence E_3 is thickest (Fig. 4.50) where slope fans are stacked over the Upper Cretaceous continental slope. The depocentres broadly coincide with those of the Upper Cretaceous and attain 1.8 seconds (TWT) in the Orange Cone in the south and in the Lüderitz and Walvis Basins. In the extreme north it reaches 2.4 seconds (TWT) in a compactional depocentre above the Skeleton Rift (Fig. 4.48).

Listric faulting, slump scars, slope channelling and well-defined slope fans (Fig. 4.32, shotpoints 1900-2300) are common along the Tertiary shelf break. Contourites are often

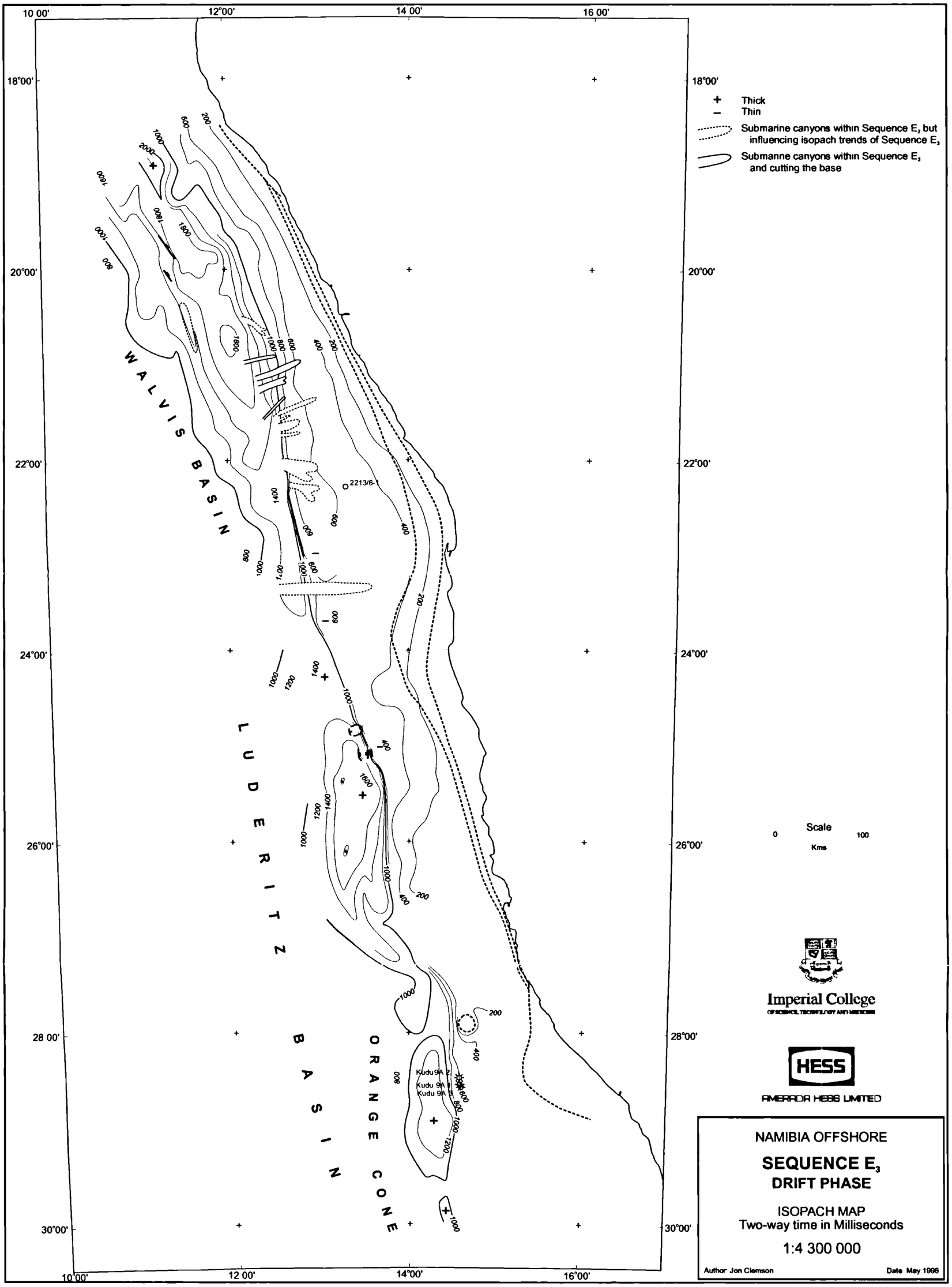


Figure 4.50 Offshore Namibia - isopach map of Sequence E_3 (Drift Phase)

seen along the slope (Fig. 4.51). Reflections in the basin are short and wavy, becoming continuous to the west. Submarine erosion has scoured out a coast-parallel channel 8x60 km in size (Figs 4.52, 4.53) in the Walvis Basin.

The Tripp Seamount (Fig. 4.54) occurs in the extreme southeast of the Namibian passive margin (Fig. 4.52). It erupted through the seaward-dipping reflector wedge on trend with the Orange Segment Boundary Zone. On the peneplaned summit, the water depth is 145 metres. Possible carbonates 0.2 seconds (TWT) thick on the summit (Emery *et al.* 1975) are reduced to 0.1 seconds (TWT) (*c.* 250metres) on the ECL-89 91dataset. The depth to peneplaned volcanics is therefore *c.* 400 metres. This degree of subsidence suggests a Tertiary rather than a Cretaceous volcano. This is not dissimilar to Palaeogene-Neogene subsidence of 600m for adjacent oceanic crust (Morgan *et al.* 1995). The degree of pull-up (using 5000 m sec for volcanics and 2-3000 m/sec for sediments) suggests a Tertiary rather than a thicker, older, volcanic cone.

Next to the Tripp Seamount there is a distinctive change in seismic character above the Crimson Marker from semi-continuous to chaotic reflections (Fig. 4.54). This chaotic, gullied pattern may reflect rapid deposition of tuffs in a delta slope setting subjected to currents deflected around the cone.

The water depth map at the top of this sequence is shown in Figure 4.55.

4.6 Structural evolution

4.6.1 Late Proterozoic to Early Cambrian

The eastern margin of the Pan-African fold belt passes offshore in the central part of the Lüderitz Arch. Here on the Namibian Platform, the base of the fold belt linking the Damaran and Gariep arms has been mapped at depth (Fig. 4.21). It may extend west, below the seismic data, to a root zone or suture beneath the rifted basin. This is now beneath the outer continental margin of southern Africa or South America. If so, a salient of deep pre-Pan-African crystalline basement extends west beneath the Karoo and "Atlantic" rift

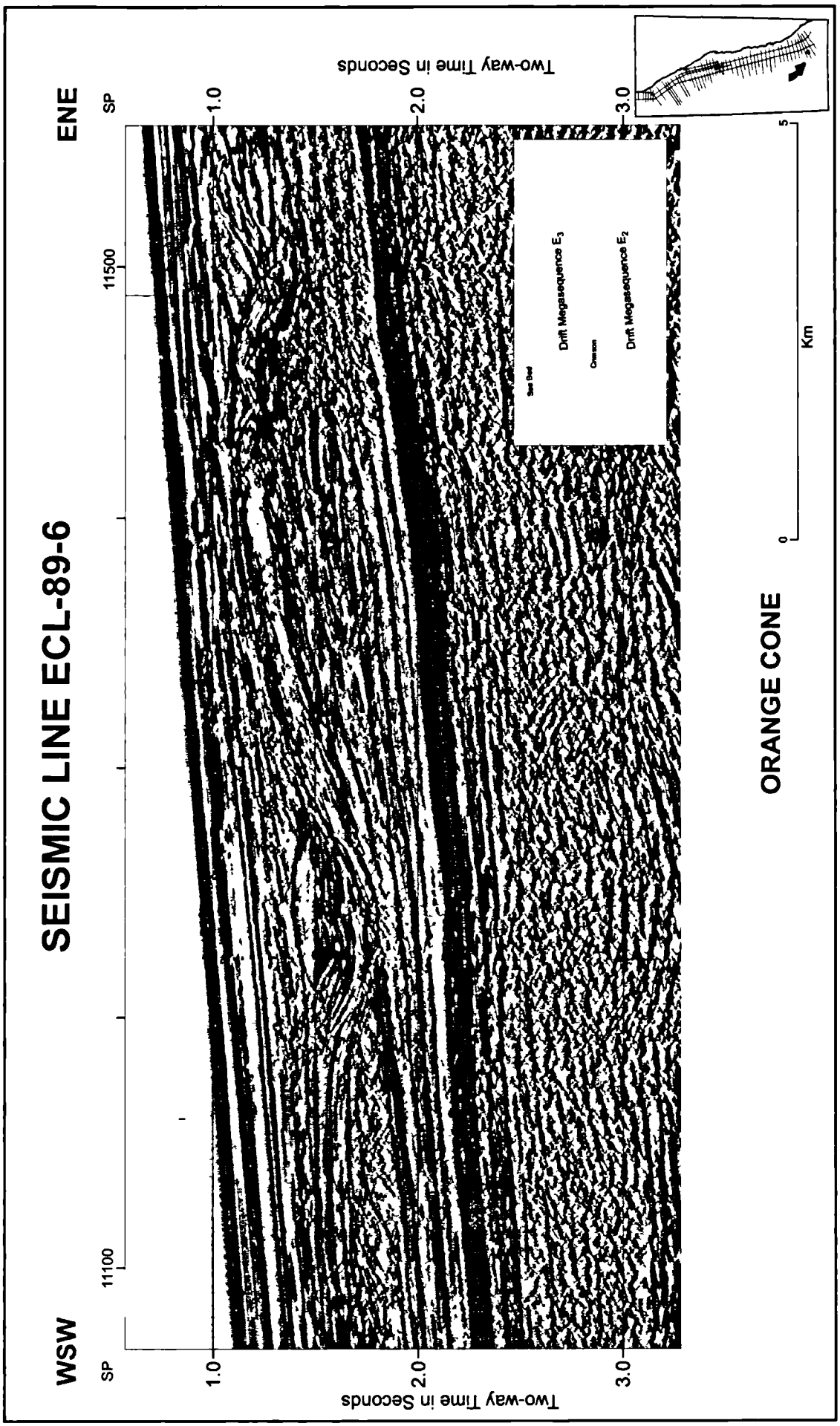


Figure 4.51 Seismic section of contourites in the Tertiary of the Drift megasequence

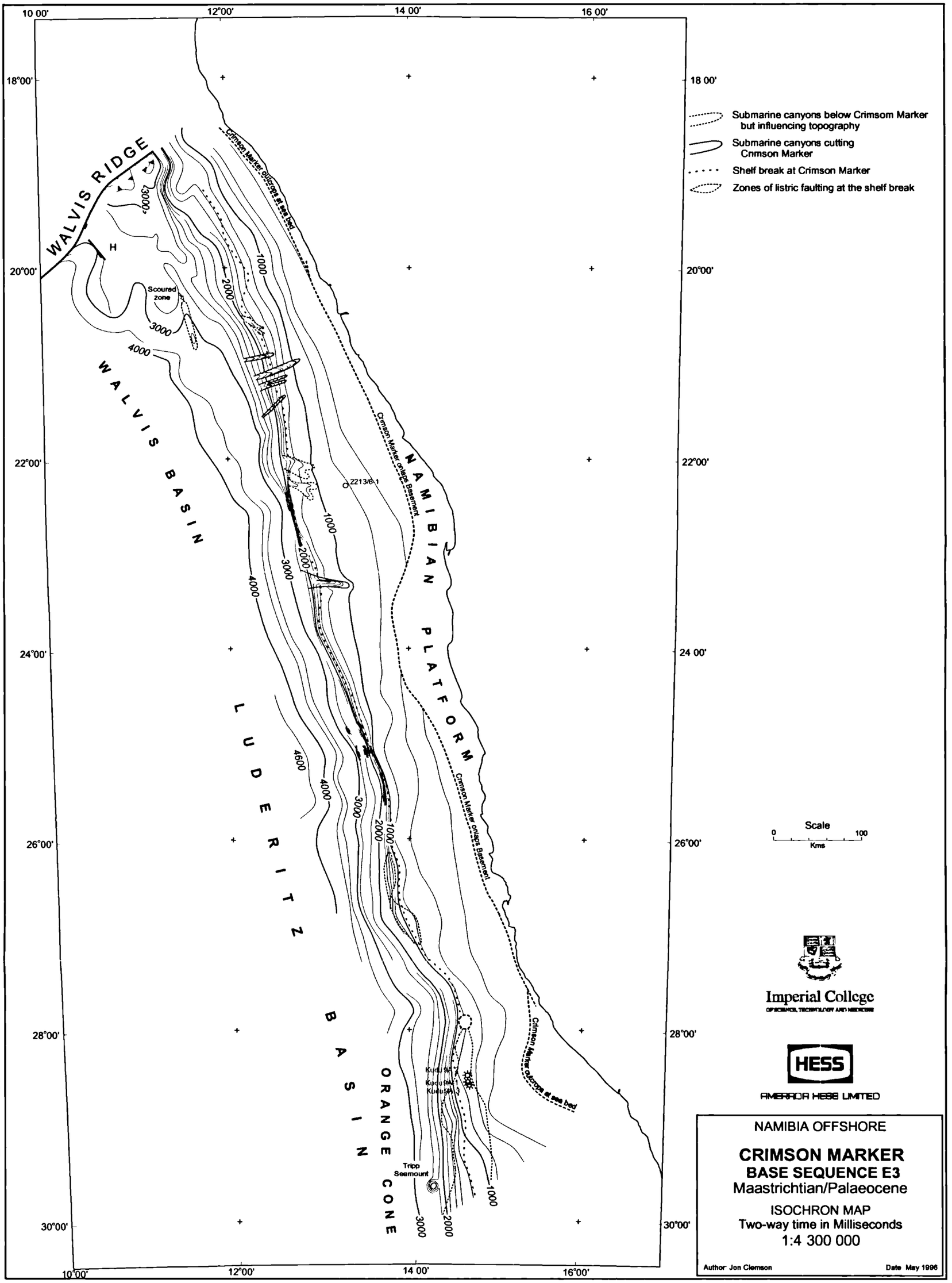


Figure 4.52 Offshore Namibia - isochron map of the base of Sequence E_3 (Crimson Marker)

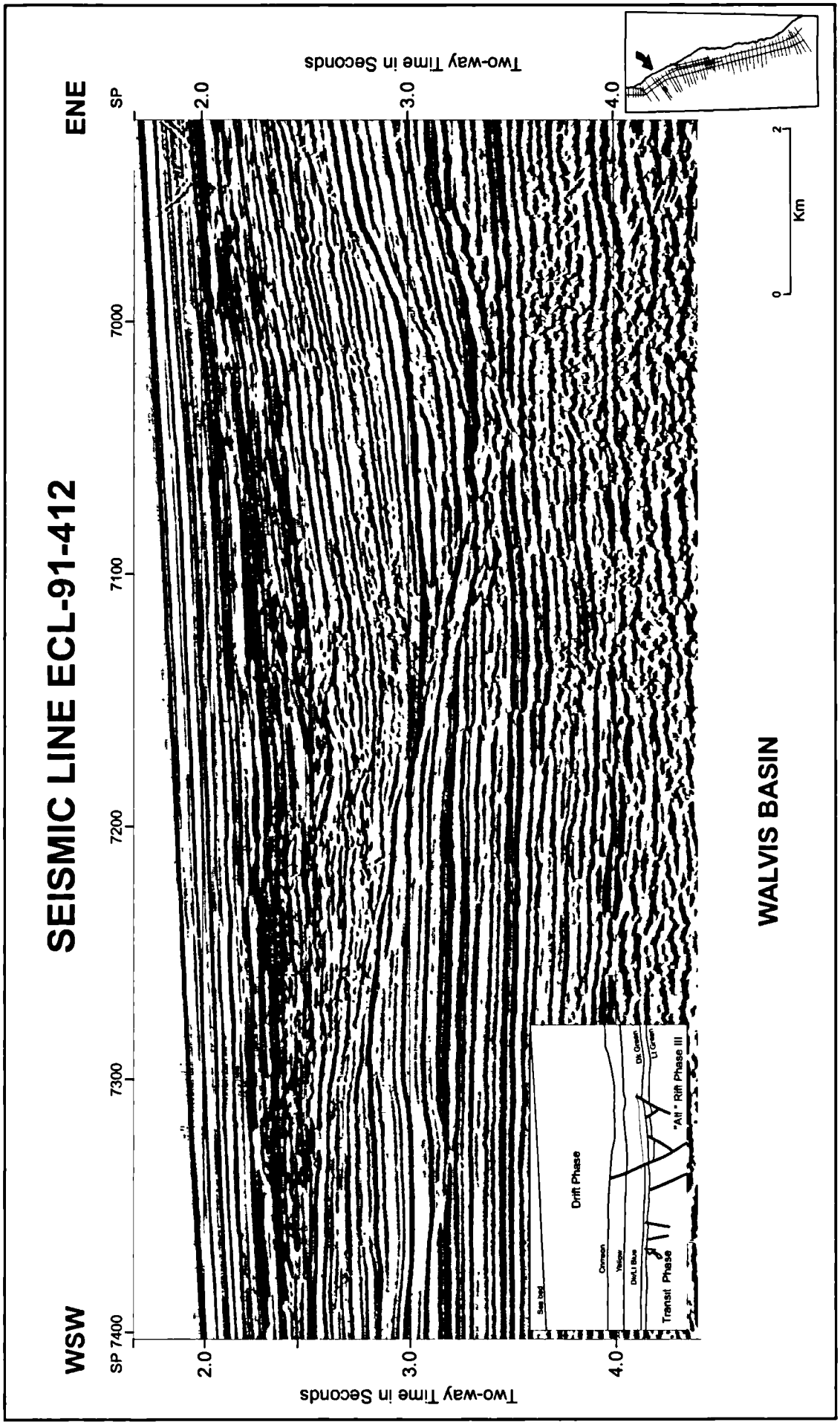


Figure 4.53 Seismic section of deep water, coast-parallel submarine erosion

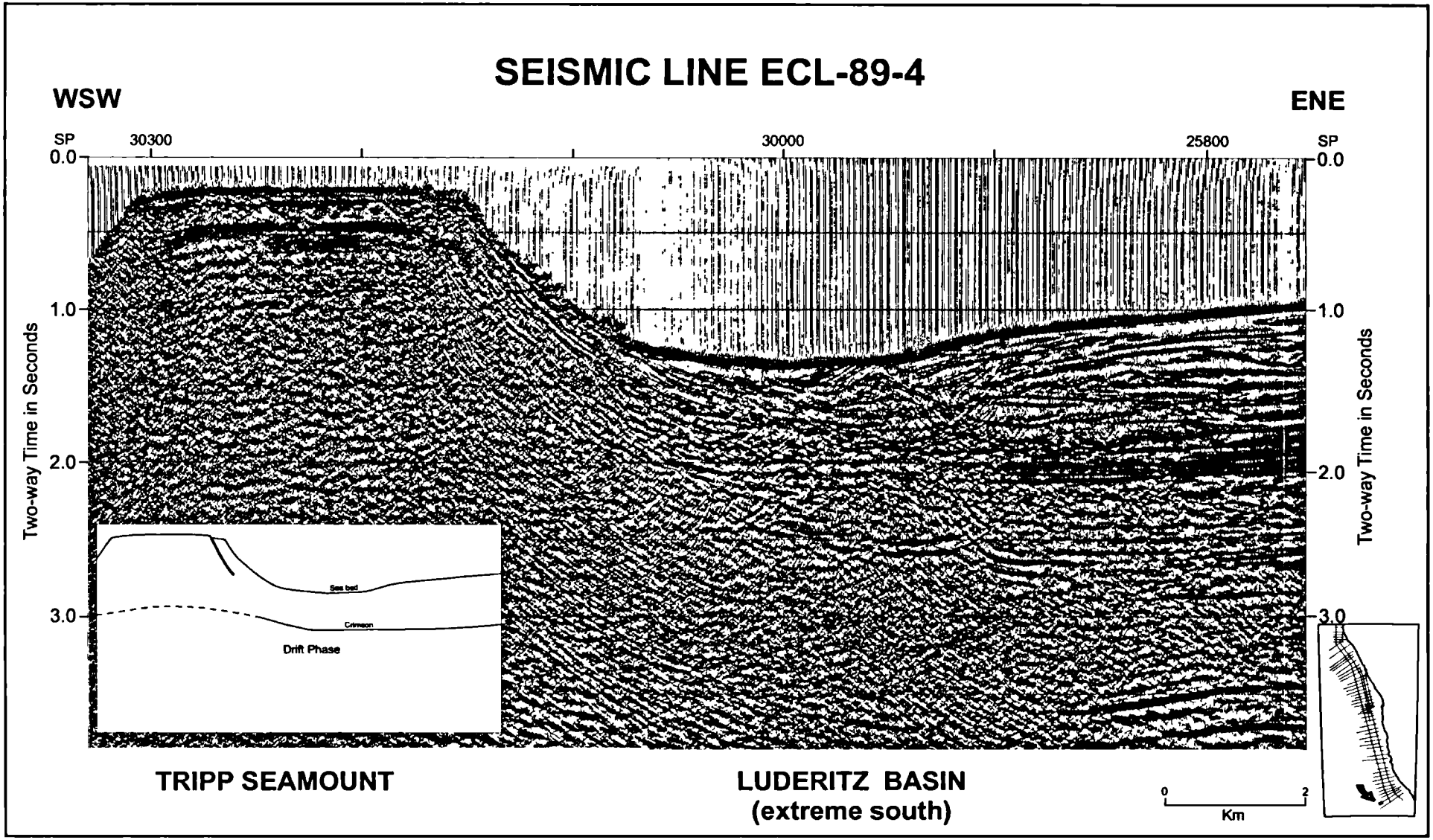


Figure 4.54 Seismic section of the eastern flank of the Tripp Seamount

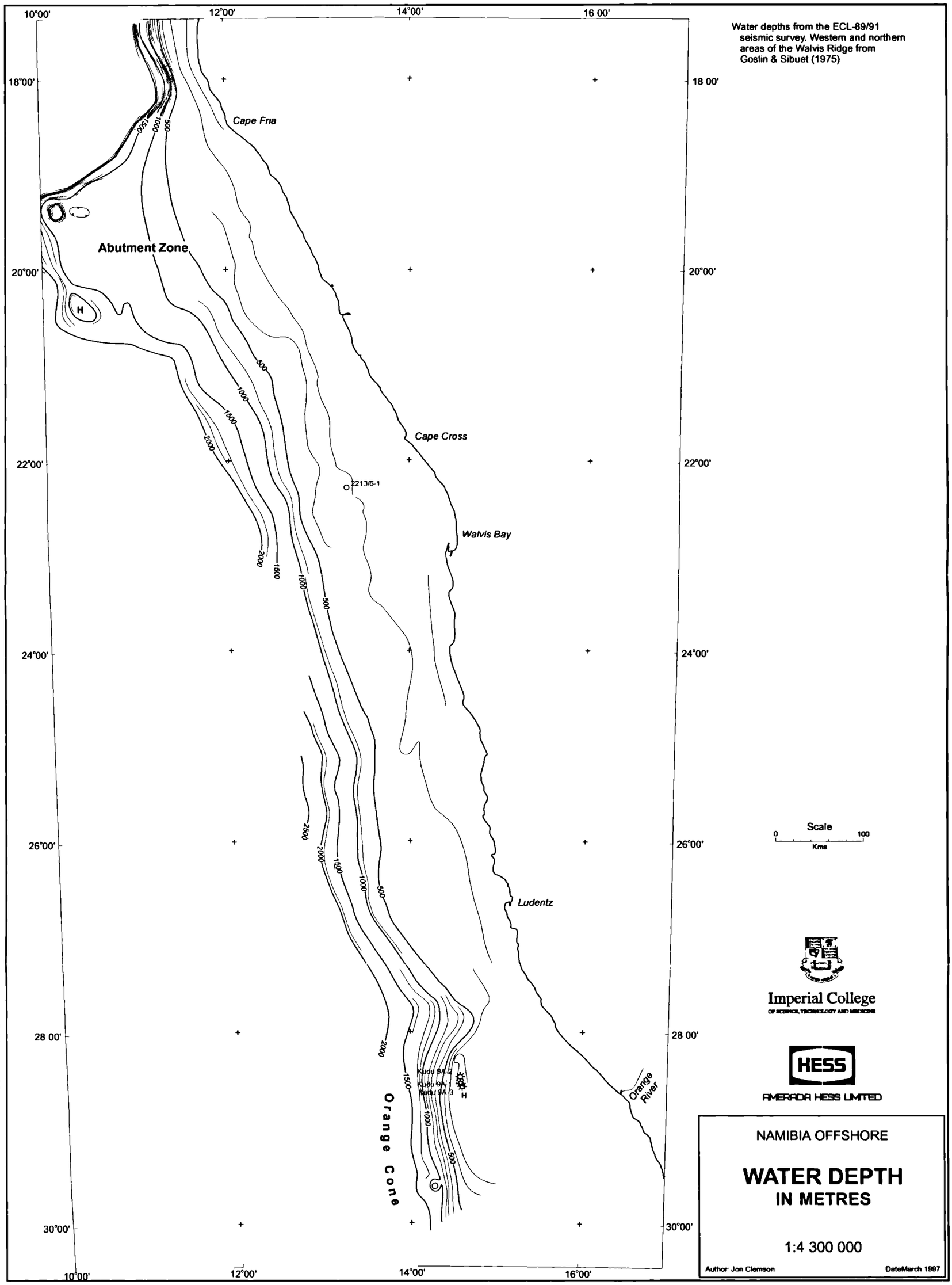


Figure 4.55 Offshore Namibia - water depth in metres

systems and may have influenced their geometries.

The junction of the Damara and Kaoko arms of the Pan-African Fold Belt occurs offshore in the Cape Cross area. Here, the two structural domains are separated by the Autseib Lineament (*Chapters 5 & 6*). This and other basement lineaments exerted an important influence on subsequent Karoo rifting.

4.6.2 Permian to Middle Jurassic (Karoo Rift and Post-Rift Phases)

Extensional tectonics preceding the break-up of East and West Gondwanaland began as early as the Permo-Triassic (Lambiase 1989). Light *et al.* (1993) describe Triassic to Mid-Jurassic rifting with Karoo sedimentation along the western margin of southern Africa. A rift phase of Permian to Early Triassic age is favoured (see *Chapter 3*).

The Karoo along the Namibian passive margin is clearly divisible into two areas, offset in the Walvis Bay area (Fig. 4.19). In the Walvis Basin it is very thick and faulted. Here, it exceeds 3.5 seconds (TWT) (8-9 km) and reaches 5.0 seconds (TWT) (10-12 km) in the Swakop Basin. The western limit is not identifiable. It is thinner in the Lüderitz Basin but may locally reach 2.0 seconds (TWT) (4-5 km). In some areas, its western margin is identifiable as an erosional pinch-out. It is also less faulted than in the Walvis Basin and many of the faults post-date the Karoo (Fig. 4.18, shotpoints 1000-2000).

The faulted area of thick preserved Karoo in the Walvis Basin is here called the Namib Rift. Whether the preserved Karoo to the south are the preserved remnants of a southern rift extension largely removed by uplift and erosion is not clear. The complex zone separating these areas is the Cape Cross Segment Boundary Zone and is discussed in *Chapter 6*.

Is the faulting in the Namib Rift Karoo in age or was it faulting associated with "Atlantic" rifting?

i) The data quality precludes the identification of fault-controlled sedimentation. This is verified in the Hyena Back-basin where unequivocal Cretaceous fault-controlled sedimentation seen on the ROL93 94 datasets (*Chapter 5*) is not identifiable on ECL-89 91 datasets. There is, however, some thickening towards major Karoo faults

(Fig. 4.23, shotpoint 2200; Fig. 4.56, shotpoint 4700) that may indicate growth-faulting. Thick fault-controlled sequences in the South Lucano Basin of South America show little thickening towards faults over a distance of 12 km (Fig. 10 of Milani and Davison 1988).

ii) Inversion on some of these faults is indicated by increasingly steep dips of rollovers into the fault plane (Fig. 4.13, shotpoints 200-600; Fig. 5.15, shotpoints 600-700; Figs 6.12 and 6.13a & b, shotpoints 6500-7600). In some cases the faults do not cut "Atlantic" rift megasequence or upper Karoo sediments, indicating that they existed by Mid-Triassic times.

iii) If the major faults that bound very thick Karoo intervals are "Atlantic" rift faults, the complete removal of an enormous thickness of "Atlantic" rift sediments exceeding the preserved Karoo interval has to be invoked. There is no evidence for large-scale uplift or erosion of the "Atlantic" rift interval, or deposition of the consequent sediments. Large amounts of uplift did occur in neighbouring onshore areas (Brown 1992) but this happened during the Drift Phase. An almost complete Drift sequence is preserved offshore.

These factors strongly suggest that most faulting in the Namib Rift is early Karoo in age.

There is evidence for rift segmentation and changes in the polarity of faulting in the Walvis Basin which is akin to rift segmentation of the East African Rifts (Bosworth 1985, Chorowitz 1989, Morley *et al.* 1990, Nelson *et al.* 1992, Gawthorpe and Hurst 1993). Unfortunately, this can only be seen along the east of the rift system. To the west, the Karoo interval quickly plunges deep beneath the "Atlantic" rift sequence and passes beneath the base of the seismic data. In the north of the Walvis Basin, the Karoo thickens west away from the crest of tilted fault blocks (Fig. 4.46). In central-southern parts of the basin, major faults are west-dipping and the east of the rift system is fault-bounded for 120 km by the Unjab Fault (Fig. 4.13). Nearby, the Koigab Fault Zone is a major west-dipping intra-grabenal fault (see *Chapter 5*)

The change in fault polarity between these two rift segments occurs near the mouth of the Unjab River (20° 20'S). There is also a structural nose at the base of the Karoo (Fig. 4.12) that may be the accommodation zone separating the two segments. The western boundary fault of the northern segment is not visible. Two changes in trend of "Atlantic" Rift Phase

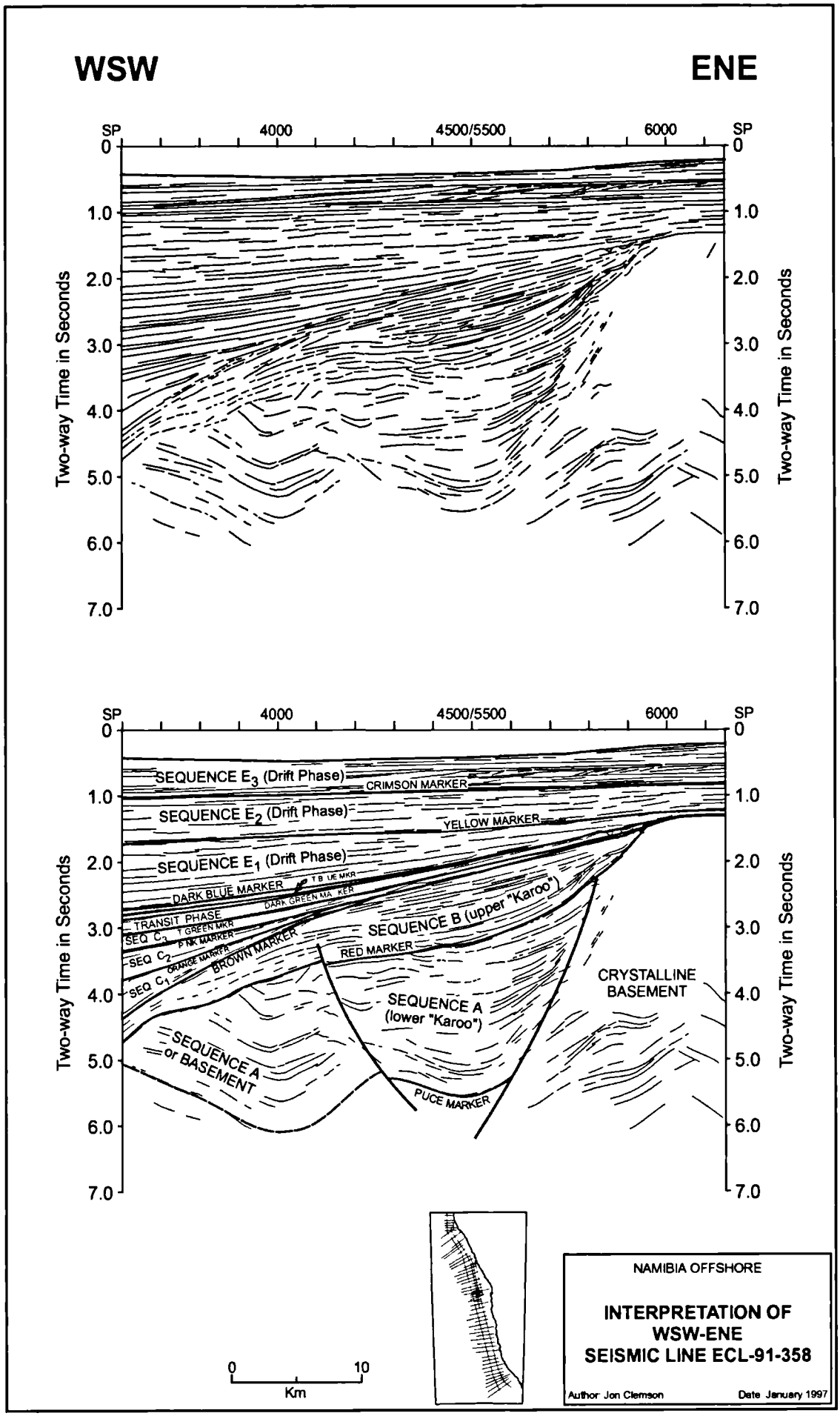


Figure 4.56 Interpreted line drawing of WSW-ENE oriented seismic line ECL-91-358

faulting at 20 S and 21 S occur in the west of the Walvis Basin. These separate the faults into three sets of arcuate faults (Figs 4.27, 4.57). The "Atlantic" faulting may have been conditioned by underlying Karoo rift structures. If so, it suggests the presence of a segmented, arcuate western boundary fault system (Fig. 4.17).

The Cape Cross Segment Boundary Zone may form a fourth southern segment. Although much of Megasequence A has been eroded in the east of this area, there is no evidence for a faulted eastern margin. NNE-SSW-oriented faults of the "Atlantic" Rift Phase in the Walvis Basin (Fig. 4.27) may reflect the trend of a western boundary fault for this segment.

These rift segments are 110-150 km long and 80-130 km across and widen to the south of the Walvis Basin. Their size is similar to the Suez Rift segments which are comparable in width and up to 140 km long (Colletta *et al.* 1988). If all the Karoo rifting is confined to these rift segments, then it is narrower than the "Atlantic" rift system. Sequence C_2 extends at least 30 km west of the Karoo rift in the Walvis Basin.

4.6.3 "Atlantic" Rift Phase

The evolution of this rift phase that led to the break-up of West Gondwanaland is illustrated in Figure 4.58.

4.6.3.1 The onset of rifting

To confine the age of rifting, stratigraphic data from neighbouring, structurally linked and better controlled basins have to be utilised. The Outeniqua Basin of South Africa was generated during movements along the Falklands-Agulhas fracture zone. Consequently, initial subsidence here should be coeval with subsidence in the orthogonally-extending rift north of the fracture zone. The published earliest rift sediments of the Outeniqua Basin are tentatively dated as Bathonian (Dingle *et al.* 1983). The Middle Jurassic (173-161 Ma) Hoachanas basalts (Gidskehaug *et al.* 1975 in Dingle *et al.* 1983) may be a volcanic episode associated with the start of rifting. Extensive volcanism also occurred in Argentina at this time (Zambrano and Urien 1974).

Figure 4.57 Segmentation of the Namib Rift - here restored to end rift times in the Early Triassic

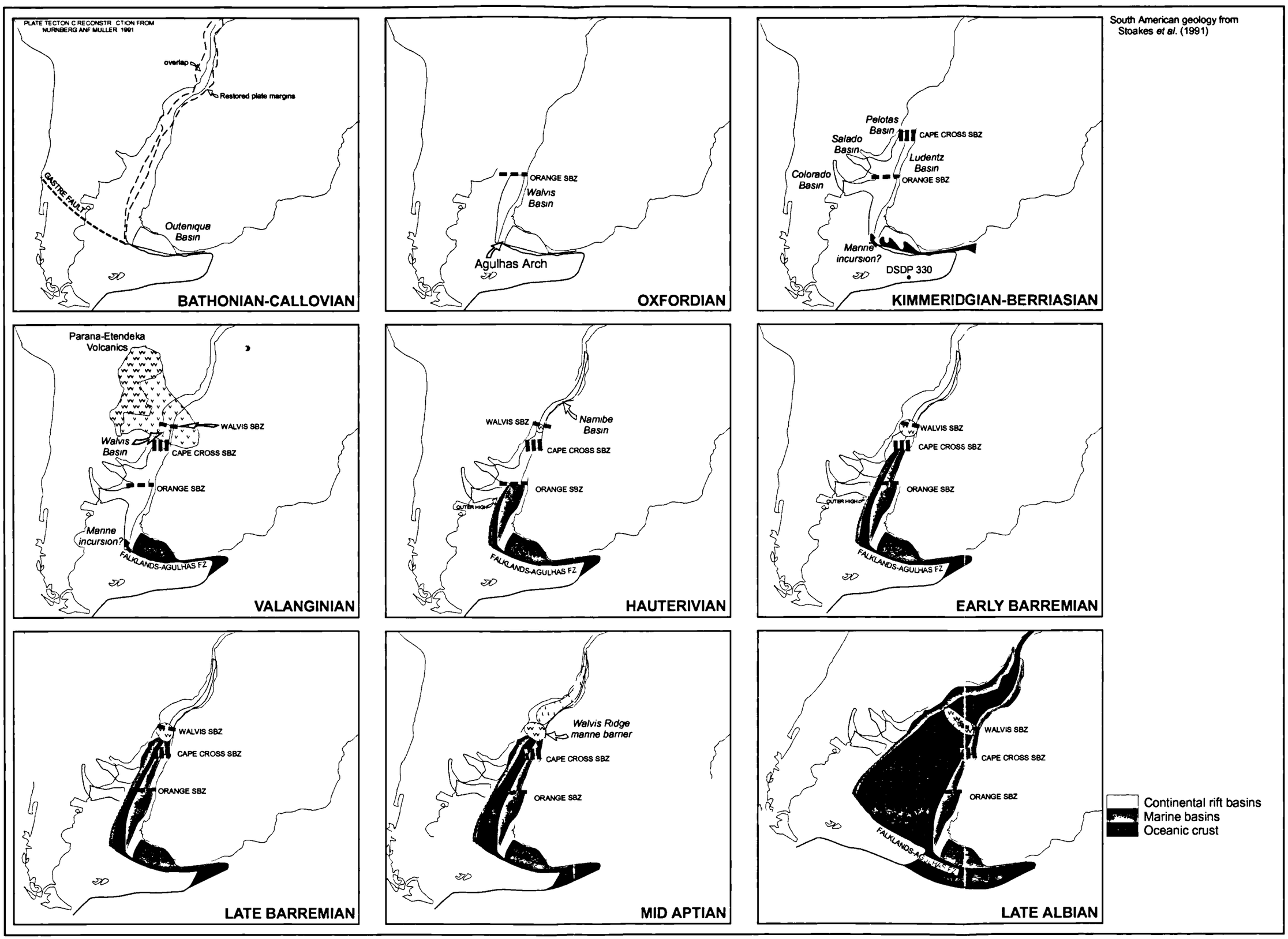


Fig. 4.58 Evolution of rifting and break-up of West Gondwanaland

Gerrard and Smith (1982) date the onset of rifting on the South Atlantic margin as Kimmeridgian and assign earlier sediments to an intracratonic stage. Their rift-onset reflector (Horizon 'T') is the equivalent to the Orange Marker identified in this thesis in the Lüderitz Basin. There is clearly evidence for rifting beneath this horizon. Light *et al.* (1992) see the rift-onset reflector on the Namibian margin as Oxfordian-Kimmeridgian in age. However, an earlier basal rift unconformity, the Brown Marker (Fig. 4.26) extending up to the Cape Cross Segment Boundary Zone, is identified here. In Block 2213A in the Cape Cross Segment Boundary Zone, a seismic facies in the uppermost part of the upper Karoo is interpreted as a volcanic sequence. It is tentatively correlated with the Middle Jurassic Hoachanas basalts. If this is so, initial rift sedimentation is Middle to Late Callovian at the earliest. Given the looseness of constraints for the onset of rifting in the Lüderitz Basin, a tentative date at the Oxfordian-Kimmeridgian boundary (154.1 Ma) is adopted.

If the Brown Marker is the rift-onset unconformity, then the Orange Marker is a lesser, but still important, marker. This is an syn-rift marker in the Lüderitz Basin but is the rift-onset marker in the Walvis Basin. It lies at the base of the reflective seismic package, Sequence C_2. This is interpreted as the Etendeka flood basalts (135-132 Ma) (Milner *et al.* 1995b) extruded in the earliest rifting in the Walvis Basin and is therefore mid-Valanginian in age.

4.6.3.2 Syn-rift unconformities

In the Bredasdorp Basin (part of the Outeniqua Basin off South Africa), van der Merwe and Fouché (1992) identify at least one phase of structural inversion during rifting. They ascribe this to stress build-up in plates adjacent to the Falkland - Agulhas fracture zone and stress release during periods of movement on this zone. Their alternative model suggests that inversion is due to small vector changes caused by a shift of the rotation poles of plate motions resulting in localised compression and extension.

The only possible evident compression or wrenching during the "Atlantic" Rift Phase in the Lüderitz and Walvis Basins is confined to segment boundary zones. It is interpreted as the result of regional stress perturbations accummulated at segment boundary zones during rifting (see *Chapter 6*). This appears to eliminate their latter model suggesting small changes in plate motion as the mechanism. The former model invokes fluctuations in plate

motion that would also be manifest in the adjacent orthogonally-rifting basins. Rather than outright compression along the Namibian continental margin, these fluctuations could result in pauses in extension and the development of the unconformities.

The Brown Marker can only be identified in the Lüderitz Basin and north to the extreme south of the Walvis Basin (Fig. 4.26). The Orange Marker (Fig. 4.27) defines the onset of rifting in the Walvis Basin. Therefore, an initial interval, Sequence C_1, can be identified in the south that is absent further north. This indicates that rifting propagated north. If so, the onset of rifting may have been still earlier in the Orange Basin and closer in age to initial rifting in the Outeniqua Basin (see above and *Chapter 6*).

4.6.3.3 The break-up unconformity

On passive margins, this unconformity is also known as the rift-drift or drift onset unconformity in a wide variety of literature. It is, as the name suggests, important in any passive margin history. For many years it has been identified as the final parting of a rifted landmass and associated with the onset of thermal subsidence and marine transgression (Falvey 1974). With realisation that break-up may not be contemporaneous along a passive margin came the realisation that the break-up unconformity may be diachronous.

The diachronous break-up of the southwest African margin has been recognised since Rabinowitz and LaBrecque (1979) identified magnetic anomalies. They saw oldest normal oceanic crust as the M11 magnetic anomaly south of the Orange River and the M4 from the Orange River to Walvis Bay. Rabinowitz and LaBrecque (1979) placed the continent-ocean boundary landwards near their 'G' anomaly. Austin and Upuchi (1982) and Austin and Divins (1986) modified the eastern boundary of the oldest normal oceanic crust located west of the Orange Basin to the M9 magnetic anomaly (Fig. 4.59). They interpreted crust to the east of this anomaly as continental crust. Other workers (Dingle 1979, Smith 1980 *in* Gerrard and Smith 1982, Austin and Upuchi 1982) subsequently place it well west of the continental slope. Gerrard and Smith (1982) defined the continent-ocean boundary with the change in reflectivity below the break-up unconformity from parabolic refractions to structured reflections. This lies slightly west of the M9 and M4 magnetic anomalies (Fig. 4.59), whereas the velocity study of Austin and Divins (1986) position it at these

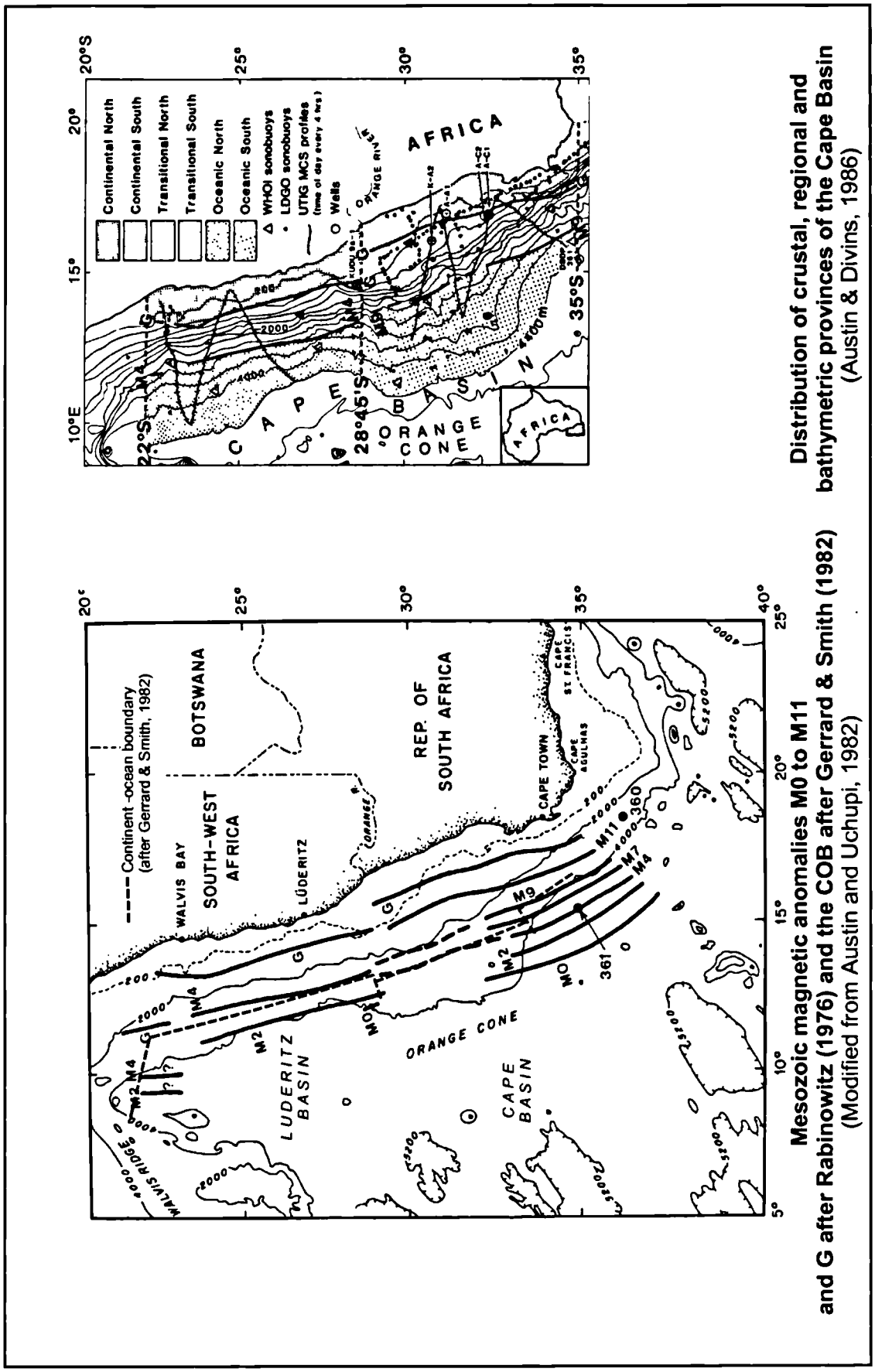


Figure 4.59 Early interpretations of the continent-ocean boundary (COB). Rabinowitz (1976) places the COB at Anomaly G; Austin & Uchupi (1982), Gerrard & Smith (1982) and Austin and Divins (1986) place the COB at the Anomaly M9 (Cape Basin) and Anomaly M4 (Luderitz Basin)

anomalies. More recently, Gladczenko *et al.* (in press) see the change in reflectivity below the break-up unconformity, as described by Gerrard and Smith (1982), as the eastern limit of normal oceanic crust generated by seafloor spreading. This tectono-magmatic break-up and initiation of seafloor spreading marks the break-up unconformity.

Gladczenko *et al.* (in press) interpret the western margin of thinned continental crust to lie beneath the wedge of seaward dipping reflectors. They also modify the eastern limit of normal oceanic crust on the Walvis Ridge Abutment Plateau. They continue it NNW contrary to the abrupt change to WNW by Gerrard and Smith (1982) (Fig. 4.59). The seismic data used in this thesis does not record rugose reflections typical of normal oceanic crust, and so it is concluded that the eastern limit of normal oceanic crust lies west of this data. Talwani *et al.* (1995) review the recognition of magnetic anomalies of normal oceanic crust and the magnetic imaging of horizontally layered seaward dipping reflector wedges.

The regional and local data examined in this thesis does not require any modification of the magnetic anomalies identified off southwest Africa south of Walvis Bay. Their chronology is determined from the time scale of Gradstein *et al.* (1994). However, this time scale lacks an M4 magnetic chronozone. The M4 magnetic anomaly is put at the boundary of the M3 and M5 magnetic chronozones. There is uncertainty in the identification of the magnetic anomalies in the Walvis Basin (see below).

Gerrard and Smith (1982), in their review of the southwest African passive margin, date the age of the break-up unconformity as Valanginian (using the time-scale of van Hinte 1976). They also accept that it may young from south to north. Light *et al.* (1992,1993) and Maslanyj (1993) (no time-scale quoted) partition the Namibian passive margin into two segments with Hauterivian and Valanginian break-up in the south and north respectively. This thesis recognises different ages of break-up in the Orange, Luderitz and Walvis Basins.

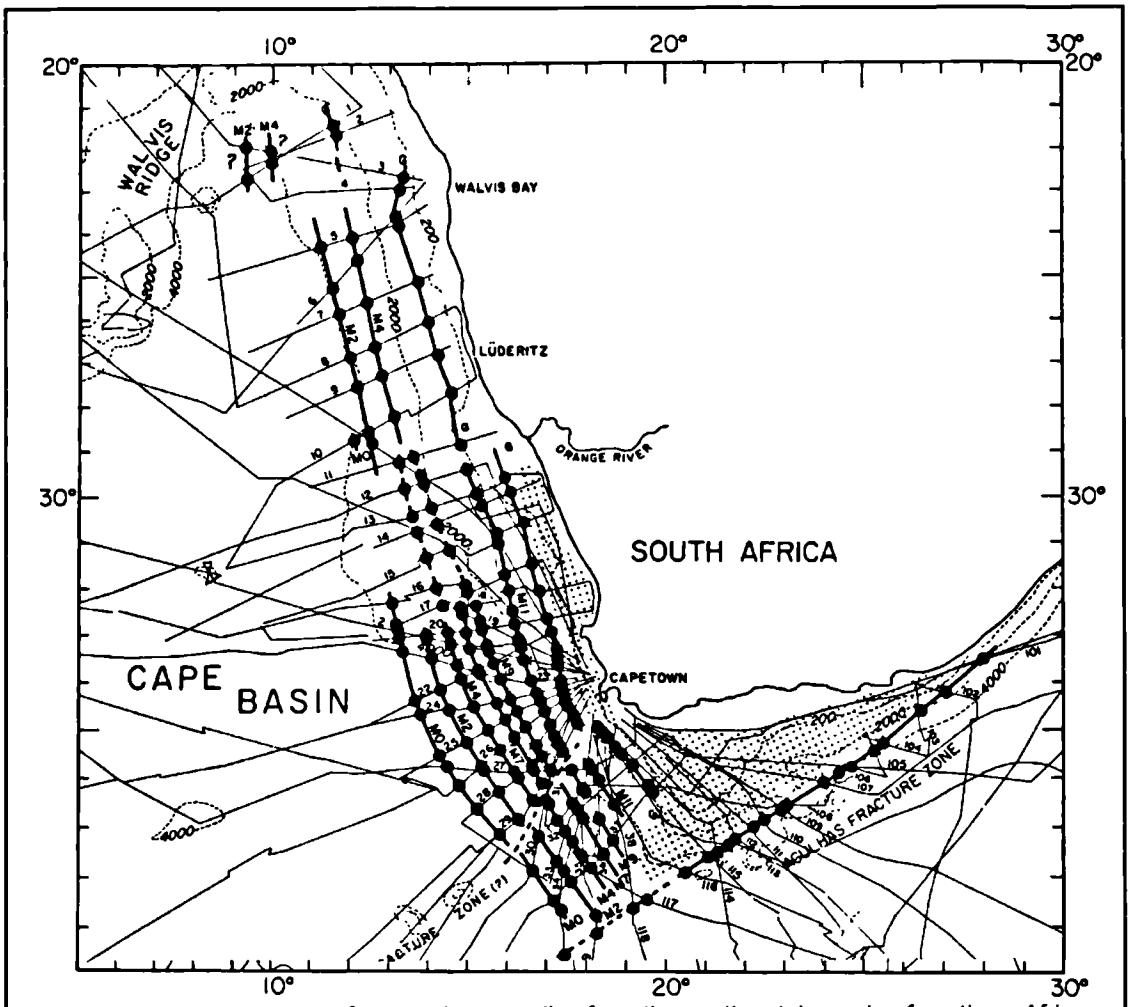
Just south of the studied area, Muntingh and Brown (1993) date the break-up unconformity as Late Hauterivian in the Orange Basin (based on the time-scale of Haq 1988). This accords with the mid-Hauterivian age of the M9 magnetic anomaly (Gradstein *et al.* 1994) offshore from this basin.

The youngest oceanic crust adjacent to the Lüderitz Basin is earliest Barremian in age, based on identification of the M4 magnetic anomaly. Transitional Phase sediments in the Kudu wells comprise marine sands and silts above terrestrial volcanics and subaerial sands. The marine sediments are Late Barremian in age (McMillan 1990). An Early Barremian age of break-up in the Lüderitz Basin is favoured.

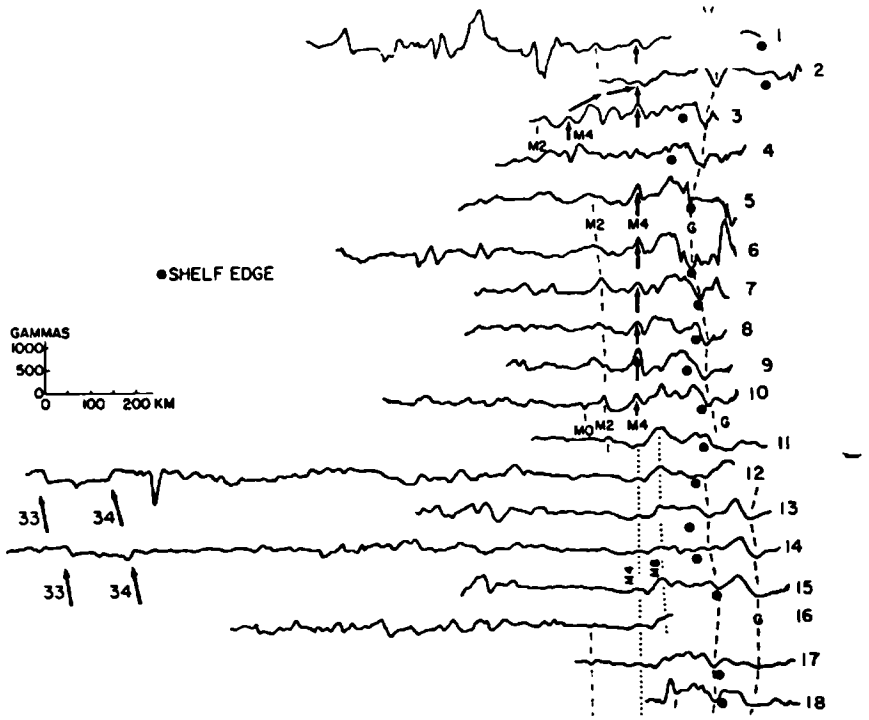
The age of break-up is less clear in the Walvis Basin. There is no well control and there is uncertainty in the identification of the magnetic anomalies in this basin. Re-examination of Rabinowitz and LaBrecque's (1979) profiles shows the uncertainty of any correlation in the Walvis Basin (Fig. 4.60). The age of break-up in the Walvis Basin lies between break-up of the Lüderitz Basin (Early Barremian) and the Namibe Basin (Late Aptian). A Late Barremian break-up age (*c.* 123 Ma) is preferred.

4.6.3.4 Rift Phase I - Sequence C_1

Early "Atlantic" rifting extended from the Falkland-Agulhas fracture zone north across the Paraná-Karoo basins to the Cape Cross area. This is akin to North Sea rifting in Zechstein times cutting across the Permian foreland basin, albeit *from* the Cape Fold Belt as opposed to *towards* the Hercynides. This provided a marine pathway into the Zechstein sea from the proto-North Atlantic many hundreds of miles to the north. A similar situation would allow restricted marine black shales like the Oxfordian-Kimmeridgian shales found in DSDP 330 on the Falklands Plateau (Barker *et al.* 1976 *in* Dingle 1983) to accumulate in a confined rift basin off Namibia. Therefore, the presence of marine sediments at an early stage in the "Atlantic" rift history cannot be excluded. Major marine sedimentation commenced in the Outeniqua Basin in Kimmeridgian times (Malan *et al.* 1990 *in* Fouché *et al.* 1992). This basin is located further west than the pre-drift location of DSDP 330 (Fig. 4.58) and towards the Atlantic rift margin. If rifting had commenced by Kimmeridgian times, a marine incursion may have occurred in the Orange and possibly the Lüderitz Basins (Fig. 4.58).



Data control and location of magnetic anomalies from the continental margin of southern Africa



Magnetic anomalies off southwest Africa

Fig. 4.60 Magnetic anomalies off southwest Africa (modified from Rabinowitz and LaBrecque 1979)

4.6.3.5 Rift Phase II - Sequence C_2

This high energy package is interpreted as extensive volcanics and correlated with the Etendeka flood basalts, erupted at an early stage of rifting in the Walvis Basin. Rifting was already under way in the Lüderitz Basin. In these two basins there is a significant difference in their respective thickness, with Sequence C_2 being over twice as thick in the Lüderitz Basin (Fig. 4.28). This is interpreted to represent differences in rates of rifting and tectonic subsidence. This assumes that the basins were not sediment-starved during subsidence, an interpretation that is consistent with the high continuity of syn-rift reflections and lack of internal onlaps. The Etendeka continental flood basalts extended right across the rift from the Paraná Basin to Namibia and were therefore subaerial in the Walvis Basin. If so, the prevailing topography must have initially been subdued. The flood basalts must also have more than kept up with subsidence as they are not confined to the basin. The west-diverging reflections do attest that some subsidence did occur. There is little evidence for syn-sedimentary thickening of volcanics into faults, except in the far south of the Walvis Basin.

Subsidence was clearly greater in the Lüderitz Basin where there is a much thicker sequence and divergence of internal reflections (Figs 4.30, 4.33). However, no basalts remain on the Namibian landmass adjacent to the Lüderitz Basin, if they were there at all. Greater subsidence in the Lüderitz Basin may have confined them to the basin. The less reflective character of Sequence C_2 in the Lüderitz Basin suggests that they form a minor part of Sequence C_2 and may be more distal from the eruptive source.

Onshore to the east of the Walvis Basin, the north-south Ambrosius Berg Fault Zone bisects the main outcrop of the Etendeka flood basalts (see *Chapter 3*). Most fault activity post-dates the lavas (Milner 1986). The Etendeka Formation has been eroded from the onshore coastal strip excepting 20°30'-21°00'S. It is presumably eroded in shallow inshore waters between the seismic database and the coast. Further offshore in the east of the Walvis Basin, Sequence C_2 usually pinches out by erosion beneath the break-up or Lower Aptian unconformities (Fig. 4.15, shotpoint 9300). The history of the Ambrosius Berg Fault Zone accords with the subsidence history of the Walvis Basin, where some rifting occurred in Rift Phase II but most occurred in Rift Phase III. This fault zone dips to the west, converse

to most faulting in the Walvis Basin. It can therefore be seen as bounding the east of a graben initiated in Rift Phase II, but becoming highly asymmetric in Rift Phase III.

Relationship of the Etendeka-Paraná flood basalts with the seaward-dipping reflectors

The Etendeka and Paraná flood basalt provinces, described in *Chapter 3,* are generally accepted as sharing a common geochemistry and provenance (for a recent correlation see Milner *et al.* 1995a). Their geochemical and stratigraphic relationship also suggests that they were the same eruptive body that has since been disrupted by continental break-up and drift to their present positions. This leads to the question: what is their stratigraphic position in relation to the "Atlantic" rift sequence and the seaward-dipping reflectors?

The flood basalts either:

a) preceded rifting,

b) occurred during early rifting or

c) occurred very late in rifting and just before the seaward-dipping reflectors.

These possible relationships are schematically illustrated in Figure 4.61.

a) If they preceded rifting, a parallel reflective sequence would be evident if preserved. This is not seen, although it can be argued that it was removed by pre-rift thermal doming associated with the Tristan hot spot. Older dating of the Etendeka-Paraná flood basalts suggests that eruption of the flood basalts occurred over a protracted period of 18 m.y. using K-Ar dating (Gidskehaug *et al.* 1975) or 10 m.y. (Turner *et al.* 1994). A protracted period allows scope for eruption and erosion of the flood basalts, the subsequent production of seaward-dipping reflectors and the onset of drift. However, recent $^{40}Ar/^{40}Ar$ chronology and magnetostratigraphy (Renne *et al.* 1996) carried out on 800m of lavas in the southern Etendeka province concluded that they were erupted over a short duration of 133-131 Ma. This closely agrees with an age of *c.* 135-132 Ma by Milner *et al.* (1995b). There are problems inherent in relating absolute ages to magnetostratigraphic ages, but this suggests that the Etendeka flood basalts (135-132 Ma) preceded the formation of normal oceanic crust in the Lüderitz Basin (M4, 127 Ma) by 5 m.y. The age of normal oceanic crust adjacent to the Walvis Basin is more problematic (see *Section 4.6.3.3*). The age adopted in this thesis (123 Ma) (see above) post-dates the

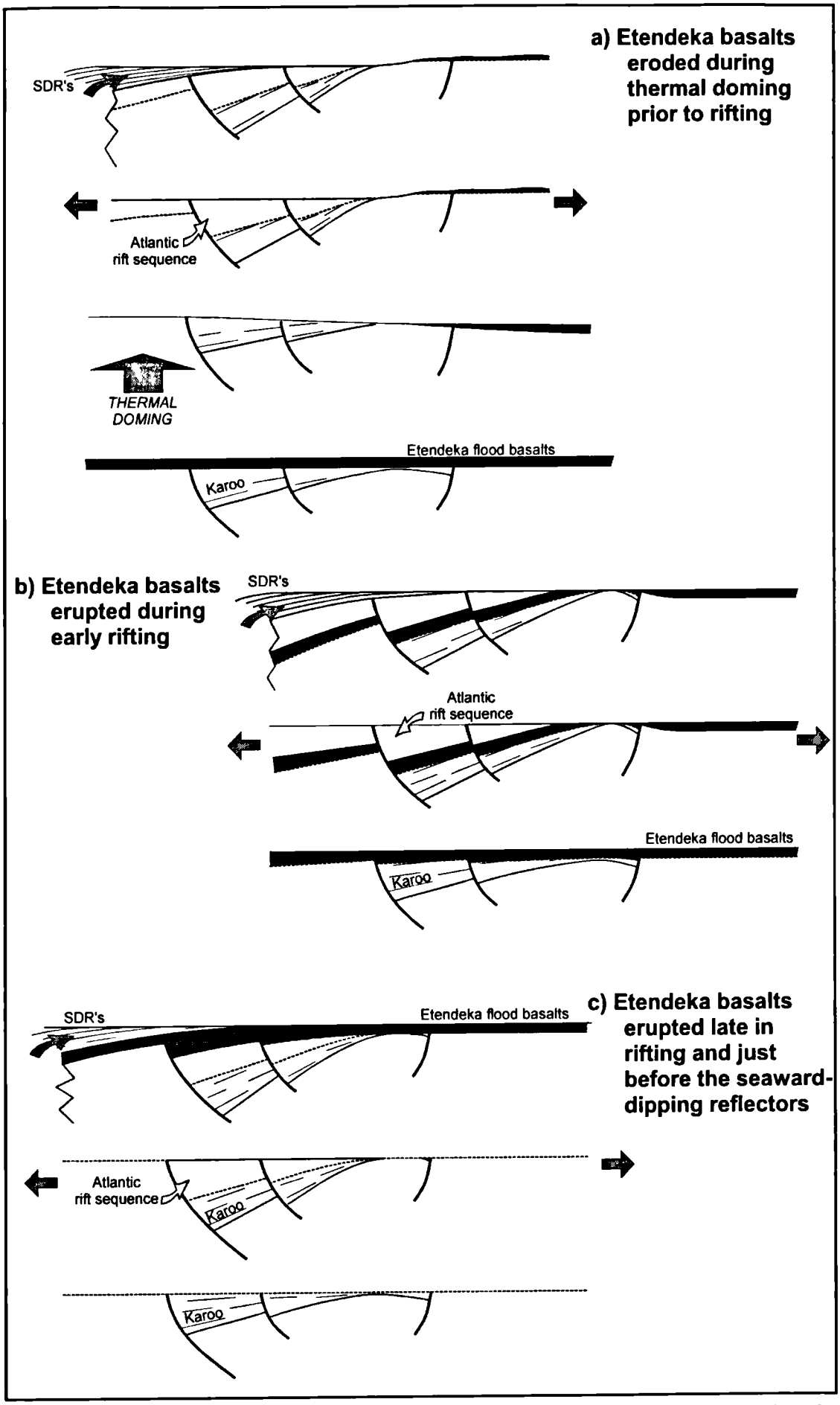


Figure 4.61 Possible relationships between the Etendeka flood basalts and "Atlantic" rifting

Etendeka flood basalts by 8 m.y. The Norwegian seaward-dipping reflectors were produced over 3 m.y. (Skogseid and Eldholm 1989) and extend 100 km west from thinned continental crust (Skogseid 1994). Gladczenko *et al.*, (in press) propose a similar width in Namibia and so a comparable timespan of 3 m.y. can be envisaged. This allows a somewhat short duration of approximately 8 m.y. for erosion of the flood basalts, rifting and subsidence, and break-up. On the Norwegian Vøring volcanic margin, Skogseid *et al.* (1992) recognise about 18 m.y. of lithospheric extension before continental break-up.

b) The seismic character of a reflective Sequence C_1 (Fig. 4.9 and *Section 4.5.3.2*) is interpreted to represent volcanics. If so, their extent, gently diverging reflections and reflection continuity suggests basalt lavas erupted in early rifting. Sequence C_2 thickens westwards to reach 1.0 seconds (TWT) (*c.* 2.5 km). It pinches out by erosion along the eastern flank of the Walvis Basin. Onshore, preserved Etendeka lavas are up to 880m or *c.* 0.35 seconds (TWT) thick (Milner *et al.* 1992). The original stratigraphic thickness is unknown but they are estimated to have been up to 2.0 km thick (Reuning and Martin 1957). The relationship between the Etendeka Formation and the Ambrosius Berg Fault Zone can be correlated with the offshore structural history (see *Section 4.6.3.5*). Minor faulting in Rift Phase II/Etendeka Formation times became much greater in Rift Phase III and ultimately resulted in a highly asymmetric graben - the Walvis Basin. Subsequent end-rift erosion in the east preserved the western portion as a deep half-graben.

c) If they were erupted very late in rifting and just before the seaward-dipping reflectors, they would have had to flood across an active rift, resulting in a strongly diverging, reflective seismic package at the top of Sequence C_3. In the central part of the Walvis Basin, the uppermost part of Sequence C_3 is reflective but thins and pinches out to the east. Here, the upper part of Sequence C_3 is uniformly poorly reflective; a divergent reflective package cannot be identified. It is difficult to conceive a link from the reflective Sequence C_3 in the west, particularly across the poorly reflective areas in the east to the Etendeka Formation onshore, and hence this option is considered unlikely.

These arguments support b) where it is most likely that the Etendeka flood basalts were erupted at an early stage of rifting.

4.6.3.6 Rift Phase III - Sequence C_3

This sequence differs in thickness between the Lüderitz and Walvis Basins - but in contrast to Sequence C_2, it is more than twice as thick in the Walvis Basin. Like Sequence C_2, it may reflect differences in subsidence and sedimentation and suggests that the Walvis Basin was the more actively subsiding basin during Rift Phase III. This indicates a south to north diachroneity of major rifting.

The less reflective seismic character, prevalent in the lower part and east of Sequence C_3 is interpreted as a return to non-volcanic sedimentation. In the south of the Walvis Basin, there is evidence for convergent onlap onto the Pink Marker in Sequence C_3 (see *Chapter 5*). Some early basin starvation may therefore have occurred. This poorly reflective seismic facies is interpreted as a lacustrine sedimentary setting (see below). There is little evidence for convergent onlap in the less subsident Lüderitz Basin.

The more reflective west-thickening wedge in the upper part and in the west of Sequence C_3 is interpreted as the seaward-dipping reflectors of thickened oceanic crust (Fig. 4.15, shotpoints 1-2000). Hinz (1981), Austin and Upuchi (1982), and Gerrard and Smith (1982) all interpret wedges of seaward-dipping reflectors, not only in offshore Namibia but also the Orange Basin. They are present for 1750 km along the southwest African passive margin. Seaward-dipping reflectors have therefore been identified outside the 2500 km diameter plume head proposed for the Tristan hot spot (White and McKenzie 1989). They may therefore be symptomatic of the type of rifting and break-up rather than result from the presence of a hot spot (see *Chapter 6*).

The abrupt character change at the time of break-up is interpreted as the initial marine transgression creating a restricted Atlantic Ocean. It is regarded as the break-up unconformity south of the Walvis Ridge. Whether this was coeval in the Lüderitz and Walvis Basins cannot, at present, be proven. However, there is indirect evidence that it may have been later in the Walvis Basin (*Section 4.6.3.3*).

Light *et al.* (1992) date the break-up unconformity as Valanginian (Horizon 'R') in the Lüderitz Basin but later, in the Hauterivian (Horizon 'Q'), in the Walvis Basin. Light *et al.* (1992) show Horizon 'R' plunging down in the Walvis Basin to coincide with their Horizon 'T' (= Orange Marker) at the base of the rift sequence (Fig. 4.62). This implies that rifting had *ceased* in the Lüderitz Basin before it was *initiated* in the Walvis Basin. In this thesis, the break-up unconformity, the Light Green Marker (Horizon 'R' in the Lüderitz Basin) is interpreted as remaining above the syn-rift wedge in the Walvis Basin. The Pink Marker of this thesis is interpreted as equivalent to their Horizon 'R' in the south of the Walvis Basin. Rifting was possibly initiated in the Lüderitz basin in the Oxfordian/Kimmeridgian and in Valanginian times in the Walvis Basin. The Light Green Marker marking the break-up unconformity may be diachronous between the Lüderitz and Walvis Basins (*Section 4.6.3.3*). These factors strongly suggest that rift initiation and break-up frame an overlapping rift history in the Lüderitz and Walvis Basins.

The sedimentary wedge of Sequence C_3 was deposited in a confined basin prior to the seaward-dipping reflector sequence. It is interpreted as thickening west into a fault-bounded half-graben. This fault is not discernible in the Walvis Basin and is either below the displayed depth of the seismic data, or continental break-up disrupted the half-graben to leave the bounding fault on the rifted margin conjugate to the Walvis Basin. Late rift half-grabens in the Lüderitz Basin are bound on their west by large faults. In this segment of the Namibian passive margin the footwalls remain, at least in part, on the eastern conjugate passive margin.

The vertical display of the seismic data does not allow the western limit of thinned continental crust to be defined. The western part of the seaward dipping-reflector wedge is interpreted as thickened oceanic crust. This wedge exceeds 4.0 seconds (TWT) (*c.* 11 km) in the north of the Walvis Basin. Seaward-dipping reflector wedges up to 15 km thick have been documented off the eastern seaboard of the United States (Talwani *et al.* 1995).

The Outer High

The Outer High was initially defined by Gerrard and Smith (1982) as a 'marginal ridge' elevated 500-1500m above the regional 'drift onset' or break-up unconformity. Schuepbach

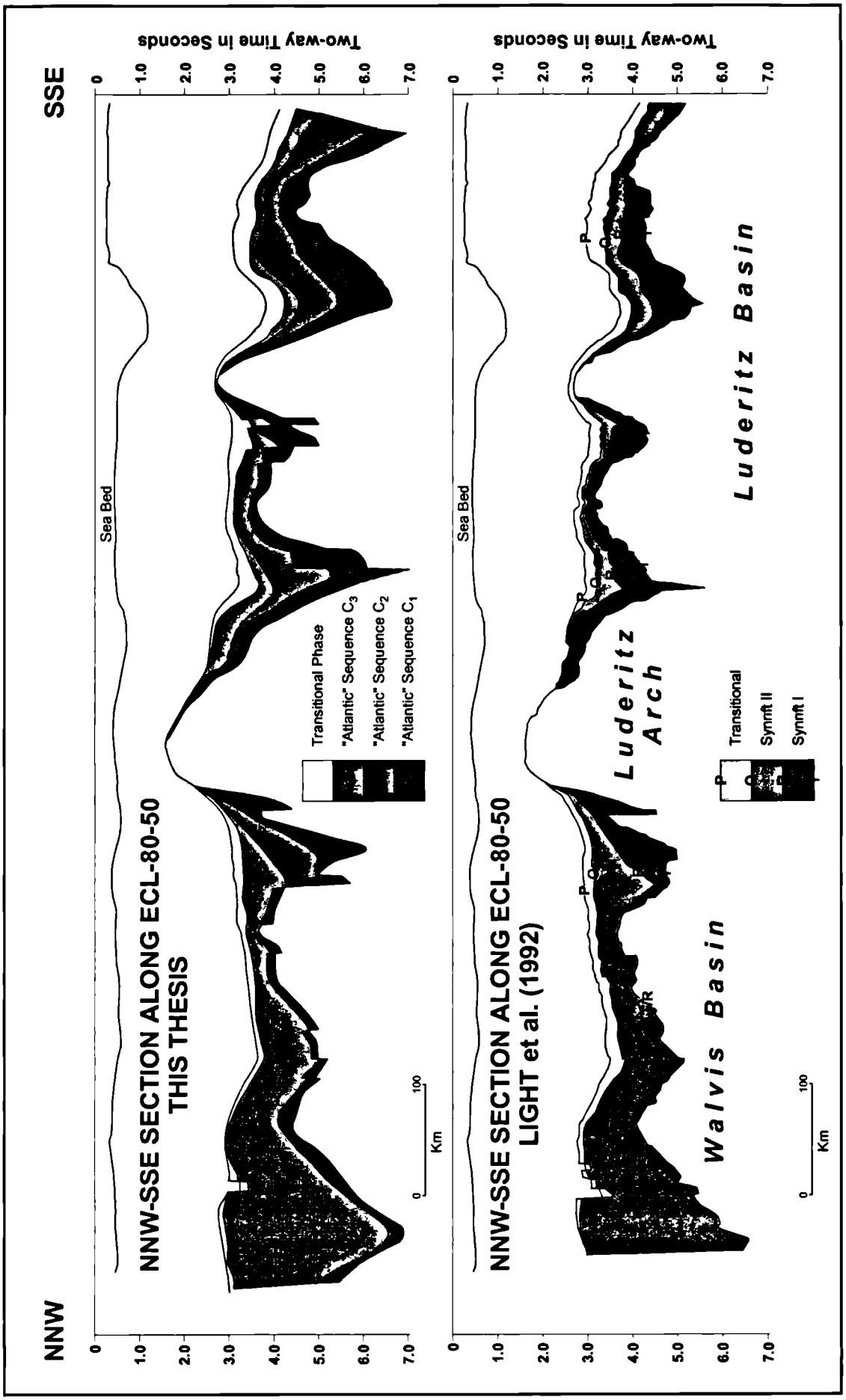


Figure 4.62 Comparison of tne interpretation of this thesis with the interpretation of Light et al. *(1992)*

and Vail (1980) interpret outer highs as comprising rifted continental crust beneath the break-up unconformity at the continent-ocean boundary. Examples studied by Schuepbach and Vail (1980) are often on non-volcanic margins. In the Walvis Basin, the Outer High lies close to the continent-ocean boundary (Gladczenko *et al.* in press) but above several kilometres of seaward-dipping reflectors. In comparison, on the Norwegian Vøring volcanic margin, Skogseid (1994) identifies maximum subsidence as *c.* 100 km east of the continent-ocean boundary and leading to an outer high. This occurred at the time of break-up. The Namibian Outer High was in existence by the end of the "Atlantic" Rift Phase; there is a subtle onlap of the overlying Transitional Phase reflections onto the landward side of the Outer High (e.g. Figs 4.13, 4.33).

Schuepbach and Vail (1980) proposed that a thermo-mechanical event immediately precedes the formation of oceanic crust. Skogseid (1994) proposed magmatic underplating associated with outer highs, a purely mechanical cause. Eldholm and Grue (1994) preferred the term 'lower crustal high-velocity body (LCB)'. They questioned whether magmatic underplating takes place when crust is highly attenuated, i.e. at a late rift stage. Crustal strength becomes negligible due to breakdown of the assumption of convective transfer when the massive mafic upwelling reaches the brittle crust (Dixon *et al.* 1989 in Eldholm and Grue 1994). They see it as a mix of cumulate gabbro and ultramafics emplaced at the base of the crust at transient break-up. The high degree of volcanism evident on the Namibian passive margin supports Skogseid (1994) and Eldholm and Grue (1994) rather than the non-volcanic mechanism proposed by Schuepbach and Vail (1980). The cause was clearly a permanent change in crustal structure as it is a permanent feature. A thermal cause may therefore be eliminated.

Outer highs are believed to have been uplifted at a late stage of rifting (Schuepbach and Vail 1980, Skogseid 1994). This appears to be so on the Namibian passive margin (Fig. 4.33, shotpoints 1-1300). Small-scale but pervasive faulting over the Outer High (Fig. 4.15, shotpoints 1-1000) postdates the creation of the high and continental break-up. This shallow faulting appears to lie above a neutral surface, as though the Outer High was flexed. The junction between thickened and normal oceanic crust is not seen on the ECL-89/91 datasets but lies west of the studied area. This flexing may indicate coupling between adjacent thickened and normal oceanic crust during early thermal subsidence. In contrast,

the faulted continent-ocean boundary of the Orange Basin (Gerrard and Smith 1982) may suggest some decoupling occurred there. The differences may be due to the proximity of the Tristan hot-spot to the Walvis Basin.

During Rift Phase III the Outer High developed in the extreme west, possibly during production of seaward dipping-reflectors. Fully developed seaward dipping-reflectors have been interpreted as entirely subaerial lavas flowing from an axial high (Mutter *et al.* 1982). Landwards towards the pinch-out, volcanics may have become subordinate to sediments as it is more distal from the extrusive source, and progressively became more so through time. On the Vøring Plateau continental margin by comparison, volcanics are interpreted as building up some 900m above sea level (Skogseid and Eldholm 1989). There, ODP Site 642 drilled through a sequence of subaerially-emplaced basalts (Eldholm, Theide and Taylor *et al.* 1989). Additionally, White and McKenzie (1989) model that, under certain thermal conditions and degrees of stretching, uplift of the extended margin may occur. In the South Atlantic, this can provide the potential for an elongate basin initially confined between the rift margin and an upthrown Outer High and later, the wedge of seaward-dipping reflectors. The sedimentary setting is unclear but the stronger and more continuous reflections may be highstands in a lacustrine or restricted marine environment. The poorly reflective seismic character suggests that there are no evaporite layers, so a lacustrine setting is favoured.

4.6.4 Transitional Phase - Megasequence D

This period in the post-rift history of the Namibian passive margin is called the Transitional Phase, but why so? In general, the post-rift history of passive margins is one of thermal subsidence with deepening waters offshore and marine transgression of shelf areas. On the Namibian passive margin, the break-up unconformity at the base of the Transitional Phase marks this initial transgression. However, the Transitional Phase is a regressive/aggradational period with the development of a shelf break in some localities. This period is coeval with the early stages of thermal cooling, perhaps when the effects of the thermal anomaly beneath the thinned crust are still felt. Regressive intervals are also compounded by high rates of erosion along the rift margin, akin to the Red Sea stage of margin development (Falvey 1974). Ensuing transgression following the significant Early

Aptian lowstand (112 Ma of Haq *et al.* 1988) shut off sediment input and drowned the subdued rift margin landscape. Regressive sequences are also evident in the Drift Phase, but they progressively back-step to the rift margin as thermal cooling exerted a strong influence on subsidence.

The base of this interval (Fig. 4.34) marks the Barremian marine transgression at the beginning of thermal subsidence. The Kudu wells did not reach the base of this interval. However they did encounter aeolian sands and alkali lavas close to TD. These are succeeded by marine sandstones and shales of Late Barremian age (McMillan 1990).

The top of this sequence, the Dark Green Marker (Fig. 4.40), is the deepest seismic reflector calibrated with the Kudu wells. Here, it is dated as Late Barremian/Early Aptian (McMillan 1990). An Early Aptian age is favoured since that agrees with the '13Atl' reflector of Muntingh and Brown (1994) separating lower and upper Drift sequences in the Orange Basin. In the wells, it is not marked by any significant log break but lies close to a change in sedimentary environment that may be linked to a major transgressive event. It marks a change from outer shelf to deeper, poorly oxygenated waters (McMillan 1990).

A string of extrusive volcanics up to 0.8 seconds (TWT) (*c.*2000m) thick is evident in the west of the Lüderitz Basin (Fig. 4.38). These are part of a series of local extrusives post-dating the Etendeka flood basalts and seaward-dipping reflectors. The Kudu wells penetrate up to 72m of subaerial high-magnesium alkali basalts (Wickens and McLachlan 1990) in Megasequence D.

There is evidence for early west-directed progradation in the Transitional Phase that subsequently dominates the post-rift sequence. It is particularly evident in the south of the Walvis Basin in the Cape Cross Segment Boundary Zone, and in the south of the Lüderitz Basin (Fig. 4.38). In the Cape Cross Segment Boundary Zone, the lowstand prograding wedge pinches out in the east and increases in thickness across the shelf to 0.4 seconds (TWT) at the shelf break. There must have been moderate water depths in the order of 250-300 metres west of the shelf break. There is also evidence for low-angle progradation west into the Lüderitz Basin.

These examples of west-directed lowstand progradation both occur west of what were to become two important drainage systems. They may be most prominent because of increased sediment input from these systems. At this early post-rift stage, their catchment areas will have been limited and confined to coastal highlands of the rift shoulder (Rust and Summerfield 1990). These early-established depocentres suggest that the young rivers exploited pre-existing weaknesses and so became the dominant drainage systems early in the post-rift history.

In the Cape Cross Segment Boundary Zone, the eastern rift margin comprised Karoo sediments. The Autseib or Omaruru Lineaments were potential weaknesses to be exploited where they influenced Karoo structure. The presence of thick Transitional Phase sediments in this area may be more than coincidental. This early exploitation was enhanced by exploitation of NE-SW Damaran trends when the drainage system had cut back beyond the prevailing Karoo outcrop. This drainage system was to become the Huab and Swakop rivers. The Huab river is quite linear, following NE-SW Damaran trends until it approaches the Lower Cretaceous Brandberg high level intrusion. This had been intruded during the "Atlantic" rifting (135-125 Ma) (Watkins *et al.* 1995 in press, *in* Milner *et al.* 1995b). Unroofing may have led to the diversion of the proto-Huab river around the north of the intrusion. It may have originally crossed the coast in the Cape Cross area and entered the nascent South Atlantic *via* the Autseib Lineament in the Jackal Embayment. In southern Namibia, the proto-Orange River may have initially exploited weaknesses created by the Orange Segment Boundary Zone (Dingle *et al.*, 1983). When the drainage system had cut back to the Pan-African basement, the Kuboos-Bremen lineament was available for exploitation.

4.6.5 Drift Phase - Megasequence E

The Drift Phase structural history of the Namibian passive margin was initially dominated by thermal subsidence and sediment loading. Later in this phase, residual thermal subsidence was secondary to sediment loading. Stacked prograding sequences built up at the shelf break from sediments brought from the African interior and worked across the shelf. Subsidence interacting with sediment supply and eustatic sea level changes led to major sequences allowing the subdivision of Megasequence E.

4.6.5.1 Sequence E_1

The long-lasting Orange Cone was established at this time - all subsequent sequences show thick sediments off the Orange River mouth. This is earlier than the Coniacian as suggested by Rust and Summerfield (1990). The Kudu wells are located in a prodelta to base of slope setting of the Orange Cone. In the basin, the seismic character typifies turbidite deposition. Slope fan sedimentation and mounding are also evident.

In the northeast of the Lüderitz Basin, the higher frequency and amplitude of seismic reflections suggests a different sedimentary facies than seen further south. This may possibly be deposition on a carbonate rather than a clastic shelf. Lenticular bodies suggest carbonate build-ups. This possible carbonate shelf has also been modified by submarine erosion early in the Drift Phase (Fig. 4.18 and Fig. 4.29, shotpoints 900-1400).

The mid-Aptian Walvis Igneous Centre is the sole significant evidence for volcanics at this time. It pre-dates the Skeleton Rift (see *Chapter 6*). By now, the influence of the Tristan hot spot had become confined to the oceanic sector of the Walvis Ridge.

The Skeleton Rift was created in mid-Aptian times. Extension appears to have been over a very short geological time in a marine setting. Most reflections strongly onlap the composite Light/Blue Markers at the base of the rift. There are no divergent reflections typical of a syn-rift sequence. Although faults cut the Turonian Yellow Marker, much of this movement is compactional (Fig. 4.48, shotpoints 300-900). This rift is considered here to have developed as a response to extension north of the Walvis Ridge inducing sinistral wrenching along the Walvis Segment Boundary Zone. At this time normal oceanic crust had been created west of the Walvis Basin where "Atlantic" rifting had ceased. This wrenching imposed renewed extension on the northern part of the Walvis Basin. This short-lived episode ceased when oceanic crust was created north of the Walvis Ridge. Between the Light/Dark Blue to Yellow markers (mid-Aptian-Turonian), the β factor was 1.15.

4.6.5.2 Sequence E_2

The Late Cretaceous is regarded as a period of high global sea level with maximum flooding in the Turonian and Campanian and a gentle decline thereafter (Haq *et al.* 1988). Continental shelves were transgressed, sediment input was reduced and carbonate production was high. Passive continental margins were particularly subject to transgressive sedimentation. At this time, a major stage of shelf aggradation and outbuilding occurred on the Namibian passive margin. This had begun in post-Aptian times in the Orange Cone and Lüderitz and Walvis Basins. However, the Turonian flooding event that is clearly evident in the Lüderitz Basin did not apparently occur in the Walvis Basin.

Brown (1992), applying apatite fission track analysis, identifies three discrete phases of enhanced denudation for onshore southern Africa. Peak denudation rates occur at *c.* 130±10 Ma, *c.* 90±10 Ma and *c.* 70±10 Ma. These are not common to any one location. The 130 Ma peak is interpreted to be confined to the southwest African rift margin. The 90 Ma peak is confined to areas in the extreme south of the Lüderitz Basin, in and south of the Orange Basin and extending into the continental interior. The 70 Ma peak was felt in two southwest African areas inshore from the Lüderitz Basin (Karasberg) and Walvis Basin (Damara Fold Belt), isolated by a stable Lüderitz Arch. These findings only agree to a limited extent with the Namibian offshore stratigraphy.

Onshore from the southernmost Lüderitz Basin where areas subjected to peak denudation at 90 and 70 Ma overlap, these findings in general agree with the offshore stratigraphic history. Rust and Summerfield (1990) used both seismic isopach and well data to determine the sedimentation history of southwest Africa and pointed out the inherent problems using point data sources for estimating rates of sedimentation. Nevertheless, in Kudu 9A-1 sediment accumulation rates attain three peaks at 120 Ma, 85 Ma and 65 Ma. Each peak occurs shortly after peaks in denudation identified in Brown's (1992) complementary study in onshore denudation. There is a time lag of 5 m.y. between Brown's (1992) peak in denudation at 90 Ma and offshore sedimentation; it coincides with the major transgression in the Turonian. In general, these peaks coincide with the major aggradational/progradational sequences in the upper part of Sequence E_1 (*c.* 115-90 Ma) and in Sequence E_2 (*c.* 90-70 Ma). These two regressive sequences and the intervening

transgression persist throughout the Lüderitz Basin, although Brown (1992) only observes the 70 Ma peak on adjacent onshore areas. The rocks which may have recorded the initial stages of uplift would have been subsequently eroded (pers. comm. K Gallagher). The 70 Ma peak can be correlated with tilting and uplift that occurred in the Late Cretaceous south of the Oystercliffs Segment Boundary Zone (Fig. 4.47) (see *Section 4.5.5.2*).

The absence of available wells in the Walvis Basin is a hindrance but general comparisons may be made. Although there have obviously been fluctuations in relative sea level, sediment progradation and aggradation dominated throughout Sequence E_1 and Sequence E_2 (Fig. 4.23) between *c.* 110 to 70 Ma. Brown (1992) identifies an important phase in onshore denudation between 80-60 Ma, well after this regressive sequence was established. Brown (1992) ascribes differences in the degree of denudation to wrench reactivation of the NE-SW Waterberg Fault and coeval normal movement of the N-S Omatako Fault. In this thesis, an Albian/Cenomanian phase of uplift is identified in the Jackal Embayment (*Chapter 5*) and Swakop Basin (*Chapter 6*). This is linked to inversion of the Waterberg Fault and local reverse movements reactivating the Omaruru Lineament. Therefore, late Early Cretaceous uplift occurred onshore and on the rift margin offshore. This event lies at the base of the major aggradational/ progradational sequence and is interpreted to have initiated the increased rates of sedimentation.

Striking Late Cretaceous listric faults dominate parts of the Lüderitz Basin. Canyon-cutting and channel incision dominate the south of the Walvis Basin and some occurs in the north of the Lüderitz Basin. Several factors appear to control the distribution of faulting and canyon-cutting. These include the relationship of Sequence E_2 to the underlying shelf break, sedimentation rates in Sequence E_2 and its lithological content, and the presence of overpressured shales.

The listric faults (Figs 4.25, 4.30, 4.42) pass down into a detachment in prodelta and delta slope clays. Most upper fault tips terminate in the upper part of Sequence E_2. Listric faulting is common where Upper Cretaceous progradation has occurred beyond the underlying clay-draped shelf break of Sequence E_1 (Fig. 4.47). This promoted instability and gravitational collapse. The main phase of listric faulting and coeval basinward thrusting occurred late in Sequence E_2, possibly in Campanian times. Listric faulting in the Walvis

Basin only occurs in the south, where there is a well-developed shelf break. Rather than downslope slip along a detachment, the rotated blocks frequently degrade into slumps deposited on the prevailing sea bed. There is no thrusting further west into the Walvis Basin.

This fundamental difference in the scale of faulting and its response to slope instability appears to have been controlled by differing lithologies. The Kudu wells, drilled in a prodelta and delta slope setting, suggest that much of the Orange Cone is clay and silt-dominated. In the south of the Walvis Basin, well 2213/6-1 drilled a sand-dominated fluvial section throughout Sequence E_2. In this basin, listric faults are confined to the steep shelf break and, unlike in the Lüderitz Basin and Orange Cone, do not extend back into the sand-dominated platform. Listric faulting may also be promoted by the development of overpressure during rapid sedimentation. This allowed faulting to extend back onto platform areas underlain by overpressured prodelta shales. Sand-dominated sections are less likely to have developed overpressure.

Sediment loading may be an important factor in triggering this listric faulting and thrusting. However, Late Cretaceous tilting south of the Oystercliffs Segment Boundary Zone may be an additional factor promoting slope instability. This uplift is mainly seen inshore (Fig. 4.47) but subtle movements of an unstable slope may have triggered slippage along the detachment.

Canyon cutting is common either side of the northern Lüderitz Arch (Fig. 4.49). This was a positive feature at this time. Canyons are absent in the northern Walvis Basin and southern Lüderitz Basin. It is notable that they are absent in the south of the Lüderitz Basin despite the presence of a well-developed shelf break. However, the Orange Cone is shale and silt-dominated in the Kudu wells. In the north of the Walvis Basin where canyons are absent, there is no well-developed shelf break and clastic input may be minor. They are absent to the west of the northern Lüderitz Arch but there, Sequence E_2 is relatively thin and the shelf break is reduced in size.

There is no evident link between fluvial channels and the canyon cutting. The mechanism by which they are produced cannot be directly linked to fluvial systems. The gently

curvilinear shelf break suggests that the Namibian shoreline was dominated by wind/current processes which reworked sediments across the shelf. The canyons appear to have been produced by slope instability. An initial slump scar may have been progressively enlarged by continued collapse of its sides and rear so that they are incised back into the shelf. Their distribution may depend on the lithology into which they are incised and the size of the available slope. The inherent instability in large sand-dominated sedimentary sections has led to canyon cutting. In shale-dominated sedimentary sections, listric faulting appears to be the major mechanism by which slope stability is restored.

Any influence of the Cape Cross Segment Boundary Zone on Sequence E_2 is passive. It isolates the Walvis Basin depocentre from a thinner sequence in the north of the Lüderitz Basin.

4.6.5.3 Sequence E_3

This final Drift sequence sees a marked reduction of sediment supply onto the shelf and periods of marine erosion. Progressive Tertiary aridification reduced sediment supply (Seisser 1978). By this time any thermal effects arising from continental rifting and breakup had almost certainly ceased. Subsidence along the passive margin was probably due to sediment loading.

Rust and Summerfield (1990) see the maximum sediment accumulation rate, expressed as bulk volume per million years, in the Palaeogene. Dingle and Robson (1992) prefer the Late Cretaceous Santonian to Maastrichtian as the period of maximum sediment supply. In the Orange Basin, Dingle and Hendey (1984) see a decline in sediment accumulation rates throughout the Tertiary balanced by a gross reduction in continental erosion rates. They argue that it is due to increasing aridity starting from the late Palaeogene. Siesser (1978) recognises weak sporadic upwelling of the Benguela Current system in Oligocene times.

4.7 Conclusions

a) Reflection seismic data has allowed the post-Pan-African sedimentary sequence of the Namibian continental margin to be divided into major tectono-stratigraphic sequences that relate to major rifting and post-rift subsidence. The Permian - Early Triassic Karoo Rift Phase was separated from the ?Oxfordian/Kimmeridgian - Barremian "Atlantic" Rift Phase by inversion, uplift and erosion. The "Atlantic" Rift Phase culminated in continental break-up and drift.

b) The Karoo Rift and Post-Rift Phases can be differentiated in the Cape Cross - Walvis Bay area and are described in detail in *Chapters 5* and *6*. Outwith this area, they are described together. The Karoo Namib Rift is identified along the Namibian continental margin from Walvis Bay to Cape Fria and broadly coincides with the "Atlantic" Rift Phase Walvis Basin. A Karoo sequence can be identified south from Walvis Bay to the Orange River, but no large-scale rifting is evident.

The Karoo rift sequence is correlated with the onshore Namibian Ecca Group in the Huab Basin and Omingonde Formation of the Etjo Outlier. The Karoo post-rift sequence correlates with the Plateau Formation. They are separated by a period of inversion, uplift and erosion correlated with a Mid-Triassic hiatus seen over much of southern Africa.

The Karoo rift in the Walvis Basin is segmented into four rift segments 110 to 15 km long and 80-130 km across. Three rift segments are interpreted to have arcuate faulted western boundaries and one is fault-bounded in the east. Their segmentation and size resemble rifts in East Africa and the Gulf of Suez.

c) The "Atlantic" rift system is broader and structurally simpler then the Karoo system. The rift fill can be subdivided into three major sequences. The initial rift sequence is confined to the Lüderitz Basin and southernmost Walvis Basin, where it dies out just north of the Cape Cross Segment Boundary Zone. Other, lesser. segment boundary zones are present in the Lüderitz Basin. The depth of this sequence precludes determination of fault patterns in the west. In the extreme southeast, reactivation of Pan-African thrusts has led to low-angle faulting during early "Atlantic" rifting. The Kudu High is interpreted to result from

movement along a reactivated thrust fault plane.

The second rift sequence extends along the entire continental margin. Rifting and subsidence were much greater in the Lüderitz Basin. This sequence is correlated with the Paraná-Etendeka flood basalts. These dominate the second rift sequence in the Walvis Basin but may be a minor constituent in the Lüderitz Basin. The volcanics flooded the entire area from the Paraná Basin to Namibia because the Walvis Basin had undergone a small degree of subsidence at this time.

The last "Atlantic" rift phase saw subsidence in both the Lüderitz and Walvis Basins, but was greater in the Walvis Basin. This rift sequence is overlain in the west by seaward-dipping reflectors. The boundary or transition zone between the extended continental crust and thickened oceanic crust is too deep to be identified on this seismic data. The Outer High is a latest rift feature found along the entire Namibian passive margin. This is due to gabbro and ultrabasic intrusion associated with the voluminous lavas of the seaward-dipping reflectors. The change from the thickened oceanic crust of the seaward-dipping reflectors and normal oceanic crust lies west of this data.

d) The break-up unconformity marks the change from production of thickened to normal oceanic crust and the marine flooding across much of the new continental shelf. The timing of break-up is diachronous along the southwest African rift margin. It occurred in discrete major segments of the rift margin, becoming younger to the north. In the Orange Basin, break-up occurred in the Hauterivian. In Namibia, break-up was earliest Barremian and Late Barremian in the Lüderitz and Walvis Basins respectively. The timing of break-up is partitioned by the major segment boundary zones.

e) In the Transitional Phase, faulting had largely ceased and subsidence was driven by thermal subsidence. However, it is dominantly a regressive sequence with sediments shed west from the Namibian Platform to prograde across the new marine shelf. The greatest sedimentation occurred west of the Orange River and Walvis Bay. Early volcanism produced several extensive tracts in the Lüderitz Basin, including volcanics at the base of the Kudu wells.

f) The Drift Phase can be divided into three major sequences of stacked sedimentary wedges prograding west across the Namibian passive margin. The Turonian hiatus that separates the lower two sequences marks a well-defined flooding surface in the Lüderitz Basin. This flooding event is obscured in the Walvis Basin by high rates of sedimentation created by Albian/Cenomanian uplift on the continental platform and the adjacent interior. The Orange River became well established early in the Drift Phase. Carbonates may occur on the northwestern flank of the Lüderitz Arch. The Walvis Igneous Centre was created in the north where the Walvis Ridge intersects the rift margin.

The middle Drift Phase sequence is dominated by listric faulting and thrusting, slumping and canyon-cutting along the outer shelf and upper and lower shelf slope. All these mechanisms are attempts to restore stability at the shelf break in a period of high progradational/aggradational sedimentation. Which mechanism dominates any particular area is dependent on the relationship of Sequence E_2 to the underlying shelf break, the sedimentation rate in Sequence E_2 and its lithological content, and the presence of overpressured shales.

As the Benguela Current became established early in the Tertiary Drift Phase, increased aridity and reduced run-off led to progressively reduced sedimentation along the Namibian passive margin.

5

STRUCTURAL EVOLUTION OF BLOCK 2213A

5.1 Introduction

5.1.1 Aims and objectives

Block 2213A is located on the eastern flank of the rifted continental margin, extending east from Walvis Basin (Fig. 5.1), across the Hinge Line onto the Namibian Platform. The regional interpretation shows this to be part of the most complex section of the entire Namibian passive margin, the Cape Cross Segment Boundary Zone. In this block, there are sub-basins on the Namibian Platform in addition to the main basin west of the Hinge Line. This block is also located close to the junction of the Pan-African Damara and Kaoko Fold Belts.

The major objective of this more detailed seismic interpretation was to attempt to define any possible transverse elements in this segment boundary zone. Once defined, the object was to assess their relationship with pre-existing basement elements and how these might have together interacted with later rifting. Any understanding of these factors also helps to determine their influence, if any, on the stratigraphic and sedimentary evolution of the area. Another important objective was to illuminate rift geometries, especially geometries established in the Karoo Rift Phase. "Atlantic" rift geometries are secondary in this block.

It is unfortunate that any margin offsets do not actually pass directly through the area possessing a dense seismic grid covering the west of Block 2213A. A large offset of the passive margin lies immediately to the north (Fig. 5.1). This element, or any other associated secondary feature (excepting north-directed subaerial palaeo-valleys, see later), does not directly affect the area. A major Pan-African lineament, the Omaruru Lineament, lies 70 km to the south and has no direct influence on Block 2213A. The extension of another Pan-African lineament, the Autseib Lineament projects into the southwest of the Block. This does not offset the "Atlantic" rift margin and was largely passive at this time, but was very important during the Karoo Rift Phase.

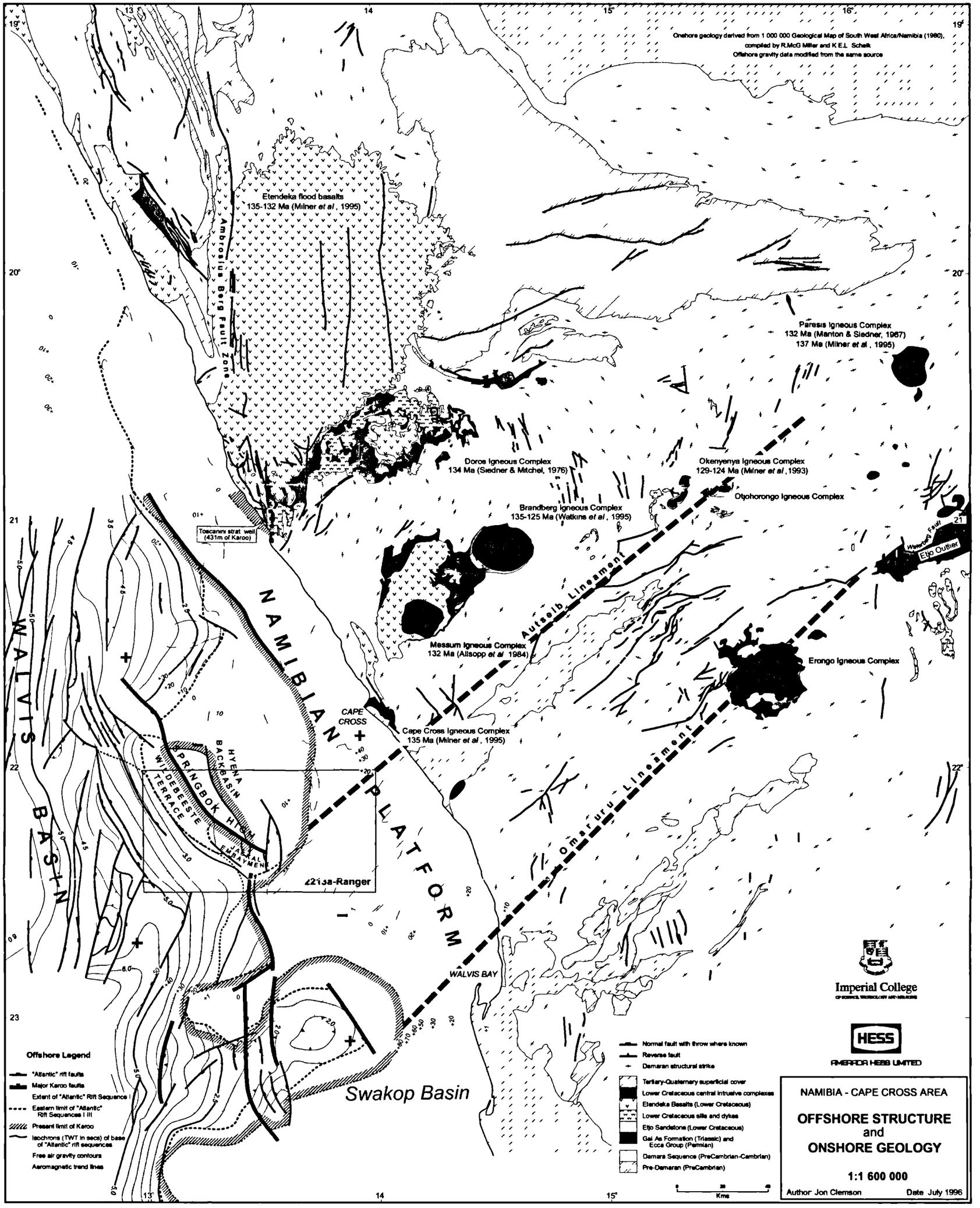


Figure 5.1 Offshore structure and onshore geology of west-central Namibia

5.1.2 Database

This interpretation is centred on Ranger-operated Block 2213A. The seismic dataset extends over 2860 line-kilometres and comprises two vintages: ROL93-2213 and ROL94-2213. Together they cover an area of 6300 km^2 (Fig. 5.2). Grid spacing varies between 1.5×1 km to 4×4 km. The data is displayed down to 6.9 seconds (TWT). These datasets overlay the regional ECL-89 & 91 datasets. Seismic interpretation was carried out on a LANDMARK workstation using the 2D application.

The quality of the ROL93/94 datasets is a marked improvement on the ECL-89/91 datasets. They have an improved signal to noise ratio giving better resolution of syn-rift and pre-rift reflections. Even steep dips up to 60° are imaged; migration of these is good as reflection terminations coincide with fault plane reflections. Acquisition and processing parameters are shown in Fig. 5.3.

Interval velocities of the ROL93/94 datasets are unfortunately of limited help in determining the nature of syn-rift sequences. Beneath the Late Barremian break-up unconformity, they quickly exceed 4-5000 m/sec in the syn-rift section, even after an empirical correction of 10%. In the east, interval velocities of the Karoo section exceed 5000 m/sec. Even shallow basement interval velocities exceed 6000 m/sec. Such high velocities across all syn-rift and pre-rift sequences hamper the identification of high velocity lithologies such as volcanics or carbonates.

The major interpreted horizons are linked in with the regional ECL-89/91 datasets and thus the available well control is the same as the regional interpretation. This is limited to the Kudu wells 700 km to the south. A certain amount of lithological data is available from Ranger-operated well 2213/6-1.

5.1.3 Geophysical interpretation

Two additional "Atlantic" Rift Phase and Drift Phase markers have been mapped besides horizons picked in the regional interpretation. The horizons interpreted in the Block 2213A area are shown in Table 5.1. Their ages are discussed in *Section 5.3.*

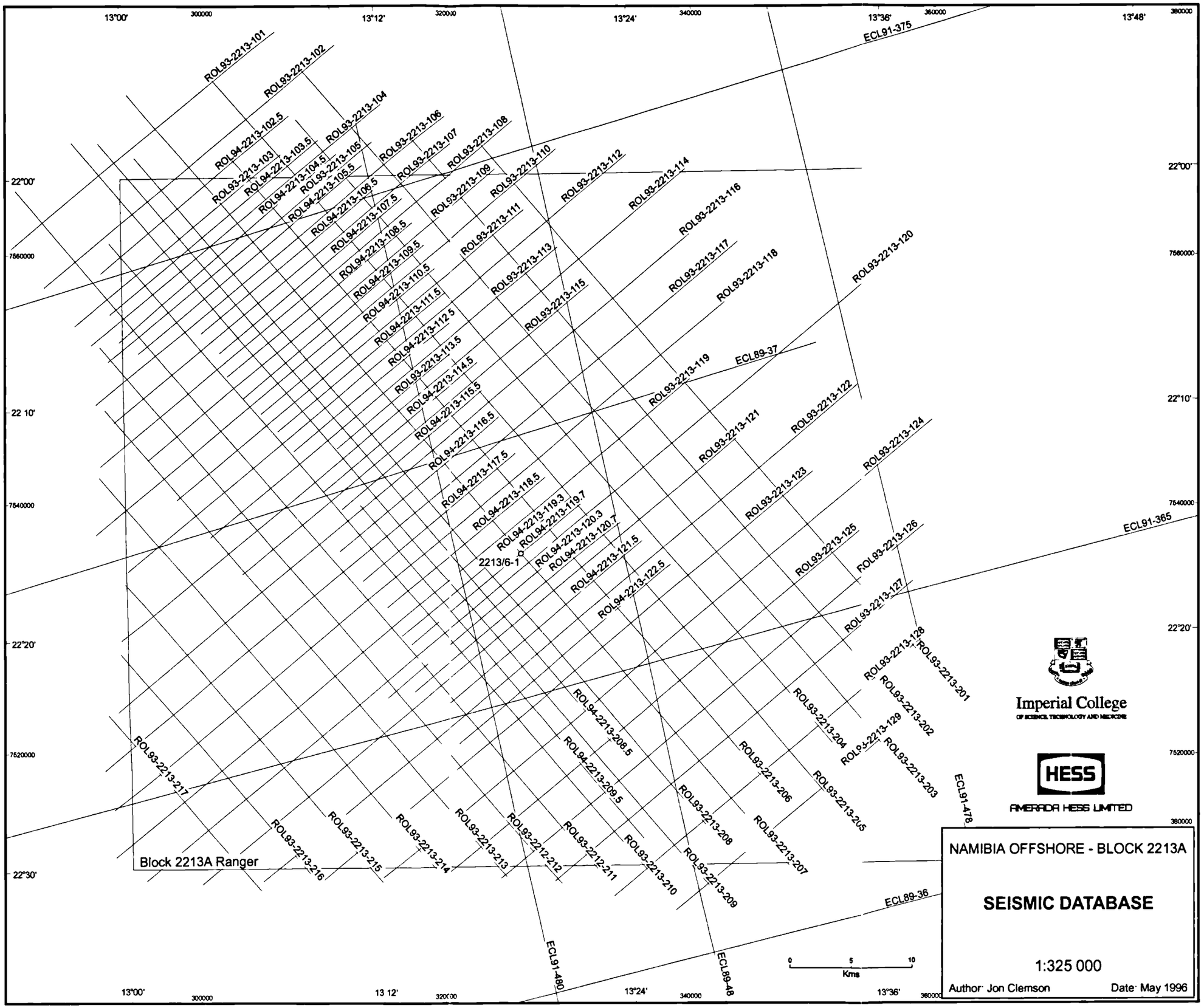


Figure 5.2 Seismic database of Block 2213A

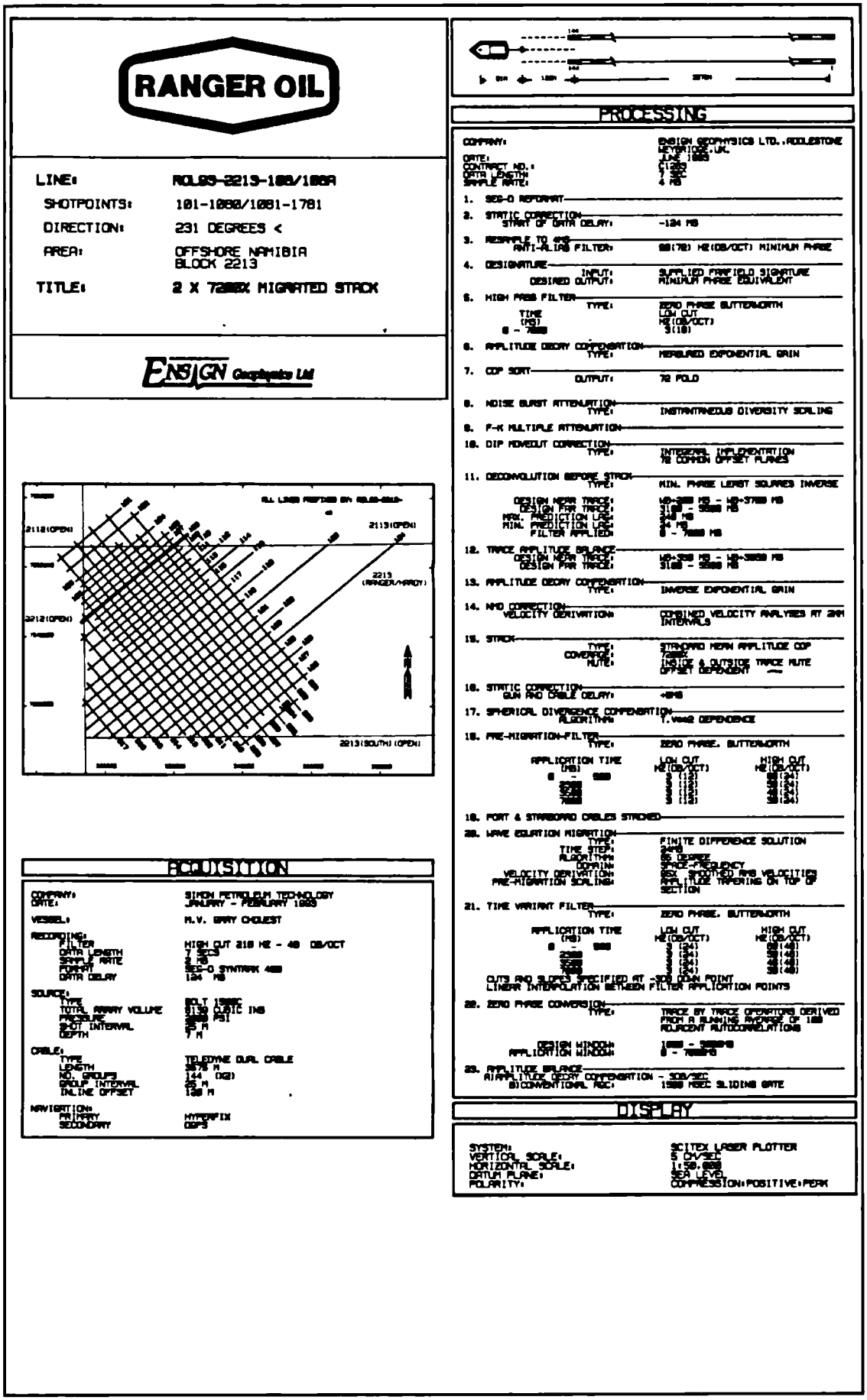


Figure 5.3 Acquisition and processing parameters of the ROL93-2213 and ROL94-2213 seismic surveys

Table 5.1 Stratigraphy of Block 2213A

Horizon	Sequence	Age	Interpretation
Sky Blue Marker			
	Sequence E_2	Mid-Apt. to Late Albian/Cenom	Early Drift Phase
Dark Blue Marker			
	Sequence E_1		"
Light Blue Marker		Early to mid-Aptian	
	"		"
Dark Green Marker	~~~~~~~~~~~~~~~~	Early Aptian	~~~~ c. 118 Ma.~~~~
	Sequence D		Transitional Phase
Light Green Marker	~~~~~~~~~~~~~~~~	Late Barremian to Early Aptian	~~~~ c. 123 Ma.~~~~
	Sequence C_3		"Atlantic" Rift Phase III
Rose Marker			
	"	Early Haut. to Late Barremian	"
Pink Marker			132 Ma
	Sequence C_2		"Atlantic" Rift Phase II
Orange Marker		Mid to latest Valanginian	135 Ma
	Sequence C_1		"Atlantic" Rift Phase I
Brown Marker		?Oxf./Kimm to mid Valang.	~~~~ c. 154 Ma.~~~~
	Sequence B		Karoo Post-Rift Phase
Red Marker		Late Triassic to ?Mid Jurassic	~~~~~~~~~~~~~~~~
	Sequence A		Karoo Rift Phase
Puce Marker		Permian to Early Triassic	~~~~~~~~~~~~~~~~
	Crystalline Basement		Crystalline Basement
		PreCambrian to Cambrian	

The additional interpreted reflectors include:

- The Sky Blue Marker, a low to moderate amplitude, semi-continuous to continuous positive reflector. This is a local but important Drift Phase unconformity, intermediate with the Dark Blue and Yellow Markers.
- The Rose Marker, a moderate to high amplitude, semi-continuous to continuous negative reflector between the Pink and Light Green Markers. In the Jackal Embayment this is a local unconformity truncating structural highs. To the west in the Walvis Basin, it is a downlap surface with sediments pinching out to the west. This marker is a syn-rift horizon and therefore not calibrated with any wells.

5.2 Structural elements.

Block 2213A and adjacent areas can be divided into several, largely fault-bounded, structural units. These are, working basinwards:

- Namibian Platform.
- Hyena Back-basin.
- Springbok High.
- Wildebeeste Terrace.
- Jackal Embayment.
- Walvis Basin

These are shown in Figure 5.4 and described below. Major faults often refer to fault systems. Figure 5.5 shows the location of figures described in the text.

Namibian Platform

This area, like most of the Namibian rift margin, has been peneplaned at the basal Drift Phase Lower Aptian unconformity (the Dark Green Marker) and the Albian/Cenomanian unconformity (the Sky Blue Marker) (Fig. 5.6). There are few fault offsets of this surface except at exhumed faults (see below). It is a largely featureless surface, with some minor local erosional topography and a general dip gently basinward to the WSW. To the southwest, the platform is fault-bounded and juxtaposed with the Jackal Embayment. In the northwest, it dips into the Hyena Back-basin. Here, semi-regional ROL93 lines suggest that

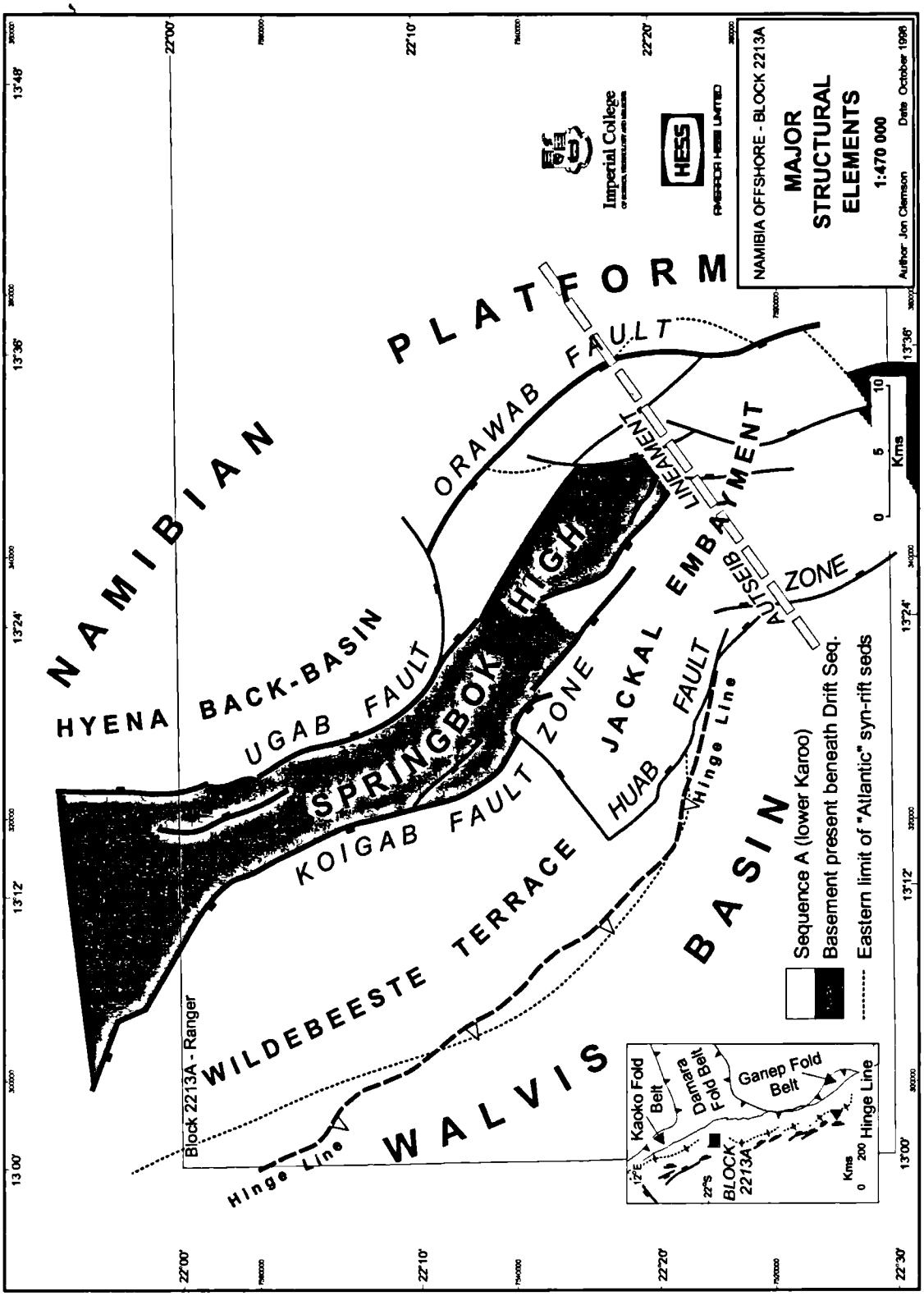


Figure 5.4 Major structural elements

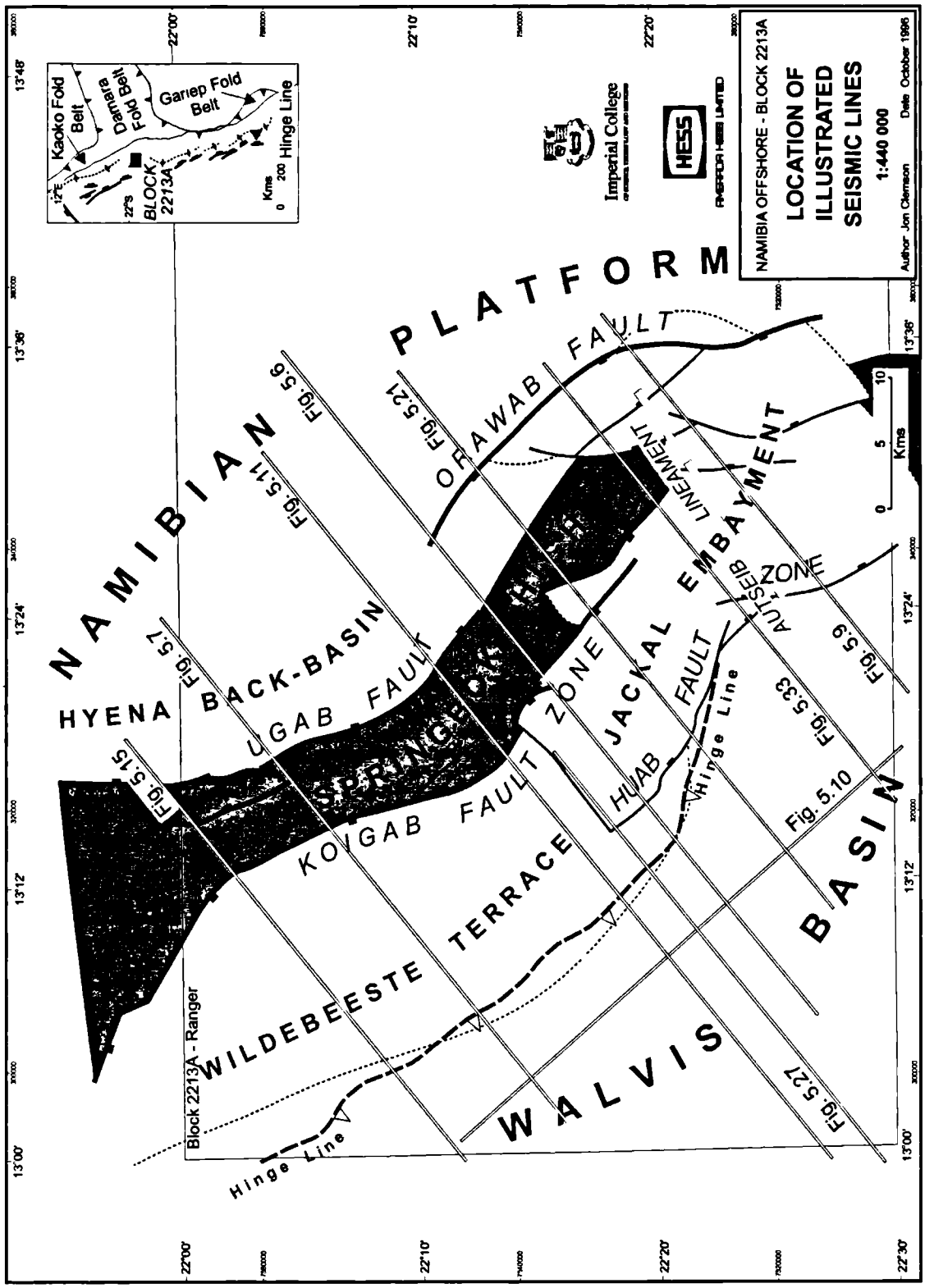


Figure 5.5 Location of illustrated seismic lines

it is underlain by lower Karoo (Permian-Early Triassic) sediments (Fig. 5.6). Here also, Apto-Albian sediments onlap onto the Namibian Platform. In the southeast, the underlying sequence is unresolvable on the ROL93/94 and ECL-89/91 datasets.

Hyena Back-basin

The Springbok High isolates this half-graben from the major basinal areas to the west. It is bounded to the WSW by a NNW-SSE oriented arcuate normal fault system, the Ugab Fault. This fault (Fig. 5.7, shotpoint 1510) is divided into three segments (Fig. 5.8), linked by relay ramps. Fault-controlled sedimentation produced proximal fans shed northeast into the basin, with sediments derived from the footwall of the Ugab Fault. A basal unconformity (Fig. 5.7) truncates the Permian-Lower Triassic section beneath this half-graben. This unconformity is correlated with the Upper Barremian break-up unconformity of the Walvis Basin (the Light Green Marker). Fault-controlled sedimentation ceased in Apto-Albian times, from when also the basin was no longer a separate entity on the Namibian Platform.

Springbok High

The Springbok High is a NNW-SSE-oriented elongate horst over 30 km long and 4 to 7 km wide. The Hyena Back-basin is down-faulted to the northeast. To the southwest a large and important normal fault, the Koigab Fault Zone (Fig. 5.7, shotpoint 1280), separates it from the Wildebeeste Terrace and Jackal Embayment. On this prominent high, crystalline basement lies directly beneath Aptian or younger sediments (Fig. 5.7, shotpoint 1280-1510). Fault hangingwalls, set into the crystalline basement, preserve outliers of Megasequence A (see *Section 5.4*).

The Koigab Fault Zone comprises several *en echelon* segments. In the north, where the Springbok High juxtaposes the Wildebeeste Terrace, major segments are hard-linked by breached relay ramps (Fig. 5.8) (cf. Trudgill and Cartwright 1994). To the south where younger sediments of the Jackal Embayment juxtapose the Springbok High, a relay ramp separates two major segments. Southwards, the Koigab Fault Zone passes into a highly faulted accommodation zone (cf. Morley *et al.* 1990) as normal faulting becomes displaced landwards to the Orawab Fault. This accommodation zone terminates the southern end of

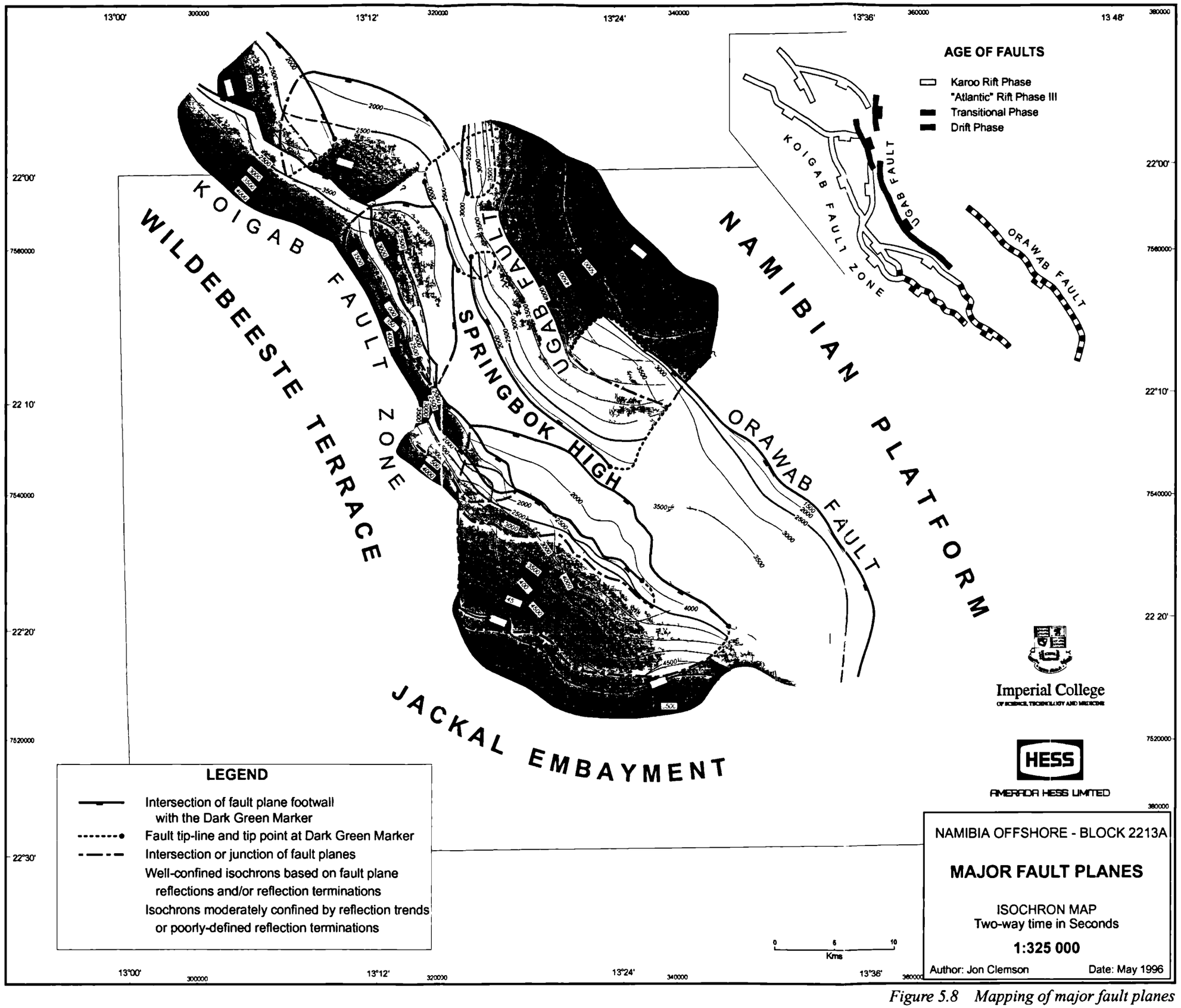


Figure 5.8 Mapping of major fault planes

the Springbok High. The northern end of the High lies outside the detailed study area. Regional mapping shows a major east-stepping margin offset with an "Atlantic" syn-rift salient just to the north (Fig. 5.1). The Springbok High plunges north into this salient. The Koigab Fault Zone is part of the Koigab Fault System, an important structural element in Block 2213A and is dealt with in detail in *Section 5.4.2.1*

Wildebeeste Terrace

This is located between the Hinge Line and the Springbok High and is 50 km long by 15-20 km across. Sediments of Megasequence A dip to the WSW on the Wildebeeste Terrace. Structurally, this area is simple with relatively little faulting except along the eastern margin close to the Springbok High. Here, most second order faults dip NE towards the Koigab Fault Zone. To the southeast, the Wildebeeste Terrace is juxtaposed with the Jackal Embayment *via* a SW-NE oriented transfer fault (cf. Gibbs 1984). Like the Springbok High, the terrace plunges NNW into the "Atlantic" syn-rift salient.

Jackal Embayment

This is a complex, heavily faulted area with the "Atlantic" syn-rift succession extending 25 km east into the Namibian Platform. It is subdivided into two areas:-

i) In the northwest it lies between the Springbok High and Walvis Basin. A second order, but large, northeast-dipping fault (the Huab Fault Zone) responded to extension on the Koigab Fault Zone. This produced a faulted graben plunging southeast into the Jackal Embayment (Fig. 5.4). Here, most faults dip to the west. A transfer fault juxtaposes the northwest of this graben against the Wildebeeste Terrace.

ii) Towards the southeast, a structurally complex, heavily faulted area is located between the Namibian Platform, the southeast end of the Jackal High and the Walvis Basin. In this area, most faults dip to the east towards the NW-SE trending Koigab or Orawab Faults. These major faults are linked by an accommodation zone and bound the east of this area (Fig. 5.9, shotpoint 1420). The southern flank of this complex area has been upwarped and eroded.