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ORIGINAL

Sequence stratigraphy in the Algoa and Gamtoos basins (South Africa): a shoreline's journey since the Middle Mesozoic

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Abstract
Basin evolution models are dependent on high-quality subsurface data, normally obtained during hydrocarbon exploration activities. The limited exploration, to-date, has impeded the understanding of the geological evolution of the offshore Algoa and Gamtoos half-graben basins in the southern Cape region of South Africa. To reconstruct the main geological events of the area since the Early Jurassic, vintage borehole and seismic data as well as key outcrop observations were integrated. Using this combined dataset, we generated contemporary gross depositional environment models, as well as tested the applicability of different sequence stratigraphic models for these late Gondwana basins. The studied stratigraphic interval contains syn- and post-rift systems that were impacted by marine processes, especially in the distal hanging walls of these compartmentalized half-graben basins. Sedimentation within these depocenters primarily occurred above the hanging walls, while the footwalls formed regions of basement highs. The geological characteristics of the studied succession prevent the application of the depositional sequence or tectonic system tracts models in the syn-rift succession. Because subaerial unconformities (SUs) in the distal syn-rift sequence are not detectable, a diachronous, northward advancement of the shoreline (relative sea level rise) until the late Valanginian can be postulated. The observations in the syn-rift sequence, which is bound by a basal SU, followed by third- and fourth-order transgressive and regressive cycles and a second-order maximum flooding surface at the top, can be explained with a modified genetic sequence model. In the transitional to drift phase interval, from Hauterivian to Holocene, the successions are bound by SUs and their correlative conformities. In the successions without evidence for subaerial exposure, flooding surfaces could be used as sequence-bounding stratigraphic contacts. This study reaffirms the notion that while the sequence stratigraphic concept is model-independent, sequence models are sensitive to depositional scale.

Keywords Sequence stratigraphic models · Syn-rift · Gross depositional environment models · Sequence boundaries · Gondwana break-up

Introduction

The application of sequence stratigraphy in identifying hydrocarbon traps in frontier basins has been successful globally (e.g., ExxonMobil Liza discovery offshore Guyana; Platon 2017; Feder 2019) and to some extent in southern Africa too (e.g., the Brulpadda and Luiperd discoveries in the Outeniqua Basin; Africa Energy Corp. 2020). However, from an economic geology view-point, a solid knowledge of the geological history is important not only for exploiting hydrocarbons while transitioning to alternative energy resources but also for siting deep geological mediums to mitigate the negative impact of anthropogenic climate change (e.g., CO_2 storage, deep burial of hazardous waste; Hong et al. 2015). Moreover, despite serious collaborative scientific efforts in the past decade to stabilize the sequence stratigraphic method (e.g., Catuneanu et al. 2011, Catuneanu 2019a, b, 2020, Catuneanu and Zecchin 2020), terminology is still inconsistently used by different schools of thought not only to define stratigraphic surfaces but also to interpret the geological history of stratigraphic successions. This has resulted in multiple sequence stratigraphic models that interpret the same data differently.

This article is part of the Topical Collection on *Coastal and marine geology in Southern Africa: alluvial to abyssal and everything in between*

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Although a working petroleum system was proven in the Algoa and Gamtoos basins of South Africa, data acquired to-date yielded limited exploration success unlike in the neighboring Bredasdorp Basin (e.g., Malan 1993; McMillan et al. 1997). Consequently, no robust sequence stratigraphic work exists for the Algoa and Gamtoos basins (Ayodele et al. 2020; Caku et al. 2020), and this limits, especially in the offshore regions, the understanding of the (a) sedimentary facies distribution, (b) basin development history, and (c) nature of the petroleum systems (Muir et al. 2020). Herein, a mid-Mesozoic to Holocene sequence stratigraphic framework is built in the Algoa and Gamtoos basins. By integrating a subset of available vintage data (seismic and wireline) and some outcrop studies, the usefulness of a few, selected sequence stratigraphic models is tested for the study area. Moreover, by combining the available data, conceptual models of the gross depositional environments (GDE) are generated and shown as maps. These GDE maps were derived from studying facies change, the vertical stacking pattern of facies in available wireline data, seismic geometries, and also by incorporating recent results from field studies conducted onshore in the Algoa and Gamtoos basins.

Geological background

Stratigraphic framework

The Algoa and Gamtoos basins, together with the Pletmos and Bredasdorp basins form part of the larger Outeniqua Basin,

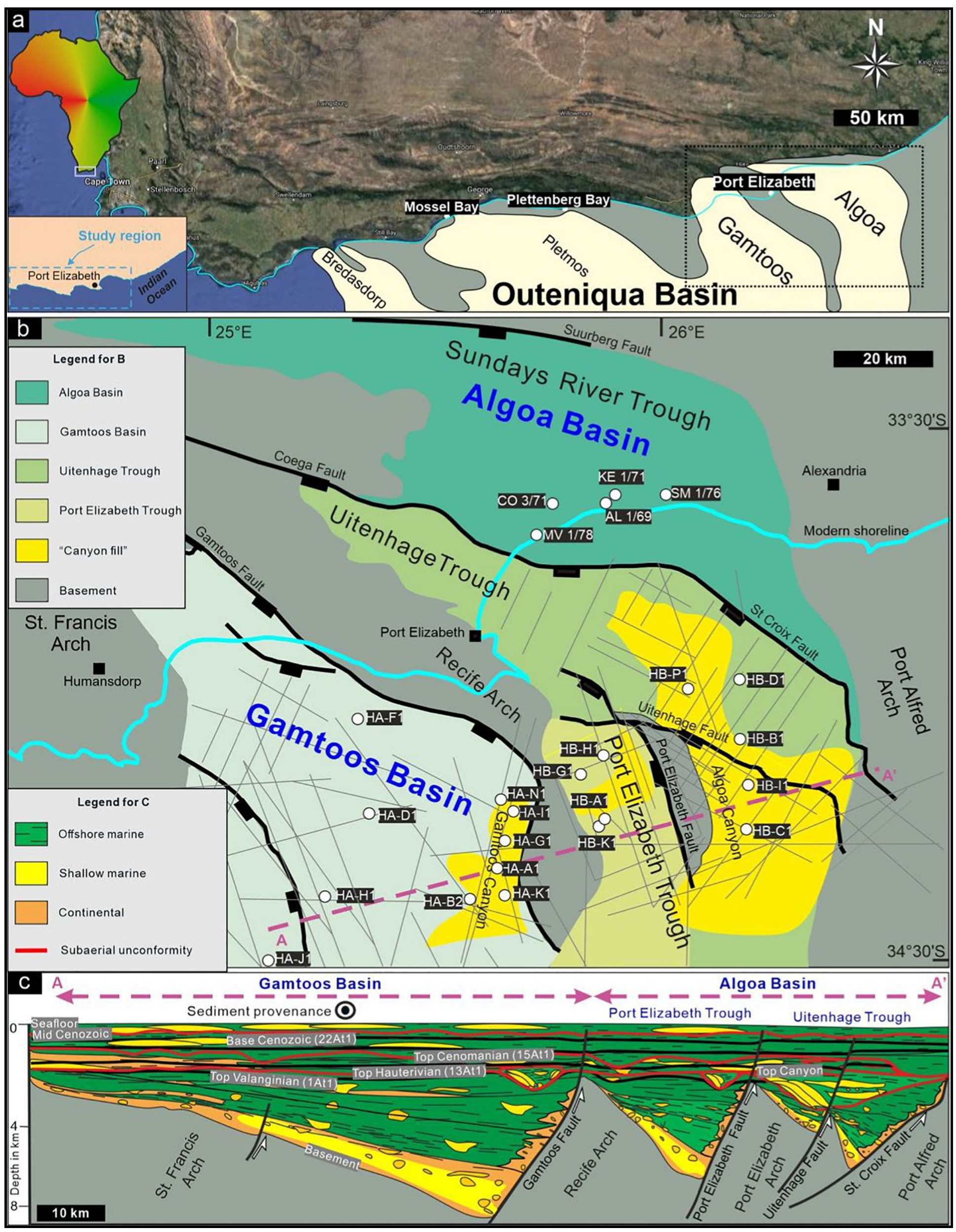


Fig. 1 **a** Regional southern Africa map, showing the location of the greater Outeniqua Basin. **b** Simplified onshore and offshore structural elements map (not taken at seafloor) of the Algoa and Gamtoos basins. **c** Structural cross-section of the Algoa and Gamtoos basins (modified from McMillan et al. 1997; Broad et al. 2012; Muir et al. 2020). Base map data ©2020 Google, Maxar Technologies, AfriGIS (Pty) Ltd

located along the southern coast of South Africa (Fig. 1; Malan 1993; Brown et al. 1995; McMillan et al. 1997; Singh et al. 2005; Thompson et al. 2019; Muir et al. 2020). The Outeniqua Basin is a remnant of extensional basins formed in southern Africa during Gondwana breakup in the Early Jurassic (McLachlan and McMillan 1976; Dingle et al. 1983; McMillan et al. 1997; Thompson et al. 2019; Muir et al. 2020). While the Algoa and Gamtoos basins are adjacent to each other, sedimentation was primarily influenced by their local structural anisotropy (Broad 1990; McMillan et al. 1997; Muir 2019). The Algoa Basin is compartmentalized into sub-basins or troughs by three major bounding faults, the St Croix, Port Elizabeth, and Uitenhage faults (Fig. 1; McLachlan and McMillan 1976; Dingle et al. 1983; Broad 1990; Bate and Malan 1992; Broad et al. 2012; McMillan et al. 1997). The Gamtoos Basin contains only one major listric-type fault (i.e., Gamtoos Fault), which has a throw of 3 km onshore and 12 km offshore, and was active from Middle to Late Jurassic (Fig. 1; e.g., McLachlan and McMillan 1976; Dingle et al. 1983; Malan et al. 1990; Bate and Malan 1992; McMillan et al. 1997; Paton and Underhill 2004). The basin fill (Fig. 2) can be separated into (1) pre-Oxfordian to Valanginian rift/syn-rift phase (reflector D to 1At1); (2) Valanginian to Hauterivian early drift phase (transition phase; 1At1 to 6At1/13At1); (3) Aptian to Albian "Canyon fill" (13At1 to 14At1) and; (4) drifting (thermal subsidence) phase (13At1 to Holocene; e.g., McLachlan and McMillan 1976; Dingle et al. 1983; Broad 1990; Bate and Malan 1992; Malan 1993; Brown et al. 1995; McMillan et al. 1997; Broad et al. 2012).

The oldest rocks are conglomerates and subordinate sandstones that belong to the Enon Formation, which was deposited on alluvial fans developed from high-energy rivers during the early Middle Jurassic (or earlier) to the Early Cretaceous (Fig. 2; McLachlan and McMillan 1976; Dingle et al. 1983; Malan 1993; McMillan et al. 1997; Singh et al. 2005; Muir et al. 2017a, 2020). This basal conglomeritic unit, with thickest accumulations in the deepest portions of the sub-basins adjacent to the bounding faults (Fig. 2; Muir et al. 2017a) is coeval with, but occasionally overlain by the variegated mudstones and sandstones of the Kirkwood Formation (Fig. 2; McLachlan and McMillan 1976; Dingle et al. 1983; McMillan et al. 1997; Singh et al. 2005; Muir et al. 2015, 2017b, 2020). The Kirkwood Formation was deposited in the meandering rivers and floodplains along the dipping landscape of the hanging walls of the rift normal faults (Fig. 2; McLachlan and McMillan 1976; Dingle et al. 1983; McMillan et al. 1997; Muir et al. 2015, 2017b, 2020). Onshore, the continental deposits of the Enon and Kirkwood formations are overlain by the Sundays River Formation. In outcrops, this marine, regionally extensive unit is well known for its age-diagnostic Valanginian foraminifera (McMillan et al. 1997, 2003; Broad et al. 2012; Muir et al. 2017a, b, 2020). Unlike the Enon and Kirkwood formations, the age of the Sundays River Formation has not been determined with radioisotopic dating methods (see Muir et al. 2020 for discussion). Based on biostratigraphic proxies, its lower part can be considered coeval with the upper Kirkwood and Enon formations. Despite lacking robust age constraints, the Sundays River Formation is widely considered to mark the end of syn-rift deposition in the study region, chiefly because it is overlain by the Hauterivian to Albian transitional phase succession (McLachlan and McMillan 1976; Dingle et al. 1983; McMillan et al. 1997). These sediments are well preserved in the offshore Gamtoos Basin but not in the Algoa Basin, where they have been eroded during the late Aptian uplift. Aero-magnetic studies show that the Uitenhage Group in the Algoa Basin can reach a thickness of up to 6 km, especially in the SW part of the basin (Caku et al. 2020). The Hauterivian to Aptian uplift resulted in the Algoa and Gamtoos canyons (McLachlan and McMillan 1976; Dingle et al. 1983; Malan et al. 1990; Bate and Malan 1992; McMillan et al. 1997; Paton and Underhill 2004), which were subsequently filled with transitional phase late Aptian (13At1) to early Albian (possible early Cenomanian) inner to middle shelf marine claystones with sandstone interbeds (McMillan et al. 1997). The transitional phase succession is truncated by the regionally extensive Top Cenomanian (15At1) unconformity (Fig. 2), which is onlapped by marine-dominated Upper Cretaceous drift phase sediments (McMillan et al. 1997; Broad et al. 2012). Unconformably overlying the Mesozoic successions onshore are various Cenozoic formations comprising of the Bathurst, Alexandria, Nanaga, Salnova, Nahoon, and Schelm Hoek formations, which mostly belong to the Eocene to Holocene-age Algoa Group (e.g., McMillan and McMillan 1976; Du Toit 1979; Le Roux 1987, 1989, 1990; McMillan 1990; Illenberger 1992; McMillan et al. 1997; Hattingh 2001; Broad et al. 2012).

Tectonic setting and basin evolution

In the long-lived rift-basin system of the southern Cape, two main rifting episodes were recorded: (1) the opening of west Gondwana during the Early Jurassic and (2) the Early Cretaceous strike-slip movement along the Agulhas-Falkland Fracture Zone (AFFZ; Fig. 1; Muir et al. 2020). Based on recent U–Pb radioisotopic dating of pyroclastics and resedimented volcaniclastics, Muir et al. (2020) showed that the Uitenhage Group was deposited over a 40 myr-long-period, from the Early Jurassic to the Early Cretaceous. This recent age assessment suggests that the initial rifting in the region occurred pre-Aalenian, during the Early Jurassic as part of the rift system that was generated during the separation of East and West Gondwana, in the initial Gondwana breakup interval (Jungslager 1996; Muir et al. 2020). The second rifting phase occurred in the Early Cretaceous due to transform rifting, which is linked to the initiation of the AFFZ and the

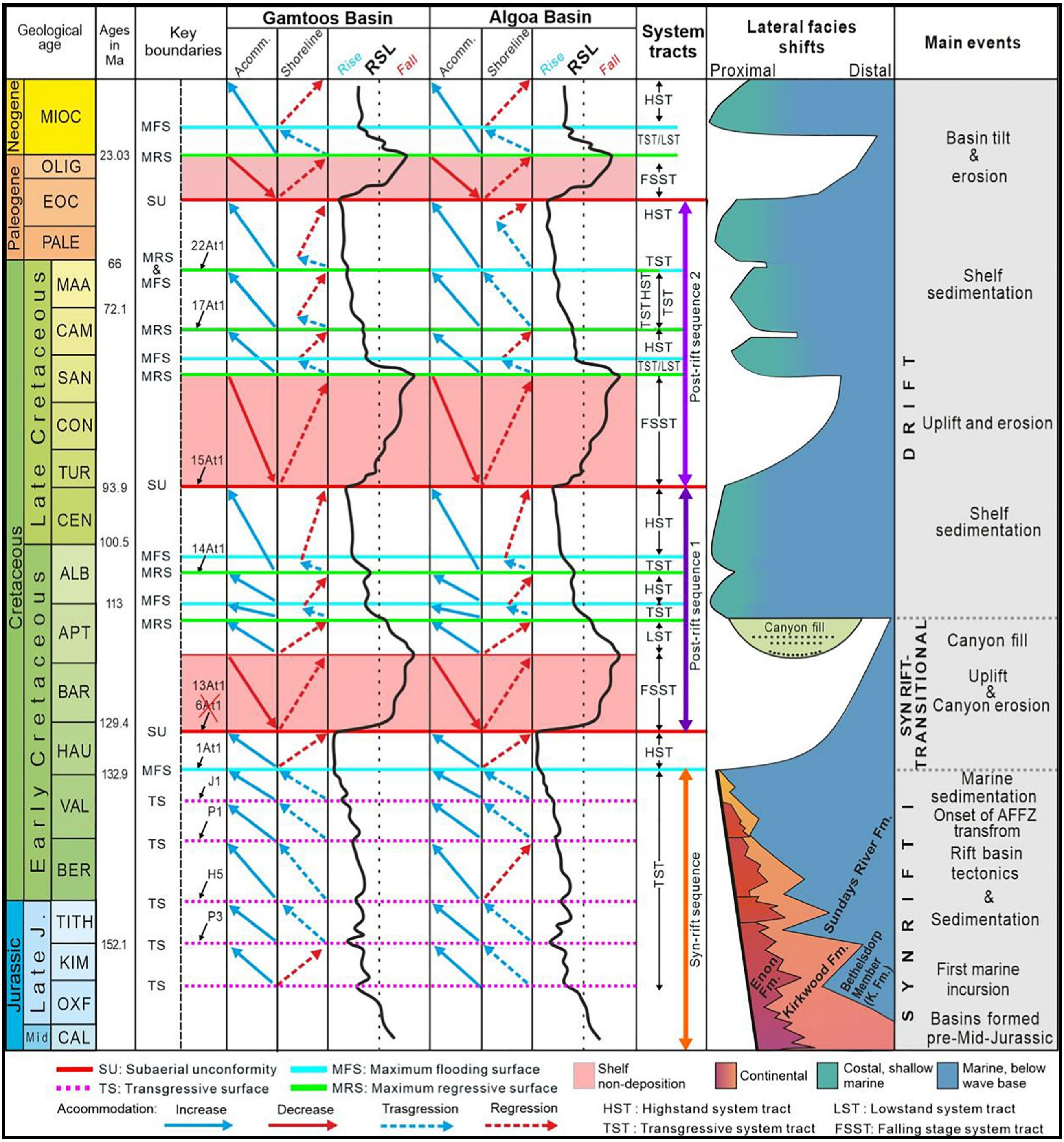


Fig. 2 Stratigraphic succession of the Algoa and basins showing major geological events from the Late Jurassic to Miocene (modified from Brown et al. 1995; McMillan et al. 1997; Baby et al. 2018; Muir et al. 2020)

opening of the South Atlantic (McLachlan and McMillan 1976; Martin et al. 1981; Dingle et al. 1983; Broad 1990; Bate and Malan 1992; Ben-Avraham et al. 1993; Paton and Underhill 2004; Muir et al. 2020). This second rift phase (late Valanginian transitional phase) was shown to correspond to the M21–M10 magnetic signatures with a radioisotopic age of ~ 145 – 122 Ma (Martin and Hartnady 1986). During the post-rifting phase, the basin underwent several uplift events, the first of which occurred during the Barremian – Aptian (6At1 to 13At1; Fig. 2; McLachlan and McMillan 1976; Dingle et al. 1983; Malan 1993; Brown et al. 1995; Thomson 1999; Paton and Underhill 2004). After the syn-rift phase, the second major erosional event was caused by uplift in the distal/offshore part of the basin in the Late Cretaceous (15At1 to 22At1; Fig. 2; Malan 1993; Baby et al. 2018) and resulted in the "Drift Sequence" (sensu Broad et al. 2012; thermal subsidence driven). The last notable uplift event occurred during the Oligocene, when the basin tilted to the N, deeply eroding the drift sediments on the shelf (Hattingh 2001; Baby et al. 2018).

Material and methods

Vintage datasets (Fig. 3), consisting of seismic and borehole data, were purchased from the Petroleum Agency SA (PASA). Generally, the wireline data are of moderate to good quality, the two dimensional (2D) seismic data is poor to moderate quality and three-dimensional (3D) seismic data varies from moderate to good quality. This dataset would require reprocessing to further enhance the seismic imaging, eliminate multiples, increase the vertical resolution, and minimize seismic misties between different vintages; however, these processes are beyond the scope and budget of this study.

Interpreted two-way time (TWT) maps were depth converted using multiple methods (i.e., V0k, layered cake and average velocities), following which isopach maps were generated to delineate the stratigraphic thickness variations in the basin. In the Algoa Basin, the complex subsurface successions required a complex velocity model such as the V0k method to depth convert the TWT maps (Fig. 4a). In the Gamtoos Basin, due to its less complicated basin structure, the average velocity model derived from wireline checkshot data yielded favorable maps (Fig. 4b). The limitation of reflection seismic resolution, a challenge in this study, is discussed in Catuneanu (2019a, b) and Catuneanu and Zecchin (2020), and addressed in the "Discussion."

Understanding of the shoreline trajectories, vertical stacking patterns of the facies, geometry of stratal terminations, and spatial facies changes are building blocks of any robust sequence stratigraphic framework (Neal et al. 2016). A reliable evaluation of the rock record is best achieved with those sequence stratigraphic depositional models that integrate different types of datasets (core, outcrop, wireline, seismic surveys; e.g., Neal and Abreu 2009; Catuneanu et al. 2011). There are currently several conventional stratigraphic models grouped into depositional, genetic, and T-R sequence models as shown in Fig. 5. Depositional sequence models use SUs as sequence boundaries, while the genetic and T-R sequence models use shoreline trajectories (MFS and MRS) to define a sequence boundary (e.g., Embry et al. 2007; Catuneanu et al. 2011).

Gross depositional environment modeling in this study followed the workflow presented in Fig. 6. This workflow serves as a set of guidelines, rather than strict rules that can be used from data loading into the data analysis software (Petrel E&P Software Platform), to interpretations, to the final step of gross depositional model building. Concerted effort was made to integrate outcrop, core, wireline, and seismic data in order to achieve comprehensive interpretation of the depositional history.

Results

Syn-rift I observations

Aalenian to upper Kimmeridgian

The Enon Formation is described from onshore outcrops as a predominantly immature, poorly sorted, pebble to cobble

Data type	Algoa Basin Quantity	Algoa Basin Years acquired
Onshore wells	6	1968-1978
Offshore wells	9	1978-1987
Offshore seismic survey (2D)	71 lines	1976-1989
Onshore seismic survey (2D)	6 lines	1968-1977
Offshore seismic survey (3D)	1 X 424 km^2	2001

Data type	Gamtoos Basin Quantity	Gamtoos Basin Years acquired
Onshore wells	NA	NA
Offshore wells	10	1978-1990
Offshore seismic survey (2D)	20 lines	1975-1987

Fig. 3 Inventory of the dataset from the Algoa and Gamtoos basins obtained from the archives of the Petroleum Agency of South Africa). Base map data ©2020 Google, Maxar Technologies, AfriGIS (Pty) Ltd

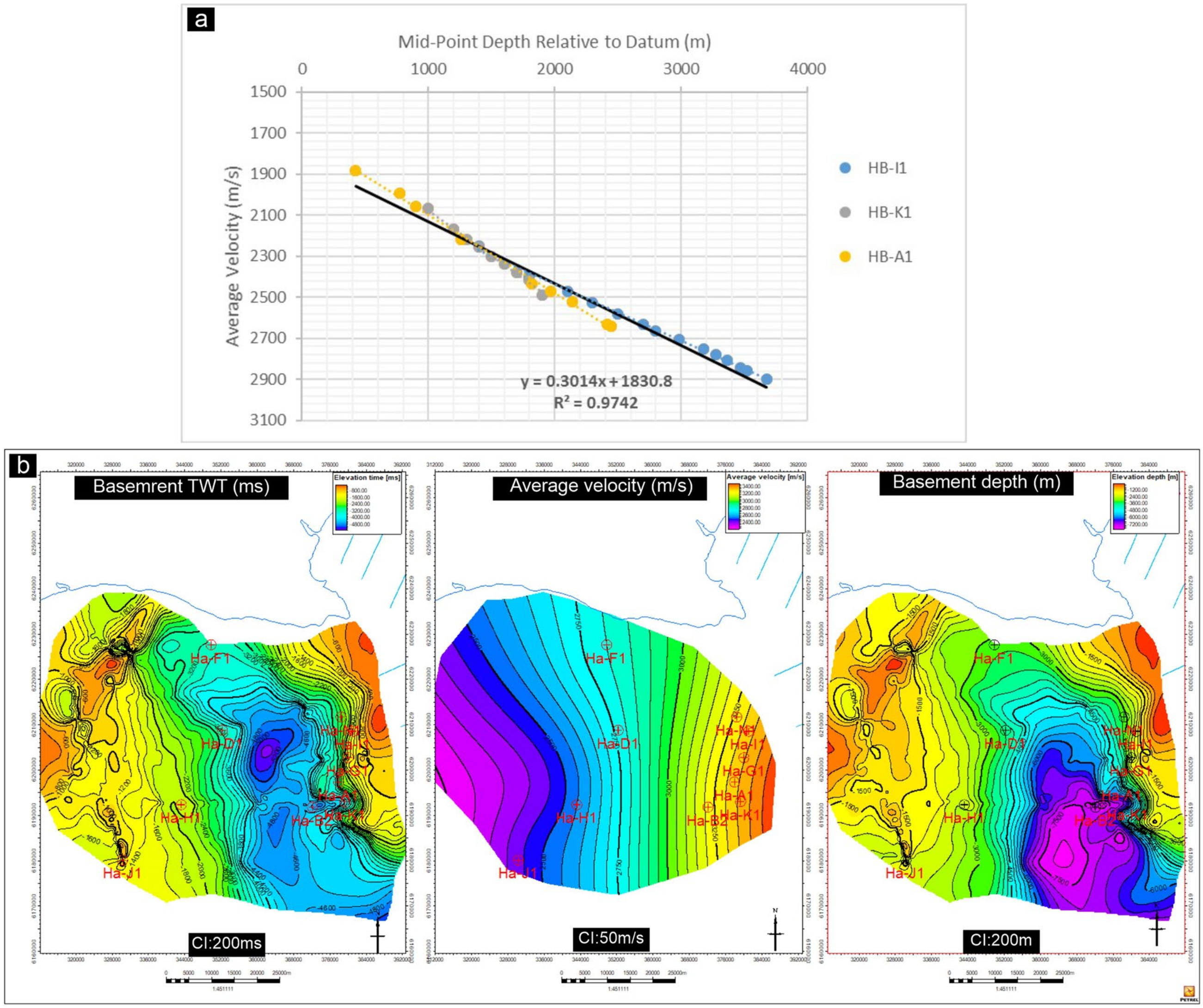


Fig. 4 **a** Interval Velocity vs Mid-Point Depth. Sedimentary rocks in the Algoa Basin show an increase of velocity with depth, without any velocity inversion. V0: 1830 m/s, k: 0.3014. Data points are from Hb-I1, Hb-K1, and Hb-A1 wells. **b** Gridded TWT Basement map multiplied by average velocity from check shot data to produce the depth maps in the Gamtoos Basin. This process was repeated for all surfaces

conglomerate with subordinate sandstones (Fig. 7a; Muir et al. 2017b). In the Algoa Basin, this succession shows lateral facies variability shown by alternating low to high gamma-ray (GR) values. In the S borehole HB-C1, the low GR values, ranging from 44 to 151 American Petroleum Institute (API), are detected over a ~ 85-m-thick unit, with two overall coarsening upwards packages, whereas in the N, high GR values dominate (Fig. 7c). The more proximal HB-P1 is dominated by > 400 m of serrated GR signatures (44 to 151 API) consisting of alternating coarsening-upward and fining-upward trends. Overall, the borehole contains more sandy facies relative to the HB-C1 borehole. The lower part of borehole HA-J1 shows fining-upward trend in shale and clay succession followed by coarsening-upward trend in silty/shaley successions that give way to fining-upward trend in sandstones. Overall, borehole HA-J1 intersected a ~ 130-m-thick basement to upper Kimmeridgian succession (GR: 64–180 API). In the center of the Gamtoos Basin, borehole HA-H1 is dominated by > 700-m-thick fining-upward units (GR: 30–112 API). However, the lower part shows a high net sand-to-shale ratio, while the upper succession shows silty and claystones facies. Near the Gamtoos Fault, borehole HA-B2 intersected a > 265-m-thick succession of shales and clays that contain some isolated coarsening-upward sandy facies (GR: 42–145 API). Borehole HA-K1, which is closer to the Recife Basement High contains a > 1720-m-thick succession of predominantly coarsening-upward units (GR: 36–120 API; Fig. 7c).

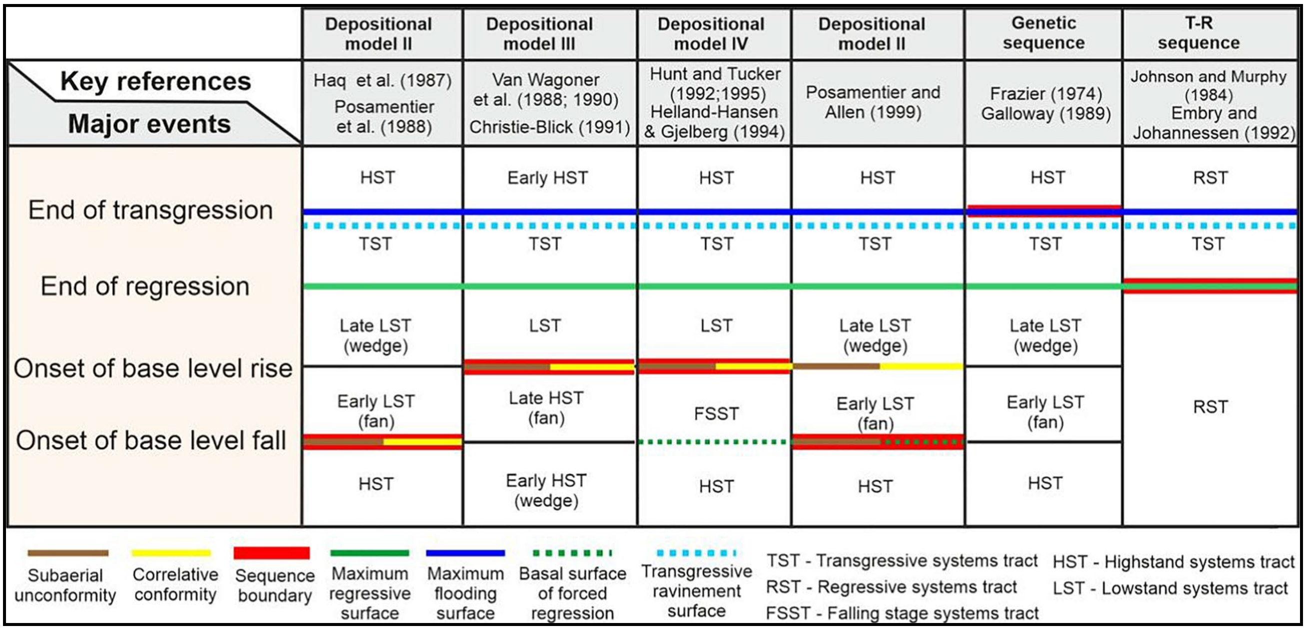


Fig. 5 Sequence models, and their bounding surfaces. LST, lowstand systems tract; TST, transgressive systems tract; HST, highstand systems tract; FSST, falling stage systems tract; RST, regressive systems tract; T–R, transgressive–regressive (modified from Catuneanu 2002)

This Aalenian to Kimmeridgian succession onlaps (in some places downlaps) onto the Basement D reflector, generally showing higher energy seismic reflectors than the overlying and the underlying succession (Fig. 7b). The internal reflector geometries are commonly discontinuous and chaotic. This succession has been subject to intense erosion in the Uitenhage Trough, while being less eroded in the Port Elizabeth Trough where it terminates against the Basement D Reflector. Although this erosion is extensive in the Algoa Basin, this succession is preserved in some isolated areas, such as borehole HB-P1 location. The absence of this succession in most parts of the Algoa Basin makes it challenging to confidently correlate it across the basin (Fig. 7b). In the Gamtoos Basin, the syn-rift succession is better preserved, and shows thickening and folding (due to a later tectonic inversion; Thomson 1999) towards the Gamtoos Fault, in addition to westward pinching near the borehole HA-J1 (Figs. 7 and 8b). A thickness map from seismic mapping (Fig. 8a) shows a prominent depocenter near the N/S trending limb of the Gamtoos Fault. There is also evidence of clinoforms prograding from the W towards the Gamtoos Fault (Fig. 7b). This progradational succession is overlain by dimming chaotic reflectors, which are subsequently overlain by subparallel and continuous reflectors of the upper Kimmeridgian succession (Fig. 7b).

Post-Kimmeridgian to Early Valanginian

The most dominant rock unit of this interval is the Kirkwood Formation, which consists of mostly variegated mudstones and sandstones with subordinate conglomerates that formed in meandering rivers with wide floodplains and lakes (Fig. 9a; Muir et al. 2017b). The formation contains a rich and diverse fossil biota (e.g., theropod dinosaurs, freshwater fish, reptile, plants) that further supports the continental nature of the depositional setting (Muir et al. 2017b). The Lower Valanginian thickens towards the S and attains a thickness of ~ 620 m in borehole HB-C1 (Fig. 9c). Borehole HB-B1 consists of ~ 320-m-thick, alternating fining-upward and coarsening units with high sand-to-shale/clays ratio (GR: 35–82 API). The borehole HB-C1 intersected predominantly shales and clays and a 330-m-thick, coarsening-upward sandy unit (GR: 40–140 API) in the lower half of the succession (Fig. 9c). The upper part of borehole HB-C1 is dominated by a ~ 310-m-thick, shaley succession with very limited sand content (GR: 70–140 API). In the Gamtoos Basin, the general vertical grains size trend is stacked, comprising mostly coarsening-upward and rare fining-upward units (Fig. 9c).

In the Port Elizabeth Trough, where this interval is preserved, seismic reflectors are chaotic and discontinuous in the N-S direction (Fig. 9b). Contrary to the underlying

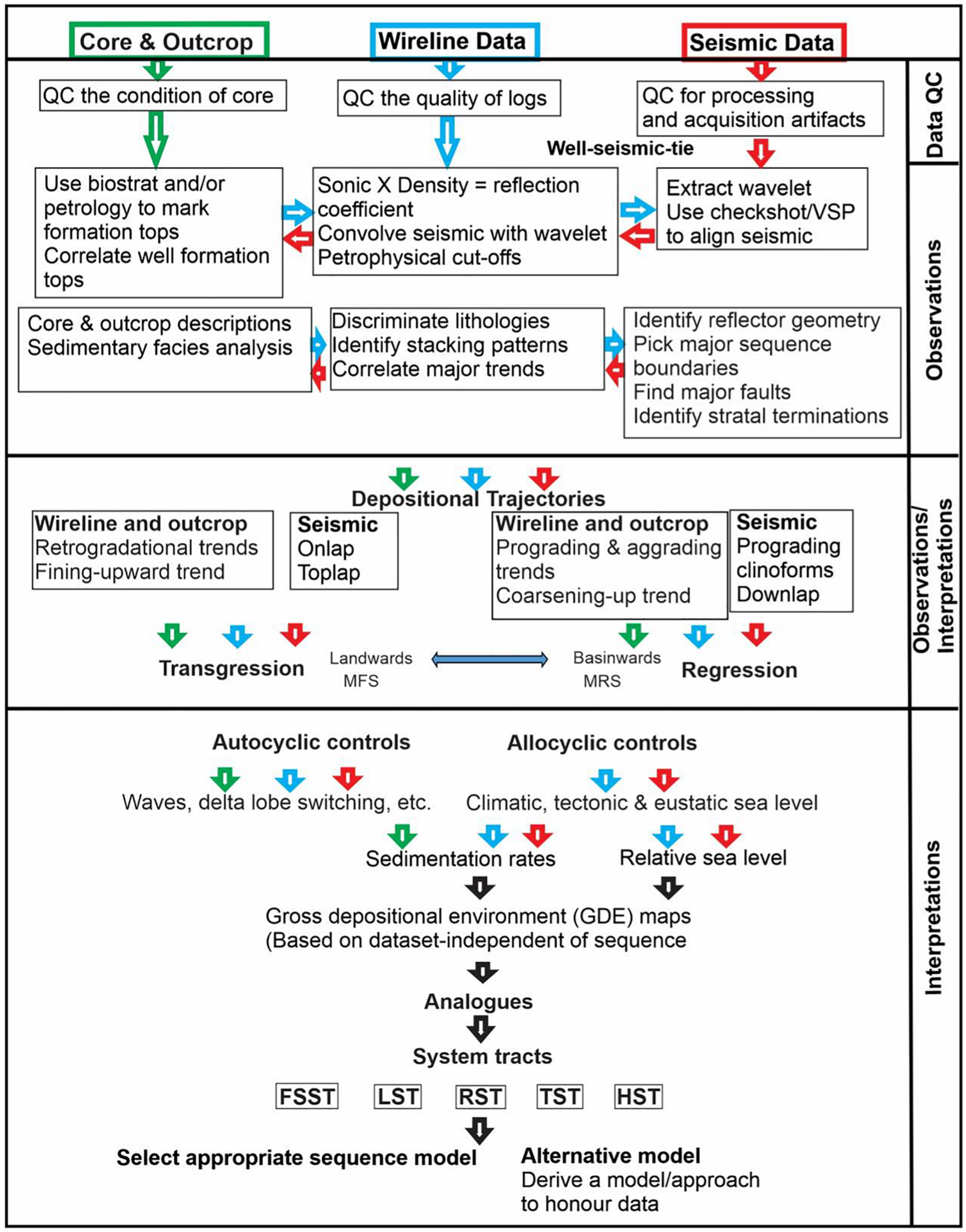


Fig. 6 Proposed workflow for sequence stratigraphic interpretations and building depositional models (adopted from Neal et al. 1993; Catuneanu 2006 p. 6; Miall and Strasser 2018; Neal et al. 2016; Burgess et al. 2016)

successions, which form a westward pinching wedge in the Port Elizabeth sub-basin, the wedge geometry in this stratal unit is less defined (Fig. 9b). On the seismic lines, most faults appear to propagate from the Top Tithonian, through to the Top Valanginian reflector, with very few faults observed in the older successions (Fig. 9b). Furthermore, thickness maps show a change in the depocenter strike direction from N-S in the Late Jurassic to NW–SE in the Early Cretaceous (Fig. 8). Overall, in the Algoa Basin, this unit shows dimming seismic reflectors in contrast to the surrounding reflectors. In the Gamtoos Basin, the Lower Valanginian unit, which onlap on the Top Berriasian reflector, contains bright reflectors that are subparallel and continuous (Fig. 9b). Towards the W, in the hanging walls, this unit is truncated at the top by the Top Valanginian (1At1) unconformity (Fig. 9b).

Syn-rift I interpretations

Aalenian to upper Kimmeridgian

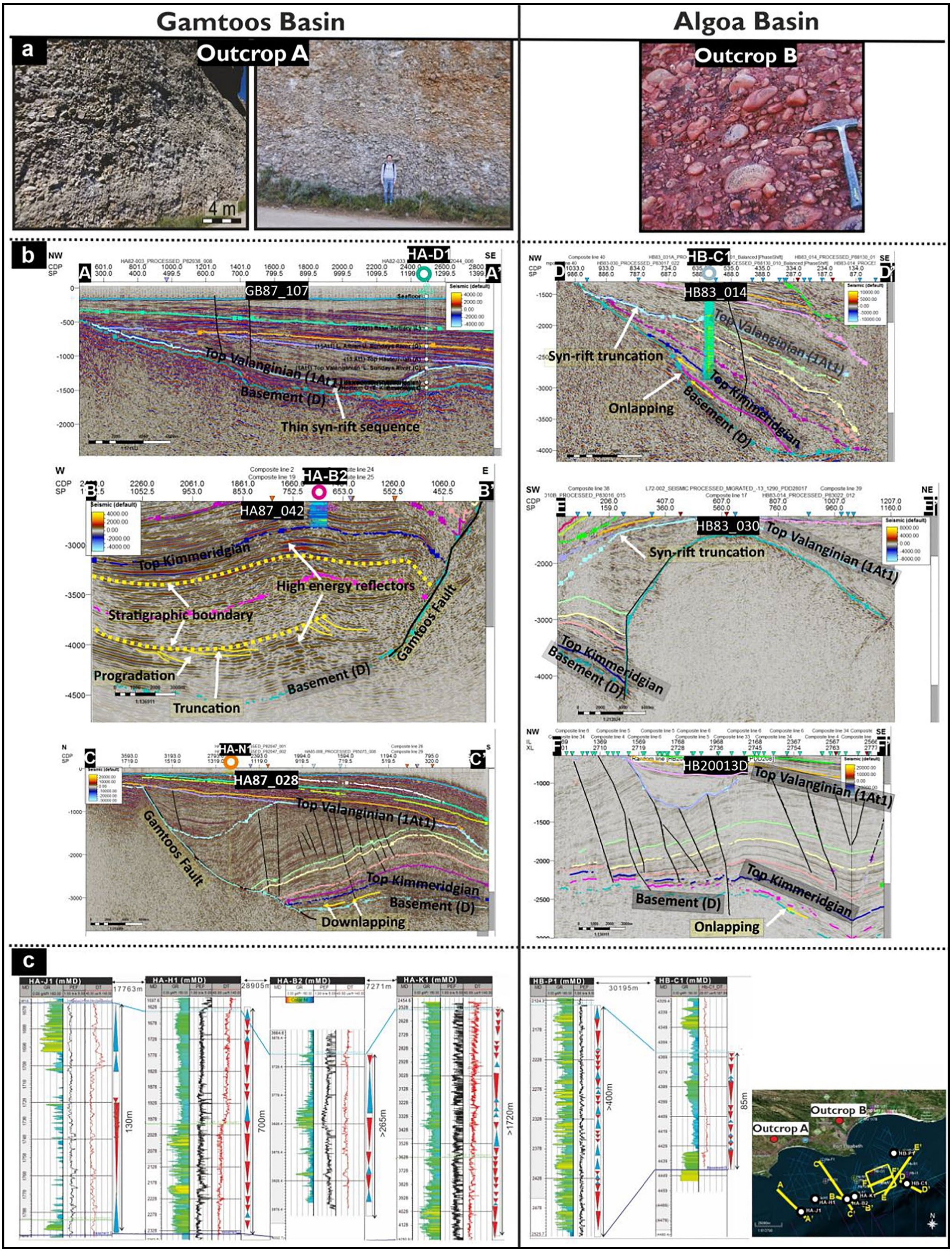
In the Algoa Basin, borehole HB-P1 intersected a succession with high net sand-to-shale ratio, while the more distal HB-C1 shows limited sand input (Fig. 7c). The presence of isolated coarsening-upward sandstones within the shaley interval in the distal borehole HB-C1 could represent prograding delta mouth bars, or sediments eroded from the basement subcrops. The combination of coarsening-upward and fining units and clay interbeds suggest that the depositional setting was probably alternating between coastal floodplains and shallow marine environments during a period characterized by fluctuating slow rise of RSL and sediment supply (Fig. 10a). This fluctuation is attributed to short lived tectonic pulses in syn-rift settings, resulting in increasing accommodation space (transgression), followed by longer period of tectonic quiescence which allows progradation of sediments (Martins-Neto and Catuneanu 2010). According to McMillan et al. (1997), borehole HB-A1 in the Port Elizabeth Trough is dominated by a microfauna that suggest a shallow marine-transitional setting, while borehole HB-K1 contains continental red beds, pebbly sandstone, and lignite-bearing claystones. Although these boreholes are close to each other, their different facies suggest contrasting marine vs. continental settings, with the red beds and lignite-bearing units possibly having formed on emergent basement highs (Fig. 10a).

There is significant lateral lithological heterogeneity in the Gamtoos Basin wireline data, with logs showing varying inferred grain-size and facies trends across the basin, a feature common in highly compartmentalized syn-rift successions (e.g., Chorowicz 2005; Holz et al. 2017). The lower part of borehole HA-J1 is dominated by shaley facies, overlain by well-defined, channelized, fining-upward sandstones (Fig. 7c). In contrast, the lower part of borehole HA-H1 is dominated by proximal high-energy, coarsening-, and fining-upward sandstones, which are overlain by a flooding surface and fine-grained sediments that are characteristic of low energy settings. Although the upper half of the borehole shows an overall coarsening-upward trend, the very low net sand-to-shale ratio suggests either decreased sedimentation rates, or a shoreline advancing landwards at faster rate than sediment input, which is typical during transgression (Fig. 2; Catuneanu 2006). In borehole HA-B2, the interval is mostly claystones, inferred to represent a predominantly low energy, distal depositional environment, with isolated sandstones representing rare events of higher energy sedimentation, possibly as basin floor fans in a deeper water setting (Fig. 10a). The proximity of borehole HA-K1 to the Recife Arch (Fig. 1) suggests that the coarsening-upward sandstones were probably eroded from the basement high and deposited as alluvial fans.

Most of the basal early rift sediments are not intersected by boreholes and the seismic resolution is very poor in the study area, consequently the interpretation of this succession is reliant on the onshore geological studies (e.g., Muir et al. 2015, 2017b; Muir 2019). These studies show that in the Algoa and Gamtoos basins, the Basement to Top Kimmeridgian, conglomerate-dominated succession of the Enon Formation was deposited primarily in high-energy, alluvial fan and braided river setting proximal to basin margin extensional faults, whereas its more distal facies equivalent, the mudstone and sandstone-bearing Kirkwood Formation, was a product of meandering rivers with vast floodplains that supported large, freshwater lakes. Due to the limited data resolution and data coverage, stratal geometry of this succession in the Algoa Basin remains largely unknown. In the Gamtoos Basin, the pre-Aalenian to upper Kimmeridgian succession thickens towards S of the Gamtoos Fault, indicating active faulting during deposition of this succession (Fig. 8a). The N-S striking, southern part of the fault was probably more active, creating larger accommodation space in S than in the N. Seismic data (Fig. 7c) shows eastward prograding reflectors (clinoforms) above the Basement D reflector overlain by chaotic seismic reflectors. Since progradation in a nearshore depositional context is typically a transitional to marine process, prograding clinoforms (Fig. 7c) are taken as evidence for a pre-Kimmeridgian marine incursion in the Gamtoos Basin. However, due to the unavailability of borehole data intersecting these progrades, the possibility of these progrades representing a deltaic environment cannot be ruled out. In which case, these progrades would suggest a transitional setting.

Post-Kimmeridgian to Early Valanginian

Dataset from this succession supports the widespread fluvial floodplain setting of the Kirkwood Formation established from outcrops studies (Muir et al. 2015, 2017b and references therein). The main depocenters appear to be localized near the NW–SE striking hanging walls, from the late Tithonian to early Valanginian (Fig. 8a, b). Unlike in the earlier depositional phase, when sedimentation was mainly along the N-S trending sector of the Gamtoos Basin, isopach maps shows active faulting along NW–SE strike from the Tithonian to Valanginian (Fig. 8a, b). This created accommodation space for marine conditions as the shoreline advanced landwards. This increase in accommodation could have resulted from the fault strain following pre-existing crustal scale structures of the underlying Paleozoic Cape Supergroup (Martin et al. 1981; de Wit 1992; Paton and Underhill 2004; Muir et al. 2020). Seismic mapping suggests that the sediments were supplied from the NW to S-SE, which is consistent with Kirkwood Formation provenance studies (Shone 1976). Although Muir et al. (2015) reported a localized SW to NE paleocurrent direction, this discrepancy is likely due to the meandering nature of the rivers in the Kirkwood Formation. According to McMillan et al. (1997) and Muir et al. (2017b, 2020), microfossils in the Kirkwood Formation also show evidence for low energy, lacustrine environments (Colchester Member) that were, among others, inhabited by freshwater algae, and thus these organic matter–rich lake deposits are also potential source rocks in the study area. However, data suggest that the lacustrine environment by this time was probably due to


Gamtoos Basin
Algoa Basin
a
Outcrop A
4 m
Outcrop B
b
NW
SE
HA-D1
GB87_107
Top Valanginian (1At1)
Basement (D)
Thin syn-rift sequence
HB-C1
HB83_014
Syn-rift truncation
Top Valanginian (1At1)
Onlapping
Top Kimmeridgian
Basement (D)
W
E
HA-B2
HA87_042
Top Kimmeridgian
High energy reflectors
Stratigraphic boundary
Progradation
Truncation
Basement (D)
Gamtoos Fault
SW
NE
HB83_030
Syn-rift truncation
Top Valanginian (1At1)
Top Kimmeridgian
Basement (D)
N
S
HA-N1
HA87_028
Top Valanginian (1At1)
Gamtoos Fault
Top Kimmeridgian
Basement (D)
Downlapping
HB20013D
Top Valanginian (1At1)
Basement (D)
Top Kimmeridgian
Onlapping
c
HA-J1 (mMD)
17763m
HA-H1 (mMD)
28905m
HA-B2 (mMD)
7271m
HA-K1 (mMD)
130m
700m
>265m
>1720m
HB-P1 (mMD)
30195m
HB-C1 (mMD)
>400m
85m
Outcrop B
Outcrop A

◂**Fig. 7** **a** Enon Formation outcrop images (taken from Muir et al. 2017b with permission from the author). **b** Seismic lines examples over the Algoa and Gamtoos basins. **c** Wireline logs intersecting the Kimmeridgian succession in the Algoa and Gamtoos basins. Base map data ©2020 Google, Maxar Technologies, AfriGIS (Pty) Ltd

oxbow lakes on the floodplain and drowning estuaries during transgression (Fig. 10b). In addition to the lacustrine setting, the Bethelsdorp Member in the lower Kirkwood Formation indicate the presence of low energy conditions, albeit in a marine setting, due to sea incursion during the Late Jurassic (McLachlan and McMillan 1976; McMillan et al. 1997; McMillan 2010; Muir et al. 2017b). This marine flooding appears to have coincided with the change to NW–SE trending depocenters during the Late Valanginian to Early Berriasian (Fig. 8a, b). The newly created accommodation space could have aided the marine flooding in the proximal onshore setting as the shoreline advanced towards N. The Bethelsdorp Member, which is a bioturbated, gray shaley succession, outcropping onshore in the Uitenhage Trough (e.g., near Jachtvlakte) attains a thickness of 400 m (Muir et al. 2017b). It also contains tabular sandstone beds that lack terrestrial fossils or red paleosols, contrary to the rest of the units in the Kirkwood Formation (Almond 2012; Muir et al. 2017b). This Late Jurassic marine influence in the early rift during does not de facto suggests the presence of an ocean floor in the area (McLachlan and McMillan 1976; Jungslager 1996; Koopmann et al. 2014; Muir et al. 2017b, 2020). However, evidence for a failed, pre-Tithonian (~178 Ma old), mid-oceanic ridge (MOR) was shown in the Falklands (Malvinas) Plateau Basin (Schimschal and Jokat 2019), which is a region placed near the study area in most paleogeographic reconstructions (e.g., Lovecchio et al. 2020; Muir et al. 2020).

Syn-rift II observations

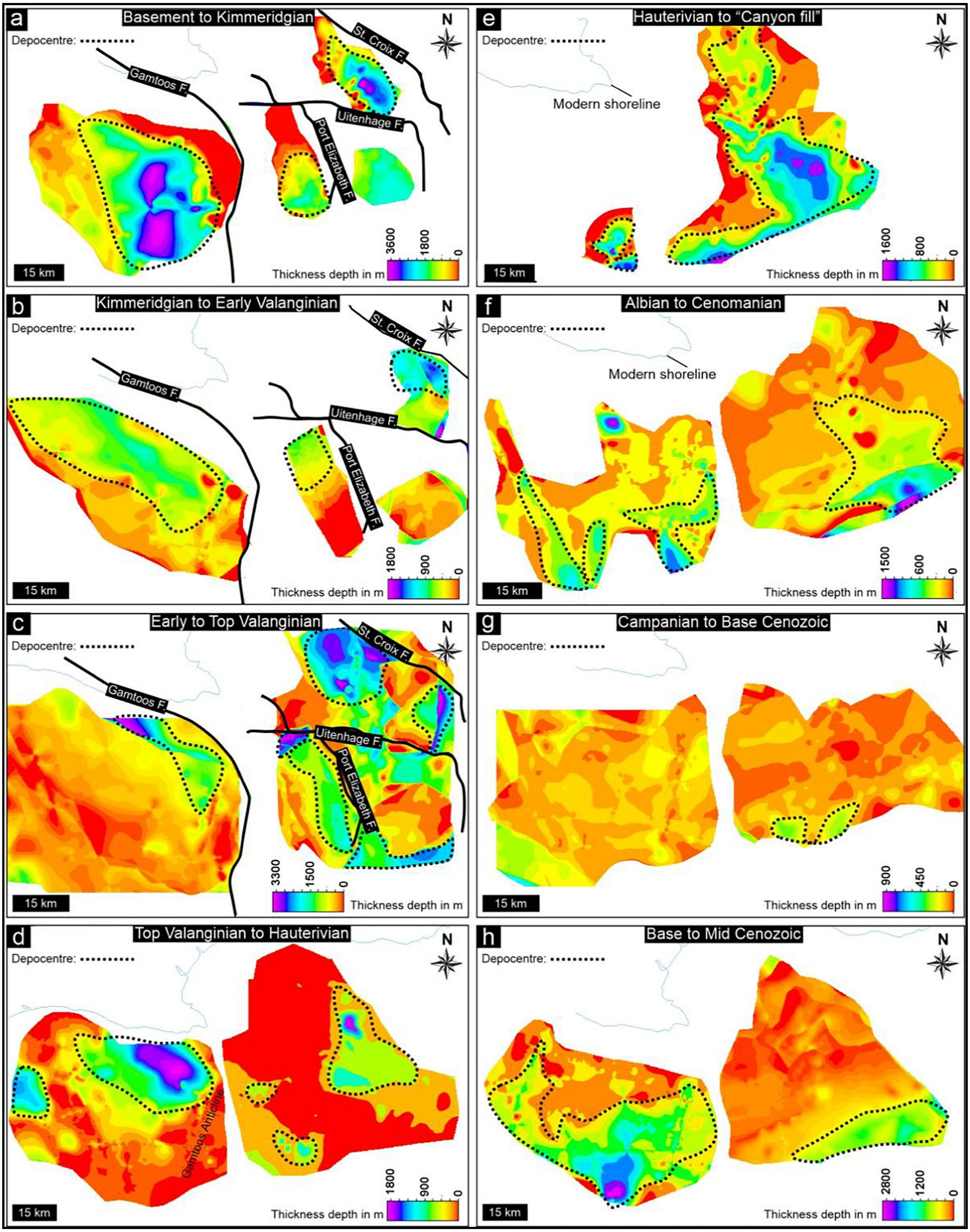
The Valanginian–Hauterivian Sundays River Formation is a mostly shallow marine succession, characterized by fossiliferous, green-gray–laminated mudstones (Fig. 11a; McLachlan and McMillan 1976; Shone 1978; McMillan 2003; Muir 2019). Syn-rift sequences generally shows lateral facies variability, with the logs dominated by alternating fining-upward and coarsening trends within the same succession. Wireline data from the upper Valanginian succession in the Uitenhage Trough shows a 190-m-thick unit of alternating low and high GR signatures (GR: 51–129 API), with coarsening-upward and fining trends in borehole HB-B1 (Fig. 11c). Borehole HB-I1, contains a > 800-m-thick logged succession dominated by low to high GR readings (GR: 52–145 API; Fig. 11c), with alternating coarsening-and fining-upward trends. In the distal borehole HB-C1, the same interval shows a coarsening-upward trend in a ~ 50-m-thick succession with relatively low GR signature (GR: 50–104 API). In the Gamtoos Basin, the upper Valanginian succession has a very low net sand-to-shale ratio, which increases towards the SW (Fig. 11b). Borehole HA-J1 is dominated by ~ 330-m-thick clay- and shale-rich unit that is sand-free (GR: 107–142 API), while borehole HA-D1 is dominated by a ~ 500-m-thick, aggrading sandy and silty unit (GR: 30–95 API; Fig. 11b). However, the uppermost 50 m in borehole HA-D1 intersected two cycles of coarsening-upward clean sands (GR: 20–45 API) separated by a flooding surface. Borehole HA-B2 is dominated by a ~ 375-m-thick unit of clean shales/clays (GR: 45–120 API) without any sand. Alternating, fining-upward and coarsening silty sands dominate in boreholes HA-G1 and HA-I1 over a thickness of 240 and 657 m with GR values of 69–104 and 50–125 API, respectively (Fig. 11b).

Most of this succession remains unresolved in the seismic data, because where preserved, the succession can be featureless and very thick (e.g., up to 3000 m in the Algoa Basin; Fig. 8c). Closer to the Port Elizabeth Fault, the reflectors in this succession show chaotic character. In the Uitenhage Trough, the succession appears to be folded (due to a later inversion; Thomson 1999) at the top, closer to the Uitenhage Fault (Fig. 11b). In both basins, the Top Valanginian reflector truncates the underlying syn-rift reflectors at the acute angle, especially towards the W (in the tilted hanging walls) and S (Fig. 11b). This succession also shows thinning towards the W and onlapping stratal terminations in W-E cross-sections (Fig. 11b). In the S, within the N-S trending sector of the Gamtoos Fault, the upper Valanginian succession is truncated by the 13At1 unconformity near the Gamtoos Anticline (Bate and Malan 1992; McMillan et al. 1997; Thomson 1999).

Syn-rift II interpretations

Based on sedimentological and paleontological characteristics (e.g., ammonites, belemnites, bivalves, gastropods, echinoids, crustaceans, polychaetes, corals), the depositional environment of the Valanginian-Hauterivian Sundays River Formation was reconstructed to span a range of marine settings from shallow marine, tidally influenced, estuarine to deltaic environments to deeper water shelf, and continental slope settings (Shone 2006; Muir 2019 p. 14–15).

Wireline data is dominated by fine-grained units, with a prominent shallow marine transgressive trend evident in borehole HB-I1 (Figs. 2 and 11c). In most places, this interval has been eroded (mostly on the tilted hanging walls), where only the lower part of the succession is preserved in some boreholes. For example, the sandy facies in the lower parts of boreholes HB-B1 and HB-C1 (Fig. 11c) might represent a period in the Valanginian before the onset of the marine transgression, when deposition was


a
Basement to Kimmeridgian
Depocentre:
Gamtoos F.
St. Croix F.
Uitenhage F.
Port Elizabeth F.
15 km
3600
1800
0
Thickness depth in m
b
Kimmeridgian to Early Valanginian
Depocentre:
Gamtoos F.
St. Croix F.
Uitenhage F.
Port Elizabeth F.
15 km
1800
900
0
Thickness depth in m
c
Early to Top Valanginian
Depocentre:
Gamtoos F.
St. Croix F.
Uitenhage F.
Port Elizabeth F.
15 km
3300
1500
0
Thickness depth in m
d
Top Valanginian to Hauterivian
Depocentre:
Gamtoos Anticline
15 km
1800
900
0
Thickness depth in m
e
Hauterivian to "Canyon fill"
Depocentre:
Modern shoreline
15 km
1600
800
0
Thickness depth in m
f
Albian to Cenomanian
Depocentre:
Modern shoreline
15 km
1500
600
0
Thickness depth in m
g
Campanian to Base Cenozoic
Depocentre:
15 km
900
450
0
Thickness depth in m
h
Base to Mid Cenozoic
Depocentre:
15 km
2800
1200
0
Thickness depth in m
N

◂**Fig. 8** Thickness maps from syn-rift to Holocene, highlighting the main depocenters during basin infill. **a** Pre-Aalenian to Kimmeridgian thickness map, showing a dominant N-S striking depocenter in the Gamtoos Basin and a NW–SE striking depocenter in the Uitenhage Trough. **b–c** NW–SE striking depocenter in the Gamtoos and Algoa basins from the Tithonian to upper Valanginian. **d** In the Gamtoos Basin, the depocenter is controlled by the geometry of the Gamtoos Anticline, in the Algoa Basin, the depocenter is a remnant of sediments not eroded during the Hauterivian to Aptian erosional event. **e** The orientation of the main depocenter was influenced by the geometry of the Algoa Canyon. **f, g, h** Drift phase depocenters located mainly towards the shelf edge

still predominantly occurring on fluvial or coastal floodplains (Fig. 2). In the Gamtoos Basin, borehole data is dominated by fine-grained successions, and is assumed to represent the dominant marine phase of deposition associated with the Sundays River Formation (Fig. 10c). The coarsening-upward sandy facies in the upper part of borehole HA-D1 could represent a deltaic or river mouth bar setting. Overall borehole data reflect the marine to nearshore character of deposition that was previously suggested for the Sundays River Formation (e.g., Shone 2006; Muir 2019).

Though this interval is severely eroded in the Algoa Basin, isopach maps in both the Algoa and Gamtoos basins show NW–SE (Fig. 8c) directed depocenters, suggesting that the syn-rift faults were still active during the later parts of the Valanginian. In the Port Elizabeth and Uitenhage troughs, this succession is folded, probably due to reactivation of the St. Crox and Uitenhage faults, respectively during later tectonic inversion (Thomson 1999). Because this succession, which can be up to 2500-m-thick, has been intersected by few boreholes (Fig. 11c), its lateral and vertical facies are poorly understood. In both basins, this succession marks a major transgressive event (bound at the top by the 1At1 sequence boundary), which erodes large tracts of syn-rift deposits represented by the Enon and Kirkwood formations (Figs. 2 and 11b). The 1At1 boundary marks a period when the Algoa and Gamtoos basins were hydraulically connected for the first time. It is thus a major flooding surface (i.e., a maximum flooding surface—MFS) that separates the older continental from the younger marine deposits (i.e., the Enon-Kirkwood formations from the Sundays River Formation), as attested by outcrops rich in marine fossils across the southern half of the Algoa Basin (Fig. 10c). It is noteworthy that while the Bethelsdorp Member in the lower Kirkwood Formation and the Sundays River Formation are lithologically alike and are both underlain by marine flooding surfaces due to their similar marine origin (e.g., Almond 2012; Muir et al. 2017b; Muir 2019), the older Bethelsdorp Member has a more localized occurrence, whereas the Sundays River Formation is regionally extensive (and coeval with the upper Kirkwood Formation).

Transitional phase observations

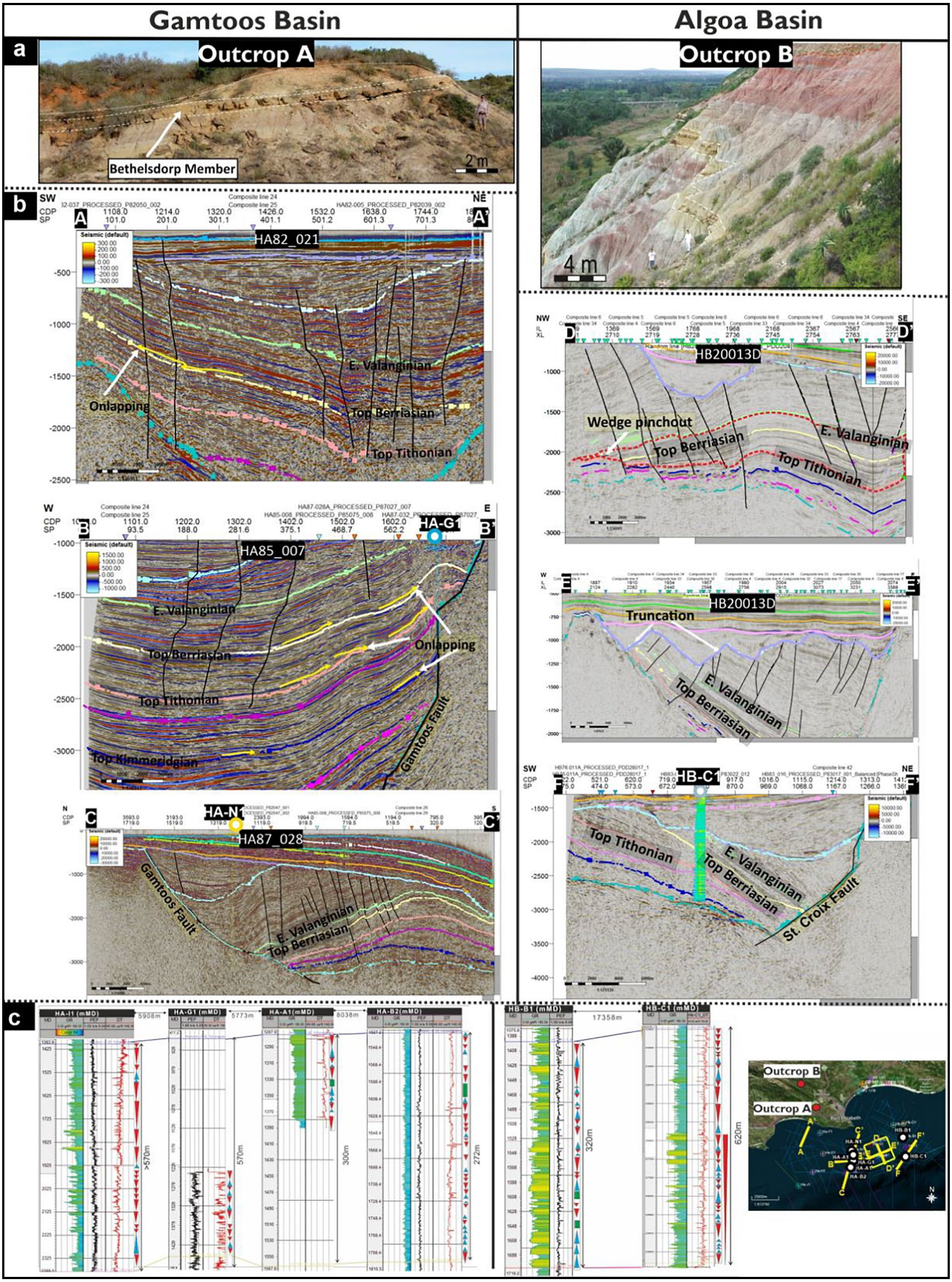
Post-Valanginian to upper Hauterivian

Most of this succession has been severely eroded during the late Aptian uplift event (Dingle et al. 1983; Broad 1990; Bate and Malan 1992; McMillan et al. 1997; Broad et al. 2012); as a result, there is very limited data available for this interval. The sequence is preserved in a total thickness of 120 m in borehole HB-B1, and shows a change from predominantly coarsening-upward at the base (~75-m-thick, GR: 45–110 API; Fig. 12b) to fining-upward at the top (~45-m-thick, GR: 54–125 API; Fig. 12b). In the Gamtoos Basin, boreholes HA-J1 (~208 m-thick, GR: 92–143 API) and HA-D1 (~600 m-thick, GR: 35–105 API) intersected a predominantly fine-grained succession that seems to show a coarsening-upward trend (Fig. 12).

In places, where the Hauterivian succession is preserved, the generally dim reflectors are parallel, semi-continuous, and show evidence for a few prograding strata dripping to the SW (Fig. 12a). Moreover, some brighter basal reflectors appear to onlap on the Top Valanginian reflector (Fig. 12a). In contrast to the younger successions, which are folded and form the so-called Gamtoos Anticline (that is more evident in the N-S trending part of the Gamtoos Fault; Thomson 1999), this Hauterivian succession onlaps onto the Gamtoos Anticline. Most of this succession is truncated by the Top Hauterivian (13At1) reflector, which in some places also truncates and forms a composite unconformity with the 1At1 reflector (Fig. 12a).

Post-Hauterivian to "Canyon fill" (early Albian)

This interval is more prominent in the Algoa Basin, along the Algoa Canyon (Fig. 13a). In the Gamtoos Basin, this succession is laterally constrained to the Gamtoos Canyon, which is significantly smaller than the Algoa Canyon. Borehole HB-H1 in the Port Elizabeth Trough is dominated by a ~65 m-thick sandy unit (GR: 28–62 API), with an overall cylindrical GR shape (Fig. 13b). Although the Uitenhage Trough is dominated by fine-grained sediments (i.e., 200-m- and 1420-m-thick in boreholes HB-B1 and HB-I1, respectively), there are some isolated, thin, coarsening-upward sandstones in this interval. The more distal borehole HB-C1 is intersected a ~470-m-thick, fine-grained unit (GR: 83–116 API) that lacks sandy interbeds (Fig. 13b). Although borehole HB-H1intersected "Canyon fill" sediments, mapping this canyon succession in the Port Elizabeth Trough is challenging, because it is absent in most parts of this trough, and seems to be localized around the borehole itself. This is exacerbated by the overall poor data quality, and therefore this succession is omitted from Fig. 13a in the Port Elizabeth Trough. Along the Algoa Canyon, seismic reflectors are very


Gamtoos Basin
Algoa Basin
a
Outcrop A
Bethelsdorp Member
2 m
Outcrop B
4 m
b
HA82_021
Onlapping
E. Valanginian
Top Berriasian
Top Tithonian
HA85_007
HA-G1
E. Valanginian
Top Berriasian
Onlapping
Top Tithonian
Top Kimmeridgian
Gamtoos Fault
HA-N1
HA87_028
Gamtoos Fault
E. Valanginian
Top Berriasian
HB20013D
Wedge pinchout
Top Berriasian
E. Valanginian
Top Tithonian
HB20013D
Truncation
E. Valanginian
Top Berriasian
HB-C1
Top Tithonian
E. Valanginian
Top Berriasian
St. Croix Fault
c
HA-I1 (mMD)
HA-G1 (mMD)
HA-A1 (mMD)
HA-B2 (mMD)
5908m
5773m
8038m
>570m
570m
300m
272m
HB-B1 (mMD)
HB-C1 (mMD)
17358m
320m
620m
Outcrop B
Outcrop A

◀**Fig. 9** **a** Outcrop A—Bethelsdorp member near Jachtvlakte. Outcrop B—Kirkwood Formation outcrop in the Algoa Basin (taken from Muir 2019; Muir et al. 2017b with permission from the authors). **b** Seismic lines examples over the Algoa and Gamtoos basins. **c** Wireline logs intersecting the early Valanginian succession in the Algoa and Gamtoos basins. Base map data ©2020 Google, Maxar Technologies, AfriGIS (Pty) Ltd

chaotic and discontinuous in the N-S direction, downlapping on the Top Hauterivian reflector, while a SW-NW cross-section shows onlapping stratal geometries onto the Top Hauterivian reflector (Fig. 13a). The lower part of this succession contains horizontal reflectors, while the top appears to be prograding from the NW to SE; incised features are also observed in this section (Fig. 13a).

Transitional phase interpretations

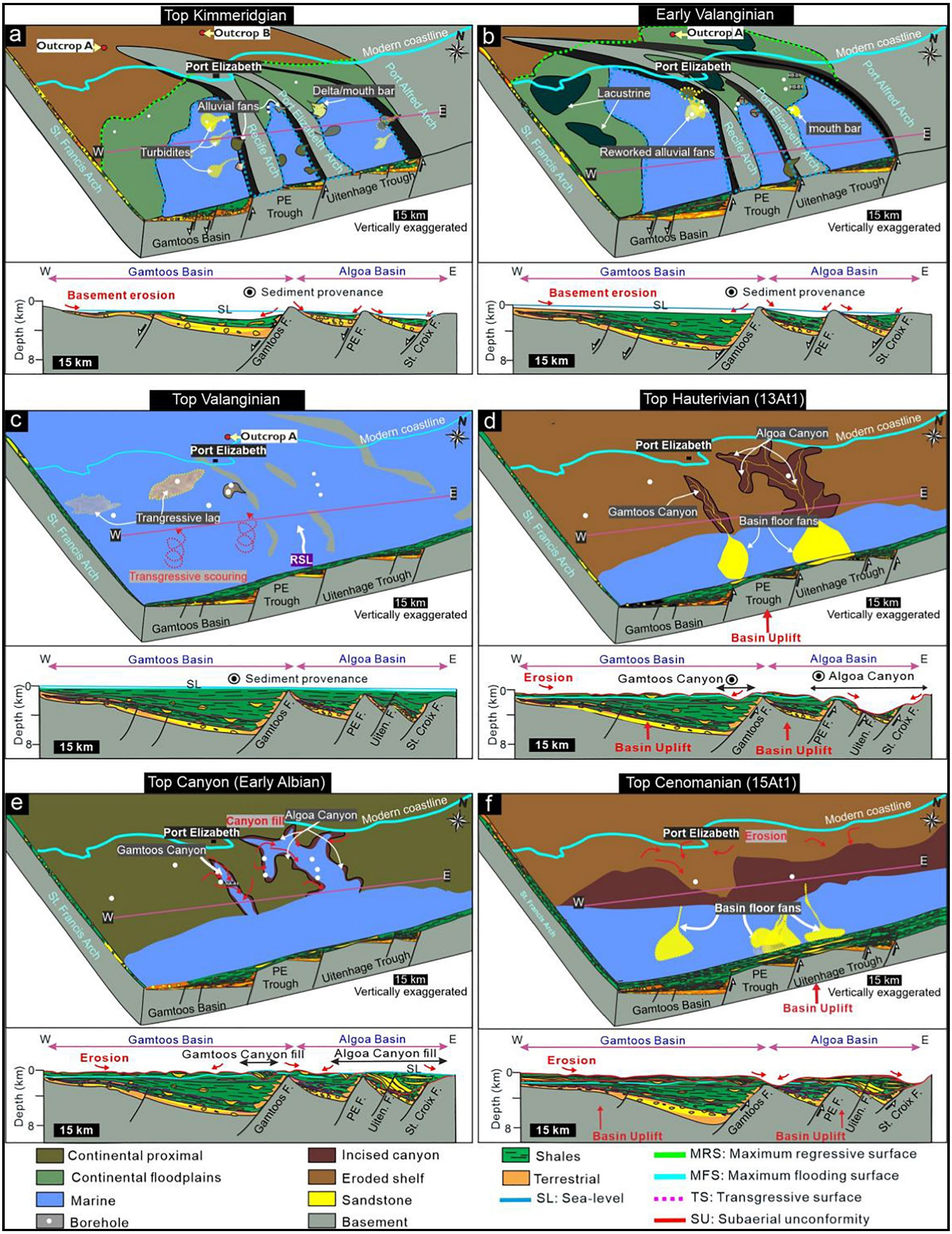
Post-Valanginian to upper Hauterivian

In borehole HB-B1, the basal coarsening-upward trend suggests a regressive shoreline, overlain by what appears to be stacked fining-upwards successions (Fig. 12b). These fining-upward deposits that are likely fluvial in origin, indicating increased depositional energy, probably during the initiation of the uplift during the late Hauterivian (Fig. 12b; McLachlan and McMillan 1976; Dingle et al. 1983; Malan 1993; Brown et al. 1995; Thompson 1999; Paton and Underhill 2004). In the Gamtoos Basin, this succession shows low energy facies that lacks sandy interbeds in both boreholes HA-J1 and HA-D1, and thus was probably deposited when the basin was still experiencing marine conditions during the early Hauterivian before the late Hauterivian/Aptian uplift and erosion (Figs. 2 and 12b). Seismic data show that the late Hauterivian unconformity was widespread across the basin, and when it formed, large tracts of the underlying syn-rift succession were eroded in both basins (but especially in the Algoa Basin; Figs. 12b and 10d). In the Port Elizabeth Trough, where the erosion was less severe, the onlapping lower Hauterivian seismic reflectors indicate an increasing accommodation space during the early Hauterivian (Fig. 12a). A common feature within this succession is a lateral change in seismic facies, where the brighter (higher energy) reflectors might indicate the presence of sands and dimmer facies indicating shales/clays (Fig. 12b).

In the Gamtoos Basin, accretional stratal geometries are observed towards the upper Hauterivian succession, which could be due to migrating bypass channels, with sediments making their way to the basin. The Top Hauterivian reflector (13At1) is highly erosive, and in some places, this reflector forms a composite unconformity with the 1At1/6At1 reflectors. In places, the Top Hauterivian reflector also erosively cuts into the syn-rift/transitional phase sediments (Fig. 12a). Towards the S, in the N-S trending part of the Gamtoos Fault, this succession onlaps on the Gamtoos Anticline (McMillan et al. 1997; Thomson 1999) and appears to be syn-tectonic in the lower part of the succession (6At1?). Although the stress field responsible for the formation of the Gamtoos Anticline is poorly understood (Thomson 1999), this structural feature shows a period of inversion, which probably formed during the Hauterivian to Aptian uplift episode (see Thomson 1999, his Fig. 9). The presence of canyons and truncational features on the shelf collectively suggest that the shoreline was pushed to the shelf edge during a RSL fall in the late Hauterivian (Fig. 10d). The shelf edge shoreline means that most sediments were being deposited as high-density basin floor fans in the distal parts of the Algoa and Gamtoos basins (Fig. 10d). This depositional unit is estimated to be similar in age to the recently discovered Brulpadda and Luiperd prospects in the Outeniqua Basin (Africa Energy Corp 2020). In the shelf regions of Algoa and Gamtoos basins, bypass channels with limited coarse-grained sediments are expected. The intensity of scouring and canyon features in the Algoa Basin could suggest that the Algoa Basin was more uplifted than the Gamtoos Basin.

Post-Hauterivian to "Canyon fill" (early Albian)

In the Algoa Basin, this interval is intersected in boreholes HB-H1, HB-B1, HB-I1, and HB-C1 (Fig. 13b). Borehole HB-H1 in the Port Elizabeth Trough is dominated by very fine-grained, coarsening-upward sands, and does not show any marine influence (Fig. 13b). Boreholes HB-B1, HB-H1, and HB-C1 on the other hand are dominated by low energy sediments (possibly marine), with very limited sand input (Fig. 13b). However, unlike boreholes HB-B1 and HB-I1, in which isolated thin, very fine coarsening-upward sands are present, borehole HB-C1 is sand-free, and thus can potentially indicate a marine setting in the Uitenhage Trough, at a time when the Port Elizabeth Trough was dominated by fluvial processes. In the Gamtoos Basin, this interval is intersected by borehole HA-A1, which shows an overall non-graded profile, consisting of coarsening-upward and fining units (Fig. 13b). The "Canyon fill" isopach map in the Algoa Basin depicts a NW–SE trending depocenter, within which sediments thicken towards the SE (Fig. 8e). The base of this succession onlaps onto the Top Hauterivian reflector, indicating a period of increasing accommodation space, whereas the upper succession is dominated by channel accretion geometries in the canyon (Fig. 13a). Basal onlapping stratal geometries on the Top Hauterivian reflector indicate a landwards moving shoreline due to possible increased accommodation space linked to a presumed rise in RSL (Fig. 10e). The upper "Canyon fill" is dominated by channel incisions and contain clinoforms prograding to SE, which were probably deposited during normal regression.



Top Kimmeridgian
a
Outcrop A
Outcrop B
Port Elizabeth
Modern coastline
Alluvial fans
Delta/mouth bar
Turbidites
Recife Arch
Port Elizabeth Arch
Port Alfred Arch
St. Francis Arch
PE Trough
Uitenhage Trough
Gamtoos Basin
15 km
Vertically exaggerated
Early Valanginian
b
Lacustrine
Reworked alluvial fans
mouth bar
Top Valanginian
c
Trangressive lag
Transgressive scouring
RSL
Top Hauterivian (13At1)
d
Algoa Canyon
Gamtoos Canyon
Basin floor fans
Basin Uplift
Top Canyon (Early Albian)
e
Canyon fill
Top Cenomanian (15At1)
f
Erosion
W
E
Algoa Basin
Basement erosion
Sediment provenance
SL
Depth (km)
Gamtoos F.
PE F.
Uiten. F.
St. Croix F.
Gamtoos Canyon fill
Algoa Canyon fill
Continental proximal
Continental floodplains
Marine
Borehole
Incised canyon
Eroded shelf
Sandstone
Basement
Shales
Terrestrial
SL: Sea-level
MRS: Maximum regressive surface
MFS: Maximum flooding surface
TS: Transgressive surface
SU: Subaerial unconformity

◂**Fig. 10** Aalenian to upper Cenomanian gross depositional models, showing the basin evolution from syn-rift to transitional and then to drift phase. **a–b** syn-rift phase deposition compartmentalized into sub-basins bound by the Gamtoos, Port Elizabeth, St. Croix Fault. **c** Late Valanginian increase in RSL over the Algoa and Gamtoos basins. **d** Hauterivian to Aptian uplift and erosion, resulting in the Algoa and Gamtoos canyons. **e** Early Albian "Canyon fill" phase. **f** Late Cretaceous uplift and erosion, resulting in the shelf/shelf edge scouring. (See Figs. 7, 9 and 11 for outcrop images noted above)

In the Gamtoos Basin, "Canyon fill" sediments are confined and laterally limited, and appear to prograde predominantly from the W, which may have been a possible sediment entry point (Figs. 13a and 8e). These eastwards prograding clinoforms appear to be eroded by a younger channel indicating an increase in environmental energy and concomitant shift from marine to fluvial conditions (Fig. 13a).

Drift phase observations

Post-Hauterivian/"Canyon fill" to upper Cenomanian

The Cenomanian is ~ 440-m-thick and contains two main coarsening-upward successions in borehole HB-C1, with the lower one being dominated by high GR readings between 63 and 85 API, while the upper one being dominated by relatively low GR signatures of 56–72 API (Fig. 14b). However, unlike the underlying succession, this interval is less sandy (dominated by fining-upward and coarsening silty sands). Borehole HA-A1 in the Gamtoos Basin contains a 62-m-thick Cenomanian succession with relatively high GR readings of 60–90 API and alternating fining-upward and coarsening units (Fig. 14b). Seismic reflectors within this succession are brighter, continuous, and onlap onto the Top Albian reflector (Fig. 14a). Seismic data also show lateral accretional stratal geometries from the N-NW towards the S-SE in the more proximal setting (Fig. 14b). The Top Cenomanian reflector truncates the Top Albian reflector and cuts into top of the syn-rift sequence. This truncation is more evident at the shelf break (which appears to have developed in the Albian), where the erosion caused highly irregular topography (Fig. 14a).

Post-Cenomanian to Lower Cenozoic

Contrary to the underlying and overlying successions, the Upper Cretaceous, which is an 80-m-thick unit in HB-C1 in the Algoa Basin, shows relatively high GR readings of 58–97 API and consists of fining-upward and coarsening trends (Fig. 15b). Although the GR readings show fining-upward and coarsening units, there is less sand in the Algoa shelf compared to the one in the Gamtoos Basin, where borehole HA-A1 is dominated by a 85-m-thick unit with low GR readings of 40–65 API (Fig. 15b). On the shelf, the Upper Cretaceous seismic reflectors onlap on the Top Campanian reflector. In the Port Elizabeth Trough, the base of this succession shows chaotic reflectors, closer to the shelf edge. In the slope setting, this succession onlaps onto the Top Campanian reflector and shows evidence of clinoforms that prograde towards SE (Fig. 15a).

Lower to Middle Cenozoic

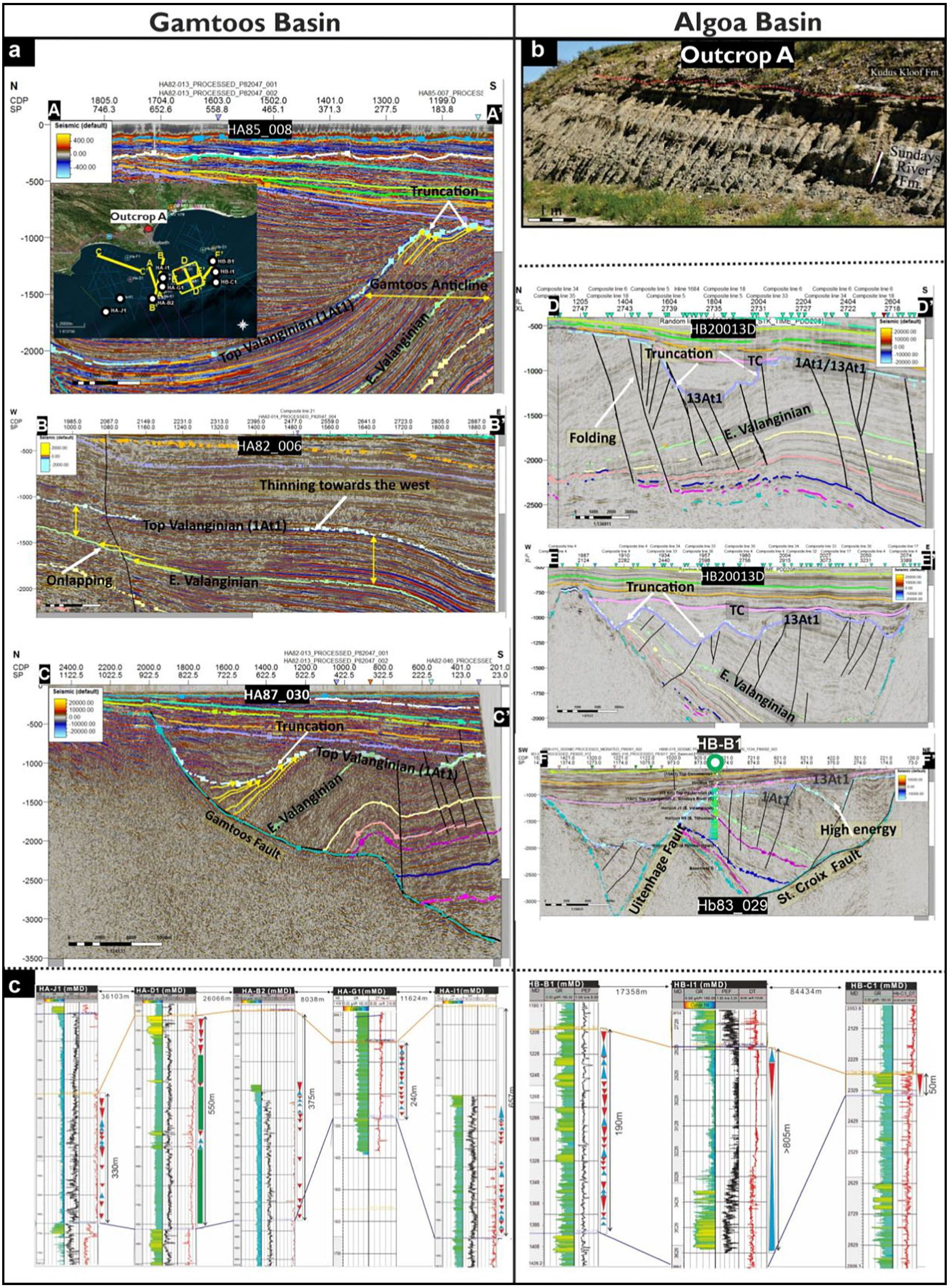
In the Algoa Basin, borehole HB-C1 contains one ~ 356-m-thick, overall coarsening-upward unit with GR readings of 38–93 API (Fig. 16b). Although borehole HA-C1 has an overall coarsening-upward trend, it is made up of smaller alternating fining-upward and coarsening units and its lower portion is dominated by shaley facies. In the Gamtoos Basin, borehole HA-A1 contains one 130-m-thick, aggrading sandy unit that has low GR reading of 30–40 API without any obvious clay or silt content (Fig. 16b).

The Base to Mid-Cenozoic reflectors are semi-continuous and show a dimming character in contrast to the underlying post-rift succession (Fig. 16a). Along a NW–SE section, these reflectors downlap onto the Base Cenozoic reflector along the shelf, while prograding on the slope/shelf edge from the N towards S. The Mid-Cenozoic reflector truncates the underlying, Cretaceous succession at an acute angle (Fig. 16a). This truncation is also notable towards the shelf edge/slope (Fig. 16a).

Drift phase interpretations

Post-Hauterivian/ "Canyon fill" to upper Cenomanian

In the Gamtoos Basin, this interval was most likely deposited in a shelfal setting, as suggested by the persistence of glauconitic claystones (McMillan et al. 1997). The lower portions of boreholes HB-C1 and HA-A1 are dominated by shaley facies, which were probably deposited during a flooding event after the Albian shoreline regression (Fig. 2). In contrast, this interval appears to be sandier in the Algoa Basin, evident by the low GR readings in the distal borehole HB-C1 (and borehole HB-I1; McMillan et al. 1997). The base of this succession onlaps on the Top Albian reflector (more so in the distal setting) and is overlain by southward prograding clinoforms that downlap on the Top Albian reflector (more evident in the proximal setting). The onlapping stratal terminations and the flooding event overlying the Top Albian boundary indicate a shoreline transgression during the early Cenomanian, which could be associated with an increasing RSL (Fig. 2). The southward prograding clinoforms and sandy facies overlying the transgressive sediments indicate increased sedimentation rates causing shoreline regression in the late Cenomanian. These prograding clinoforms are truncated by the highly erosive Top Cenomanian (15At1)


Gamtoos Basin
Algoa Basin
a
b
Outcrop A
Kudus Kloof Fm.
Sundays River Fm.
HA85_008
Truncation
Gamtoos Anticline
Top Valanginian (1At1)
E. Valanginian
HA82_006
Thinning towards the west
Onlapping
HA87_030
Gamtoos Fault
HB20013D
TC
1At1/13At1
13At1
Folding
HB-B1
High energy
Uitenhage Fault
St. Croix Fault
Hb83_029
c
HA-J1 (mMD)
HA-D1 (mMD)
HA-B2 (mMD)
HA-G1(mMD)
HA-I1(mMD)
HB-B1 (mMD)
HB-I1 (mMD)
HB-C1 (mMD)
36103m
26066m
8038m
11624m
17358m
84434m
330m
550m
375m
240m
657m
190m
>805m
50m

◂**Fig. 11** **a** Seismic line examples from the Algoa and Gamtoos basins. **b** Sundays River Formation outcrop images (taken from Muir 2019 with permission from the author). **c** Wireline logs intersecting the Kimmeridgian succession in the Algoa and Gamtoos basins. Base map data ©2020 Google, Maxar Technologies, AfriGIS (Pty) Ltd

unconformity, which forms an irregular topography in seismic data indicative of strong incision (Figs. 2, 10f, and 14). Towards the shelf edge, the Top Cenomanian unconformity is observed to erode into the syn-rift sequence. The uplift associated with this unconformity was accompanied by more than a 100-m drop in the relative sea level in the Outeniqua Basin (Baby et al. 2018). While this Upper Cretaceous erosional event did not result in as deeply incised canyons as the 13At1 erosional event, it left much of the shelf scoured. This means the shoreline was probably pushed towards the shelf edge sometime during the Late Cretaceous (Turonian to early Campanian?), resulting in shelf sediment bypass with a possibility of depositing the sands as fans in the basin (Figs. 2, 10f, and 14). Although the source of this uplift is still uncertain (Baby et al. 2018), the 15At1 unconformity is thought to have been a result of thermal subsidence in the distal offshore, which caused uplift in the proximal setting (Malan 1993).

Post-Cenomanian to Lower Cenozoic

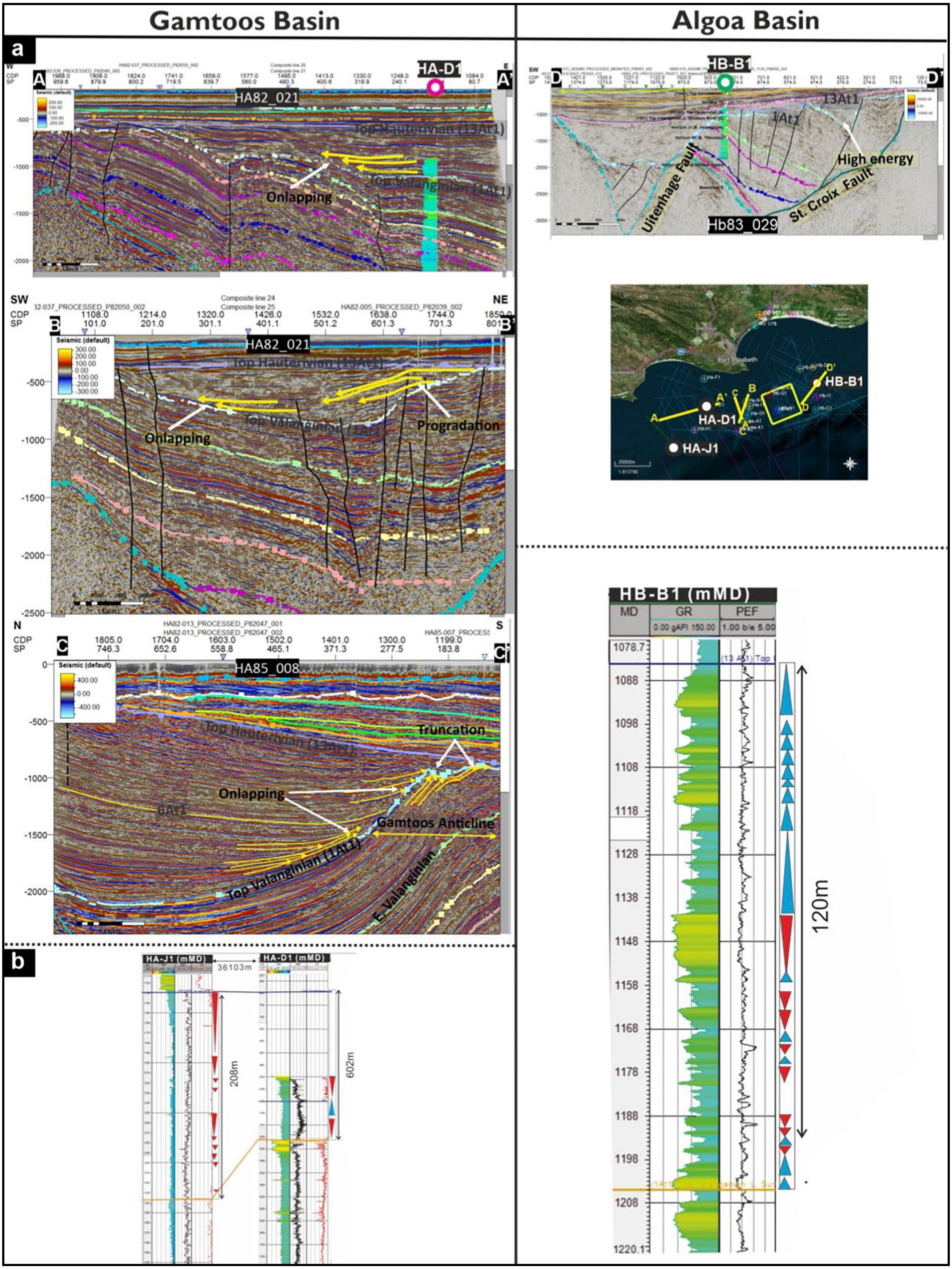
Overlying the Top Cenomanian reflector, clinoforms of the slope setting were prograding towards SE and indicate the position of the shoreline after the RSL fall (Fig. 2). Relative sea level began to increase during the Late Cretaceous and in some places, the shoreline appears to have migrated to a position geographically inland, a short distance N of the modern shoreline (Baby et al. 2018). This major transgressive period was caused by subsidence during the Campanian (McLachlan and McMillan 1976; McMillan et al. 1997). The contact between the Upper Cretaceous and the Lower Cenozoic is gradational, and thus it is challenging to identify it on lithological grounds; however, changes in microfauna from the Cretaceous and the Cenozoic are significant enough to diagnose this contact on biostratigraphic grounds.

In the Algoa Basin, the retrogradational stacking pattern in borehole HB-C1 points to a transgressive shoreline during the Late Cretaceous in contrast to the older progradational successions (i.e., regression from the Albian to the upper Campanian; Fig. 2). According to Hattingh (2001), the Lower Cenozoic succession in the Algoa Basin was deposited during high sea level, which is consistent with the observations herein. The lack of fluvial deposits in the Algoa Basin from the Late Cretaceous to Early Cenozoic (Hattingh 2001) could explain why this interval is relatively sand-free. In the proximal setting, this high sea level caused a reduction in the fluvial gradient and the eventual termination (drowning) of the fluvial system in the Algoa Basin (Hattingh 2001). Although this interval is relatively thin, it is dominated by aggradational stacking of clinoforms, while the base of the succession onlaps on the Top Campanian reflector in the slope setting, representing a period of increased accommodation space (Fig. 2). In contrast, in the borehole HA-A1 of the Gamtoos Basin, this interval shows evidence for a regressive shoreline, probably due to an active, nearby sediment source in this basin. Moreover, this succession mostly progrades and downlaps on the Top Campanian reflector without any obvious onlapping stratal terminations. Therefore, although RSL was increasing, sedimentation rates were high in the Gamtoos Basin, causing the shoreline to regress, while the Algoa Basin was undergoing transgression (Figs. 2 and 17a).

Lower to Middle Cenozoic

This succession is associated with an uplift during the Oligocene (?), which resulted in a major erosional event observed regionally on seismic data. This erosion was due to the second uplift of the Southern African Plateau and probably lasted from the Eocene to early Oligocene (Hattingh 2001; Baby et al. 2018). This period of shelf scouring reactivated the fluvial system (notably the Baakens and Shark River valleys) in the Algoa Basin, which became more prominent after the Eocene uplift (Hattingh 2001). According to McMillan et al. (1997), this interval is thicker relative to the underlying Lower Cenozoic succession and is dominated by silty clays; however, borehole data (HB-C1) shows an overall coarsening-upward sandy unit, probably sourced from the reactivated fluvial system. Similarly, borehole HA-A1 in the Gamtoos Basin is also dominated by clean sandy facies throughout (Fig. 16b). The sand at the top of borehole HB-C1 could indicate a reactivated sandy sediment source in the Algoa Basin. Post the Mid-Cenozoic unconformity (i.e., Miocene to Holocene), GR logs show low reading, homogenous, and non-graded profiles. This succession, presently being deposited on the shelf can be correlated with the Algoa Group actively being deposited onshore during over the last 20 Ma (Illenberger 1992; Hattingh 2001).

In both basins, shelfal seismic reflectors appear to prograde from N to S, and downlap on the Base Cenozoic reflector (Fig. 16a). Borehole and seismic data suggest a period of high sedimentation resulting in shoreline regression. This surface truncates the drift phase succession in a similar manner as the 1At1 unconformity truncates the syn-rift succession. However, this unconformity was caused by basin wide tilting (uplift) during the late Paleogene (Figs. 2 and 17b; Hattingh 2001; Baby et al. 2018). This unconformity is also observed in Zululand Basin in the E and along the Atlantic margin in the W (Stevenson and McMillan 2004;



Gamtoos Basin
Algoa Basin
a
HA-D1
HA82_021
Top Hauterivian (13At1)
Onlapping
Top Valanginian (1At1)
HB-B1
13At1
1At1
High energy
Uitenhage Fault
St. Croix Fault
Hb83_029
SW
NE
Prograding
HA-J1
HA85_008
Truncation
Gamtoos Anticline
6At1
E. Valanginian
N
S
b
HA-J1 (mMD)
HA-D1 (mMD)
36103m
208m
602m
HB-B1 (mMD)
MD
GR
PEF
120m

◂**Fig. 12** **a** Seismic lines examples over the Algoa and Gamtoos basins. **b** Wireline logs intersecting the Hauterivian succession in the Algoa and Gamtoos basins. Base map data ©2020 Google, Maxar Technologies, AfriGIS (Pty) Ltd

Baby et al. 2018). In the study region, tilting of the older rocks appear to be dominant along the N-S strike, with the northern side of the basin being eroded (Fig. 17b). Post the Eocene to Oligocene uplift, Hattingh (2001) onshore studies also suggest that the RSL increased to 300 m higher than the current level from the Late Miocene to Holocene, indicating the landwards most position of the shoreline before it regressed to its modern position (Fig. 17c). This regression (forced?) was probably due to the eastwards tilt of the Algoa Basin during the Late Miocene to Holocene and was responsible for creating present day terraces onshore the Algoa Basin (Hattingh 2001). However, unfortunately much of the post-Oligocene succession is below seismic resolution for us to confidently correlate with onshore studies.

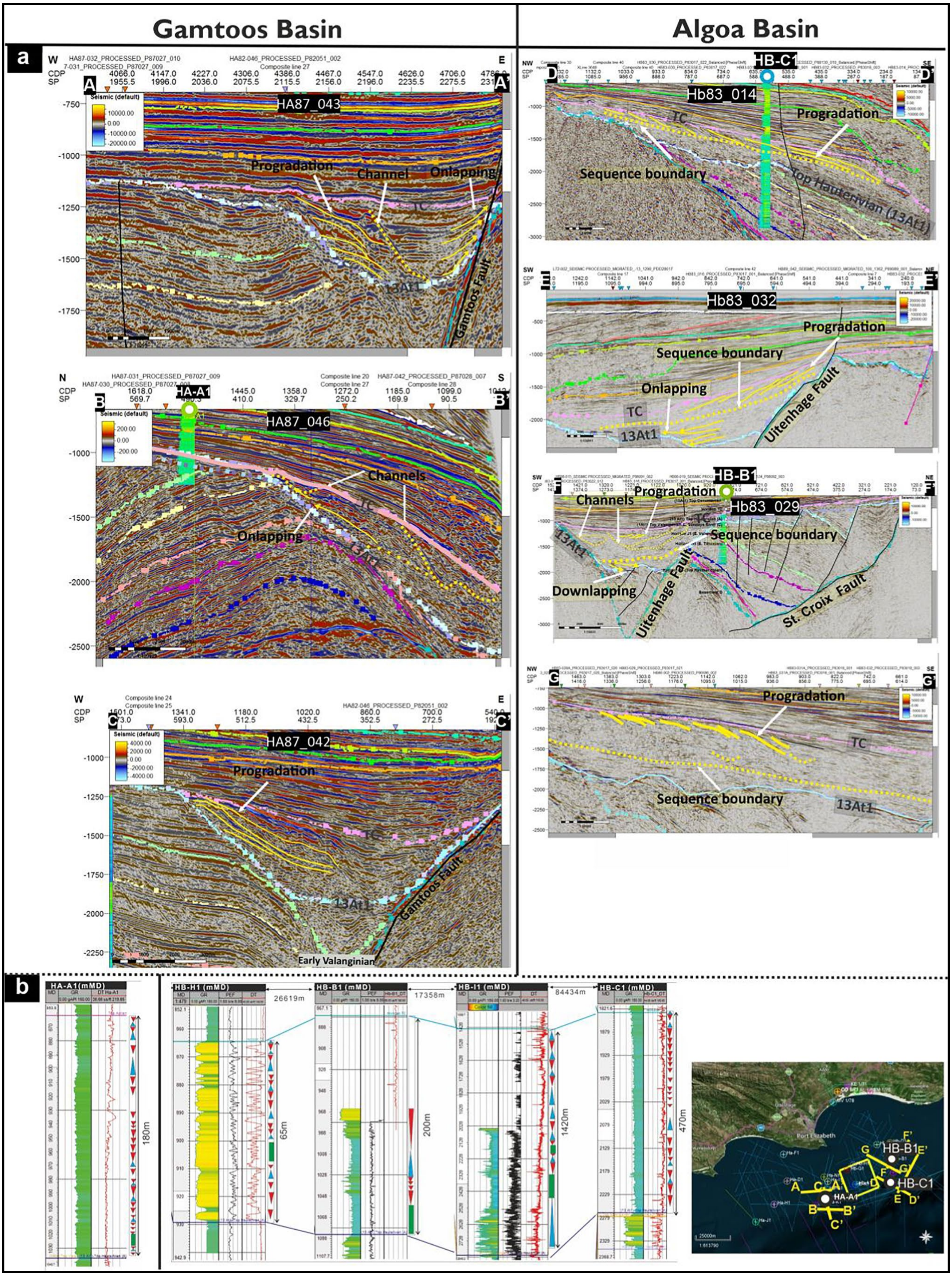
Discussion

Syn-rift sequence models

Lateral variability of syn-rift successions is mostly resultant from the differential movements along syn-depositional faults. These high facies and structural variability make it challenging to use the passive margin-based system tracts to predict lateral facies changes in a largely continental rift-basin setting (e.g., Prosser 1993; Chorowicz 2005; Holz et al. 2017). Current dataset, previous studies (e.g., Shone 2006; Muir et al. 2020) as well as studies from the Falkland Plateau Basin (Schimschal and Jokat 2019) collectively suggest that by the Late Jurassic a marine system was established in this region and relative sea-level changes started influencing the shoreline trajectories and nearshore sedimentary processes. In the Algoa and Gamtoos basins, the syn-rift sequence is dominated by the alluvial to fluvio-lacustrine Enon and Kirkwood formations, which spans a depositional period from ~ 170 to about ~ 135 Ma (Muir et al. 2020). Considering the total average thickness of these units being a few thousand meters (Muir et al. 2017a, b), it is very likely that their combined succession contains several SUs. However, the detection of these unconformities remains elusive both in outcrops and in the sparse, low resolution subsurface data.

Given the foregoing, it is possible to assume a diachronous advancement of shoreline during the syn-rift until the Top Valanginian breakup unconformity (1At1), which can be classified as a second-order MFS (high magnitude, low frequency event; e.g., Vail et al. 1977; Vail 1991; Embry 2009, p. 59; Catuneanu 2006, p. 327; Catuneanu 2019a, b; Catuneanu and Zecchin 2020). Rift basins are associated with short tectonic pulses, which can create sudden and large accommodation space increases (i.e., transgression), followed by a period of tectonic quiescence, which allows sediments to prograde (highstand) along the dipping hanging blocks (Martins-Neto and Catuneanu 2010; Holz et al. 2017). Generally, in the syn-rift successions, formation tops are picked on flooding surfaces (wave-ravinement surfaces; Martins-Neto and Catuneanu 2010; Catuneanu and Zecchin 2020; Fig. 18). Although it could be argued that these third-order flooding surfaces in the Algoa and Gamtoos basins may be MFSs (separating third-order HST and TST), the 1At1 unconformity marks the most landward position of the shoreline in the syn-rift succession, and thus it is the main higher rank (i.e., second-order) MFS (e.g., Catuneanu and Zecchin 2020). In some instances, rift systems can be associated with progradation due to high sedimentation rates; however, increasing accommodation space, due to syn-depositional faulting, will eventually result in a basin wide transgressive shoreline (Martins-Neto and Catuneanu 2010; Holz et al. 2017). Therefore, the low-order/higher rank (low frequency, high magnitude) RSL increase is accompanied by high-order/lower rank transgressive and regressive (e.g., Milankovitch) cycles. Consequently, the syn-rift interval in this study does not contain the "traditional" system tracts as observed in passive margin depositional sequence models. This is also because depositional sequence models were derived from passive margin setting (Martins-Neto and Catuneanu 2010; Holz et al. 2017).

Correlating the syn-rift sequences across the Algoa and Gamtoos basins is very challenging, because these successions are laterally constrained by paleo-basement heights due to compartmentalization common in rift basins (e.g., Chorowicz 2005). The dominant fluvial system in rift basins is controlled by the dipping landscape towards the main faults or paleo-basement heights (Martins-Neto and Catuneanu 2010). However, as RSL continues to increase, sedimentation becomes more dominant towards the proximal setting, leaving the distal footwalls in the deep marine sediment starved (Martins-Neto and Catuneanu 2010). Also, the alluvial, fluvial, and lacustrine deposits, due to their inherent laterally and vertically heterogenous nature make the correlation of rock units from one borehole to the other nearly impossible (e.g., Nádor and Sztanó 2011). The absence of easily detectable SUs within the subsurface syn-rift succession limits the use depositional sequence models II, III, and IV and T-R sequence model, which depend on the recognition of SUs as sequence boundaries (Catuneanu 2006; Embry et al. 2007; Catuneanu et al. 2011; Catuneanu 2019a, b). Holz et al. (2017) proposed the concept of tectonic system tracts; however, their model assumes the development of shallow to deep rift lakes during early syn-rift phase. Although there is evidence of lacustrine environments during the deposition of the Kirkwood Formation



Gamtoos Basin
Algoa Basin
a
HA87_043
Progradation
Channel
Onlapping
TC
13At1
Gamtoos Fault
HA-A1
HA87_046
Channels
Onlapping
HA87_042
Early Valanginian
HB-C1
Hb83_014
Sequence boundary
Top Hauterivian (13At1)
Hb83_032
Uitenhage Fault
HB-B1
Hb83_029
Downlapping
St. Croix Fault
b
HA-A1(mMD)
HB-H1 (mMD)
HB-B1 (mMD)
HB-I1 (mMD)
HB-C1 (mMD)
26619m
17358m
84434m
180m
65m
200m
1420m
470m
Port Elizabeth

◂**Fig. 13** **a** Seismic lines examples from the Algoa and Gamtoos basins. **b** Wireline logs intersecting the “Canyon fill” succession in the Algoa Basin. Base map data ©2020 Google, Maxar Technologies, AfriGIS (Pty) Ltd

(Muir et al. 2017b), there is no evidence to suggests that this lacustrine setting occupied the whole half-graben (rift basin; such as those in the East African Rifts System—e.g., Chorowicz 2005). Since the above models are limited for explaining the syn-rift evolution in the Algoa and Gamtoos basins, the question remains: which other model best fits the data in this area? Galloway’s (1989) genetic sequence model, in which sequence boundaries are defined by the transgressive MFS unconformity (also known as the breakup unconformity in syn-rift successions—e.g., Holz et al. 2017) is the only model that closely matches the observations in the study area. However, contrary to Galloway’s (1989) model, in which both the basal and top sequence boundaries are MFSs, the base of syn-rift is typically a SU atop of the basement rocks (i.e., “rift onset unconformity” in Falvey 1974 or “syn-rift unconformity” in Bosence 1998). In the Galloway model, where MFS are used as sequence boundaries, the SU is included within the succession and is thus not a sequence boundary. It has been repeatedly shown that stratigraphic boundaries should not only be limited to SUs, but to surfaces that mark a full cycle of genetically related sequences (e.g., Catuneanu 2019a, b; Catuneanu and Zecchin 2020). In this way, the genetically related facies of the syn-rift succession is bound by the key stratigraphic surfaces (e.g., SU at the base, transgressive ravinement surfaces, MFS; Figs. 2 and 18) that satisfy the upper half of Galloway’s model, without being limited to SUs as stratigraphic boundaries. The Galloway model does not include system tracts of the conventional depositional sequence models and omitting system tracts limits lateral facies prediction in sequence stratigraphy.

Transitional phase sequence models

Post-Valanginian to upper Hauterivian

This interval represents sediments that were deposited during reduced (negative) accommodation space in the Algoa and Gamtoos basins, when, due to regional uplift, the RSL dropped and the shoreline regressed (McLachlan and McMillan 1976; Malan 1993; Brown et al. 1995; Thomson 1999; Paton and Underhill 2004). The strata of this infrequently preserved succession, which overlie the low-order 1At1 MFS, are dominated by clinoforms that prograde towards SW, and show coarsening-upward and non-graded trends in boreholes HB-B1, BA-J1, and HA-A1. These observations suggest a high-stand system tract (HST) between the low-order 1At1 MFS at the base and the low-order 13At1 SU at the top (Fig. 2). The regional uplift event, which resulted in the 13At1 sequence boundary, was triggered by dextral motion along the AFFZ (Malan 1993; Brown et al. 1995; Thomson 1999; Paton and Underhill 2004). This period of uplift, which lasted from the late Hauterivian to early Aptian (6At1 to 13At1), resulted in the Algoa and Gamtoos canyons and other erosional features across the shelf area in the region (Bate and Malan 1992; McMillan et al. 1997; Broad et al. 2012). In contrast to the older syn-rift sequence, the thickness maps (Fig. 8) show depocenters that do not follow the geometry of the underlying structure. This suggests that the basin infilling during this period was primarily driven by RSL changes, as a function of eustatic sea-level change and the motion of AFFZ (Dingle et al. 1983; Ben-Avraham et al. 1993; Malan et al. 1990; Brown et al. 1995; McMillan et al. 1997; Broad et al. 2012; Baby et al. 2018), and less dependent on the Cape Supergroup anisotropy. Moreover, during this period of uplift and erosion, the shoreline retracted towards the distal setting, while the inner to middle shelf was a place of bypass. Because this basinward shoreline shift was primarily driven by the regional uplift, independent of sediment supply, a case for forced regression can be made (Fig. 10d; Hodgson et al. 2018 Fig. 10b), and the processes associated with falling stage system tract (FSST) are expected to have occurred. Therefore, it is expected that in the continental portion (i.e., northern half) of the basin low-order SUs were generated, whereas in the marine portion (i.e., southern half) of the basin, sediments bypassed on the shelf and became deposited as high-density, basin floor fans (e.g., Hunt and Tucker 1992; 1995; Helland-Hansen and Gjelberg 1994; Plint and Nummedal 2000; Catuneanu 2006, p. 178). Consequently, high potential for the development of reservoirs is expected outboard of the study area. It is noteworthy that this uplift and associated basinal deposition are similar in overall mechanism and age to processes that led to the formation of the hydrocarbon-bearing rocks in the Outeniqua Basin (i.e., Brulpadda and Luiperd discovery in Block 11B/12B; Africa Energy Corp. 2020).

Post-Hauterivian to “Canyon fill” (early Albian)

The Aptian to early Albian “Canyon fill” sediments in the shelf overlie the FSST and are characterized by fluvial incisions and prograding stratal geometries (Fig. 13). These “Canyon fill” sediments are bound by a subaerial uniformity at the base and a transgressive surface at the top (Fig. 2). These observations are consistent with the definition of the lowstand system tract (LST) on the shelf (Figs. 2 and 10e; Catuneanu 2006, his Fig. 5.6) in depositional models II, III, and IV. Although there are some low-density basin floor fans that might form during the normal regression, most of the sediments are trapped in the incised valleys during the LST, such as those in the Algoa and Gamtoos basins. This

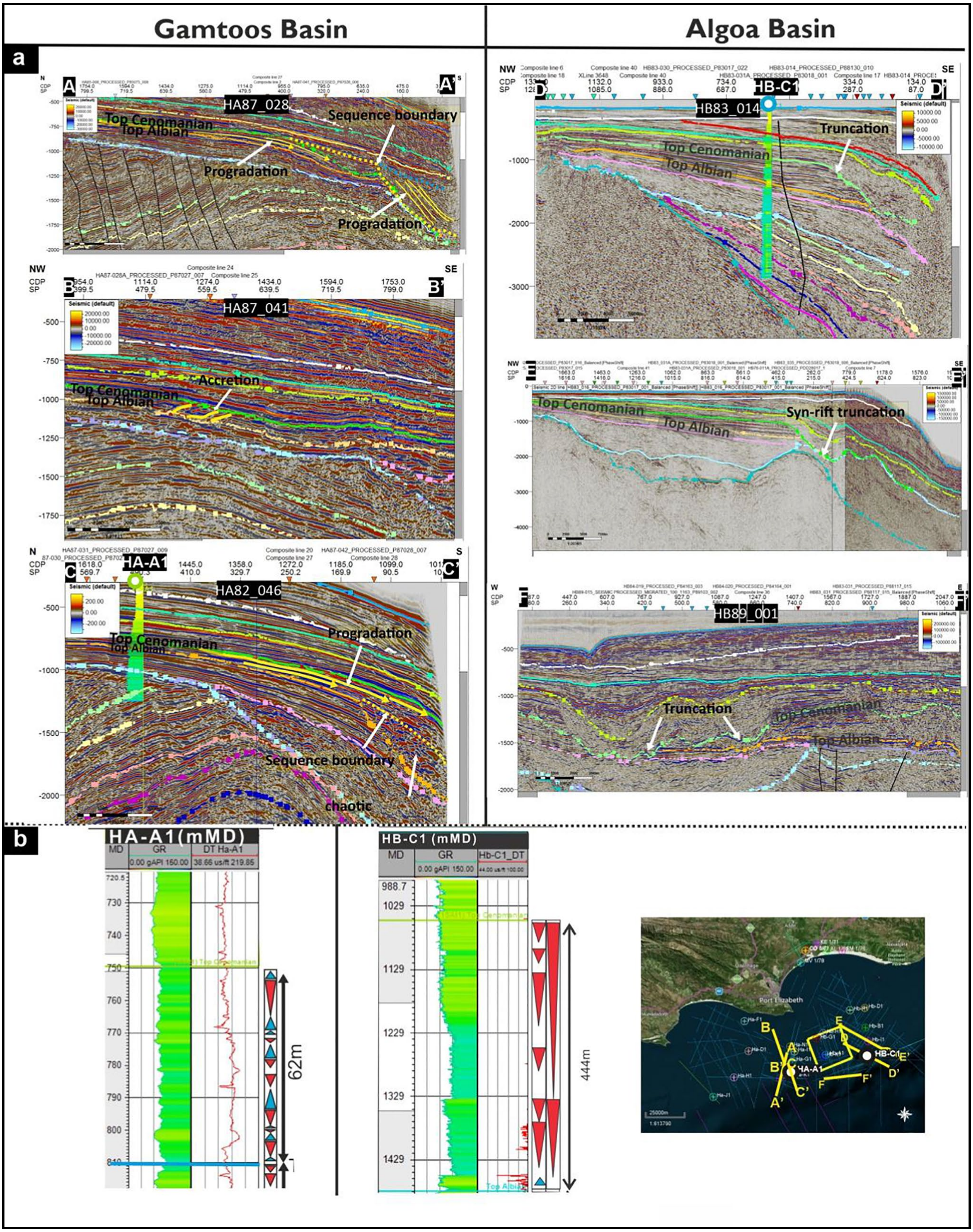


Fig. 14 **a** Seismic lines examples over the Algoa and Gamtoos basins. **b** Wireline logs intersecting the Cenomanian succession in the Algoa and Gamtoos Basin. Base map data ©2020 Google, Maxar Technologies, AfriGIS (Pty) Ltd

is because sediments, before making their way to the distal part of the basin, first tend to fill in the proximal topographic irregularities (i.e., nearshore incised valleys) that were carved out during the forced regression (Catuneanu 2002, 2006). Boreholes HB-B1, HB-I1, and HB-C1 in the Algoa Canyon are characterized by very fine-grained, silty to shaley sediments that formed during this phase of deposition. The sediments deposited in the incised canyons appear to be dominated by fine grain sizes and small channels with a low net sand-to-shale ratio, and thus are unsuitable as hydrocarbon reservoirs. The more proximal borehole HB-H1 is dominated by clean sandy facies near the canyon head; however, these sandy facies do not appear to extend toward the distal part of the Algoa Canyon. The Top Canyon reflector marks a maximum regressive surface (MRS), overlying "Canyon fill" sediments that were generated during normal regression. The MRS is overlain by thin (below seismic resolution), lower Albian transgressive system tract (TST; observable at the base of boreholes HB-B1 and HA-A1 as high GR, fining-upward shaly facies), which are then overlain by prograding, normal regressive sediments (i.e., HST), which mark the Top Albian. It has been repeatedly shown that system tracts can form independent of scale and that seismic data might not always resolve high-frequency sequence boundaries (e.g., Catuneanu 2019a, b; Catuneanu and Zecchin 2020). Unlike the "ideal" products of a full relative sea-level cycle comprising of fully developed LST-TST-HST-FSST (Hunt and Tucker 1992; 1995; Plint and Nummedal 2000; Catuneanu 2002, 2006; Catuneanu et al. 2011; Catuneanu 2019a, b), in the current dataset no SUs (that form during forced regression) are resolved in the upper (Late) Albian, which might suggest a drop in RSL or slow RSL rise when lowstand deposits formed. As a result, the Albian highstand is bound at the top by a regressive surface (maximum?), and not a SU (which could be there, but below seismic resolution).

Drift phase sequence models

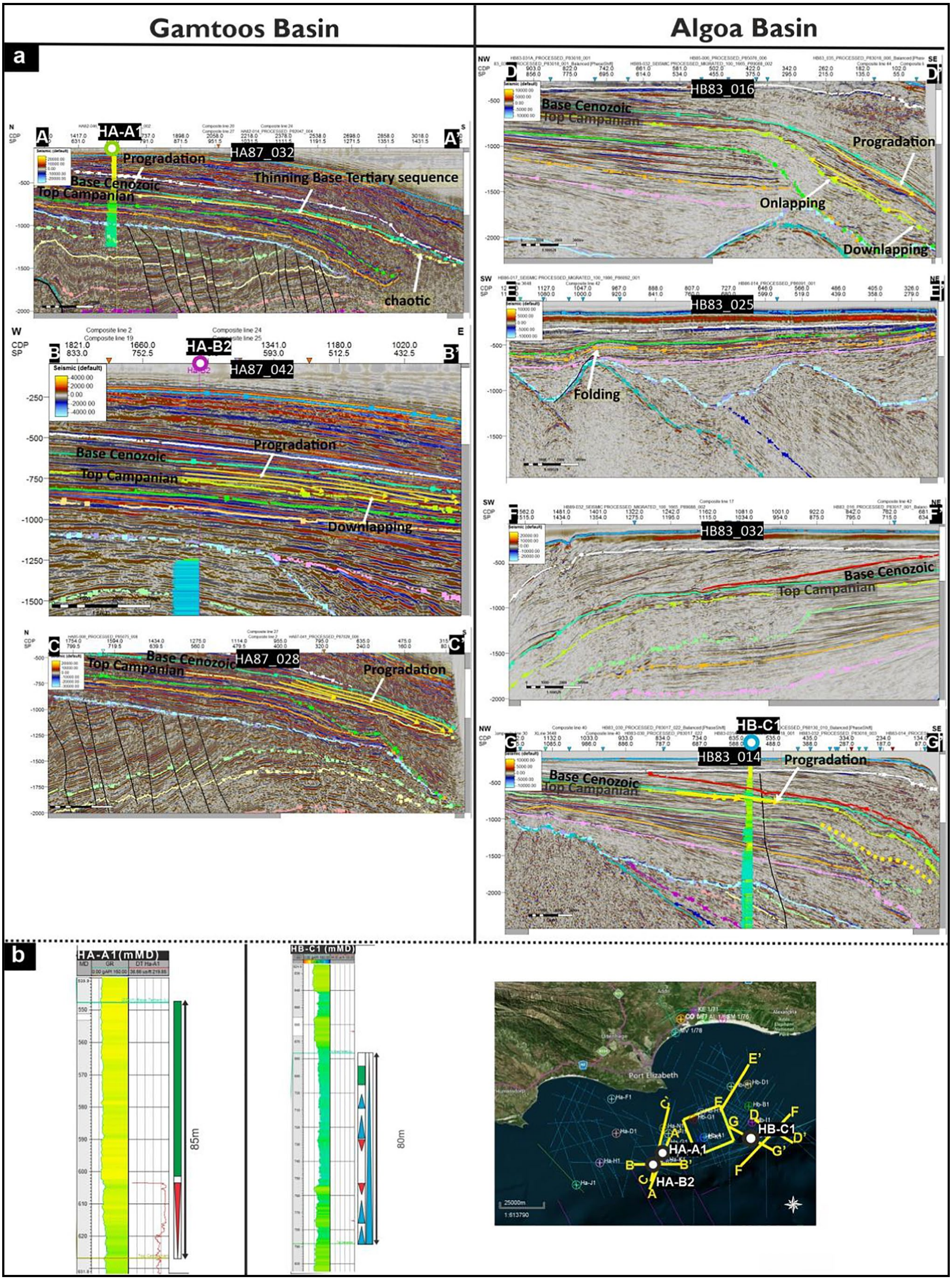
Lower to upper Cenomanian

The Cenomanian succession overlies the Top Albian regressive surface and shows evidence for increasing accommodation space in the early Cenomanian. The basal Cenomanian succession in boreholes HB-C1 and HA-A1 is dominated by shales and clays facies, which could represent an early Cenomanian flooding event. This is supported by onlapping stratal geometries in the Algoa Basin shelf. However, the flooding surface associated with this transgression is unresolvable on the seismic lines in the Gamtoos Basin due to the resolution of the data. Consequently, the lower transgressive Cenomanian deposits are separated from the upper Albian highstand deposits by a high-order MRS (Fig. 2; e.g., Catuneanu 2006, p. 327; Catuneanu 2019a his Fig. 3, 2019b). A TST-HST-TST succession like this typically forms during positive accommodation and high sedimentation rates (Galloway 1989; Catuneanu 2019a his Fig. 3, 2019b; Catuneanu and Zecchin 2020 their Fig. 13). The early Cenomanian transgressive deposits are overlain by two coarsening-upward successions separated by a high-order flooding surface in borehole HB-C1, and these represent a period when sedimentation outpaced the RSL rise (Fig. 2). In both basins, the coarsening-upward units in the boreholes are associated, in the seismic lines, with prograding clinoforms, which downlap on the Top Albian MRS. Taken together, the prograding clinoforms and the coarsening-upward units indicate a normal regressive (likely HST) shoreline during the Cenomanian.

The Cenomanian succession is truncated by a low-order erosional boundary (15At1), which in some places erodes into the syn-rift sequence (Fig. 14a). Overall, this suggests that the Cenomanian succession was deposited during normal regression and thus represents a HST that formed when the shelf was dominated by sand deposition and the more distal parts of the basin were dominated by suspension settling (i.e., shales and clays; Fig. 2). Although the origin of the Late Cretaceous event is still unclear, it has been linked with thermal subsidence in the distal part of the basin, uplift in the shelf and forced regression of the shoreline (e.g., Malan 1993; Baby et al. 2018). At this time, the shelf area was severely scoured, and at least in the Gamtoos Basin, bypass channels were generated (Fig. 14a). There are clear downlaps on a surface that might be interpreted as a basal surface of forced regression towards the shelf edge/slope (Fig. 14a; sensu Hunt and Tucker 1992, 1995; Posamentier and Allen 1999). The Top Cenomanian SU is joined with a correlative conformity (sensu Hunt and Tucker 1992, 1995) towards the shelf edge (Fig. 14). This correlative conformity is visible on the 2D seismic lines on the slope and is associated with RSL fall. The nature of the 15At1 unconformity is similar to the Hauterivian 131At surface, and thus, again, basin floor fans were likely deposited during this phase of forced regression from the Turonian to Santonian (Fig. 10f; Hodgson et al. 2018 their Fig. 10b).

Post-Cenomanian to Lower Cenozoic

In contrast to the transitional phase, where scoured out canyons are filled by deposits of the LST evidence for normal regressive deposits on the shelf, above Top Cenomanian unconformity, is lacking. This could either be due to the sediments being too thin and thus below seismic resolution or having been eroded during the subsequent transgression. However, evidence of prograding strata downlapping on the Top Cenomanian reflector in the slope suggests that the LST was preserved basinwards. On the shelf, the Upper Cretaceous succession shows evidence for progradation and



Gamtoos Basin
Algoa Basin
a
HA-A1
HA87_032
Progradation
Base Cenozoic
Top Campanian
Thinning Base Tertiary sequence
chaotic
HA-B2
HA87_042
Progradation
Base Cenozoic
Top Campanian
Downlapping
HA87_028
Base Cenozoic
Top Campanian
Progradation
HB83_016
Base Cenozoic
Top Campanian
Progradation
Onlapping
Downlapping
HB83_025
Folding
HB83_032
Base Cenozoic
Top Campanian
HB-C1
HB83_014
Progradation
Base Cenozoic
Top Campanian
b
HA-A1(mMD)
85m
HB-C1 (mMD)
80m
Port Elizabeth
HA-A1
HA-B2
HB-C1
25000m
1:613790

◂**Fig. 15** **a** Seismic lines examples over the Algoa and Gamtoos basins. **b** Wireline logs intersecting the Upper Cretaceous/Lower Cenozoic succession in the Algoa and Gamtoos Basin. Base map data ©2020 Google, Maxar Technologies, AfriGIS (Pty) Ltd

downlap on the Top Campanian MRS, while evidence of onlapping is observed in the slope and shelf edge regions (Fig. 15a). While the Base Cenozoic reflector does not appear to be erosional in the Algoa Basin, the seismic data (Fig. 15a) in the Gamtoos Basin shows some evidence for minor erosion, especially in the proximal areas. Alternatively, this supposed erosional feature could be toplaps, indicating the depositional limits of clinoforms in the updip area. Borehole data in the Gamtoos Basin show coarsening-upward clean sands, while the Algoa Basin is dominated by retrogradational strata. These observations may suggest that the Base Cenozoic reflector marks a MFS that is underlain by transgressive deposits in the Algoa Basin, and a MRS that is underlain by a HST in the Gamtoos Basin (Figs. 2 and 17a). This sequence cyclicity is similar to the Albian period, when the basin experienced increased accommodation space and high sedimentation (i.e., TST-HST-TST; e.g., Galloway 1989; Catuneanu 2019a his Fig. 3, 2019b). Moreover, the increasing accommodation space is a likely low-order event, which occurred on a regional scale.

Lower to Middle Cenozoic

Wireline data from borehole HB-C1 record silty clays at the base of the succession, which probably formed during the Late Cretaceous/Lower Cenozoic transgression in the Algoa Basin. The flooding surface associated with this transgression is overlain by prograding sands in borehole HB-C1. These sandy facies are also observed in the borehole HA-A1 in the Gamtoos Basin. This indicates increased sediment supply into the basins and a regressive shoreline. In both basins, seismic reflectors are predominantly prograding and downlapping onto the Lower Cenozoic MRS in the Gamtoos Basin and MFS in the Algoa Basin. These observations suggest that this interval was deposited as a HST in the Gamtoos Basin and TST in the Algoa Basin, until the basin was tilted (Fig. 2; Hattingh 2001; Baby et al. 2018) during the late Paleogene. The basin tilting event, which uplifted the shelf, resulted in a forced regression, which pushed the shoreline to the shelf edge, resulting in deposition in the distal basin and bypass on the shelf. Towards the shelf edge in the Algoa Basin, a correlative conformity in the distal setting joining with the low-order SU is tentatively expected, where the underlying rock units prograde and downlap onto the basal surface of forced regression. These observations are consistent with the predictions of the depositional sequence IV model. This means, at this period, the eroded shelfal sediments were deposited basinwards, probably as basin floor fans (Figs. 12d and 17b). Although there is great potential for reservoir development in the distal setting, the depth to burial of these reservoirs is very shallow limiting hydrocarbon prospectivity. Similar to the 15At1 sequence boundary in the late Cenomanian (Figs. 2, and 10f), the Mid-Cenozoic unconformity is overlain by prograding Miocene clinoforms in the slope region, indicating the distal limits of the shoreline during the normal regression that ensued after the uplift and erosion in the Eocene and Oligocene. Although onshore Algoa Basin outcrop studies (e.g., Le Roux 1987, 1989, 1990; Illenberger 1992; Hattingh 2001) show evidence for several high-order transgressive and regressive cycles from the late Miocene to Holocene, corresponding to an overall RSL change of over 300 m (see Hattingh 2001 his Fig. 5.1), the limited resolution of the current dataset does not allow the identification of these cycles (i.e., their stacking patterns, associated key stratigraphic surfaces; e.g., Catuneanu 2019a; Catuneanu and Zecchin 2020). Nonetheless, the offshore equivalent of these outcrops is shown as prograding clinoforms, which correspond to the clean coarsening-upward sands (e.g., boreholes HB-C1 and HA-A1) that were probably deposited during a low-order regression (likely HST) phase in the post-Miocene.

Conclusion

Depositional models in this study, which encompasses the Algoa and Gamtoos basins of South Africa, are based on a vintage dataset that is in dire need for further reprocessing in order to improve imaging, especially for the syn-rift section. Although the data quality varies from poor to moderate, the integration of different datasets into the stratigraphic framework provided reasonable insights for the generation of GDE maps and interpretation of the overall geological history of the shoreline's movement in this region. The dataset in the Gamtoos Basin suggest a marine incursion following the onset of rifting as early as the early Middle Jurassic. This inference is supported by recent radioisotopic dating in the region (Muir et al. 2020) as well as the postulation of a pre-Tithonian mid-ocean ridge succession near the Falkland Plateau Basin (Schimschal and Jokat 2019), which was nearby prior and during the early phases of Gondwana breakup. This marine incursion also suggests that the sedimentation in the southern Cape was influenced by marine processes and relative sea-level changes since early syn-rift phase.

Three main depositional sequences are identified in the study area encompassing the Algoa and Gamtoos basins of South Africa. The first regional succession is a syn-rift sequence, which is bound by an Early Jurassic subaerial unconformity at the base and the second-order Valanginian maximum flooding surface at the top. The sequence is made up of third and fourth-order transgressive and

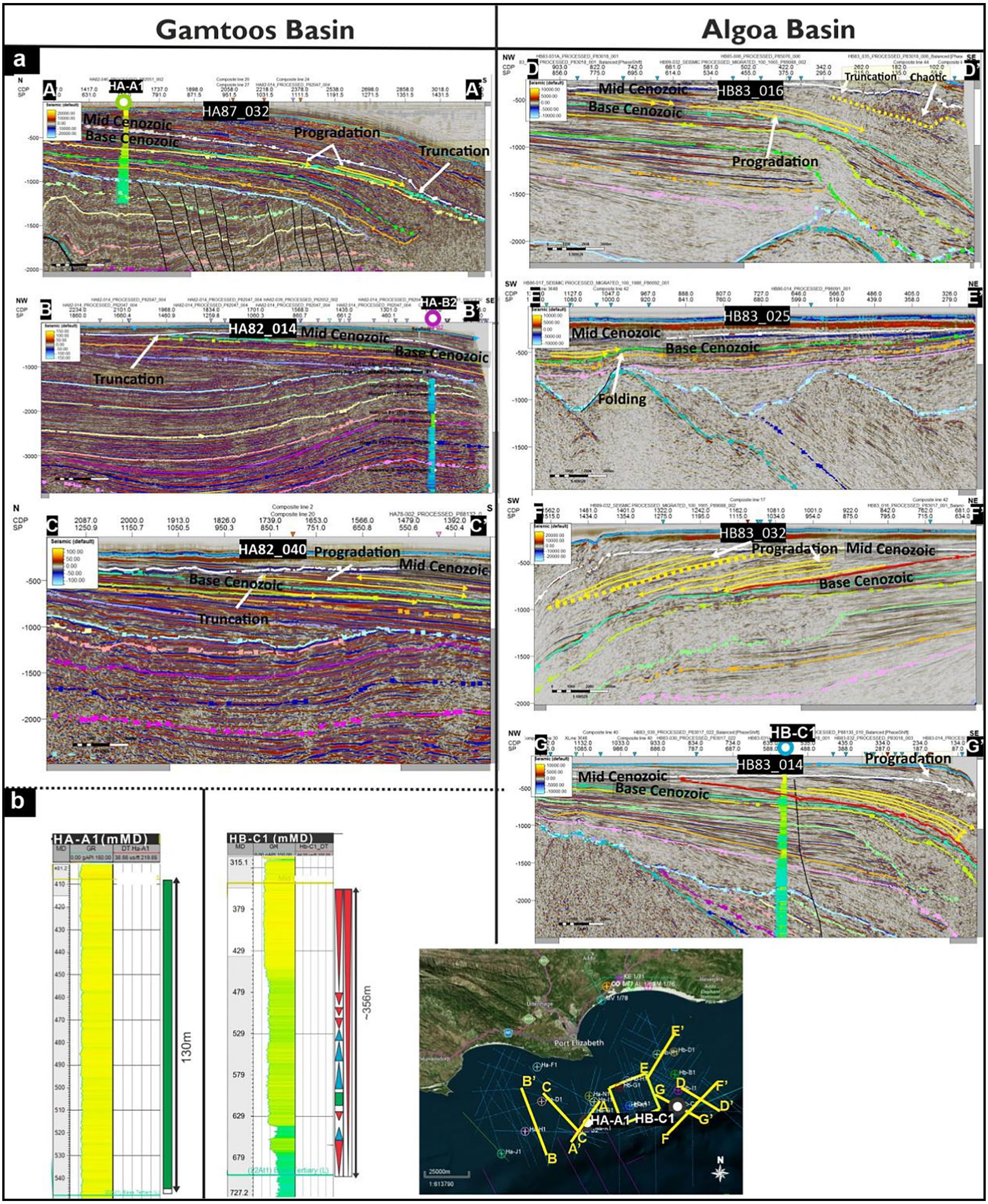


Fig. 16 **a** Seismic lines examples over the Algoa and Gamtoos basins. **b** Wireline logs intersecting the Lower to Upper Cenozoic succession in the Algoa and Gamtoos Basin. Base map data ©2020 Google, Maxar Technologies, AfriGIS (Pty) Ltd

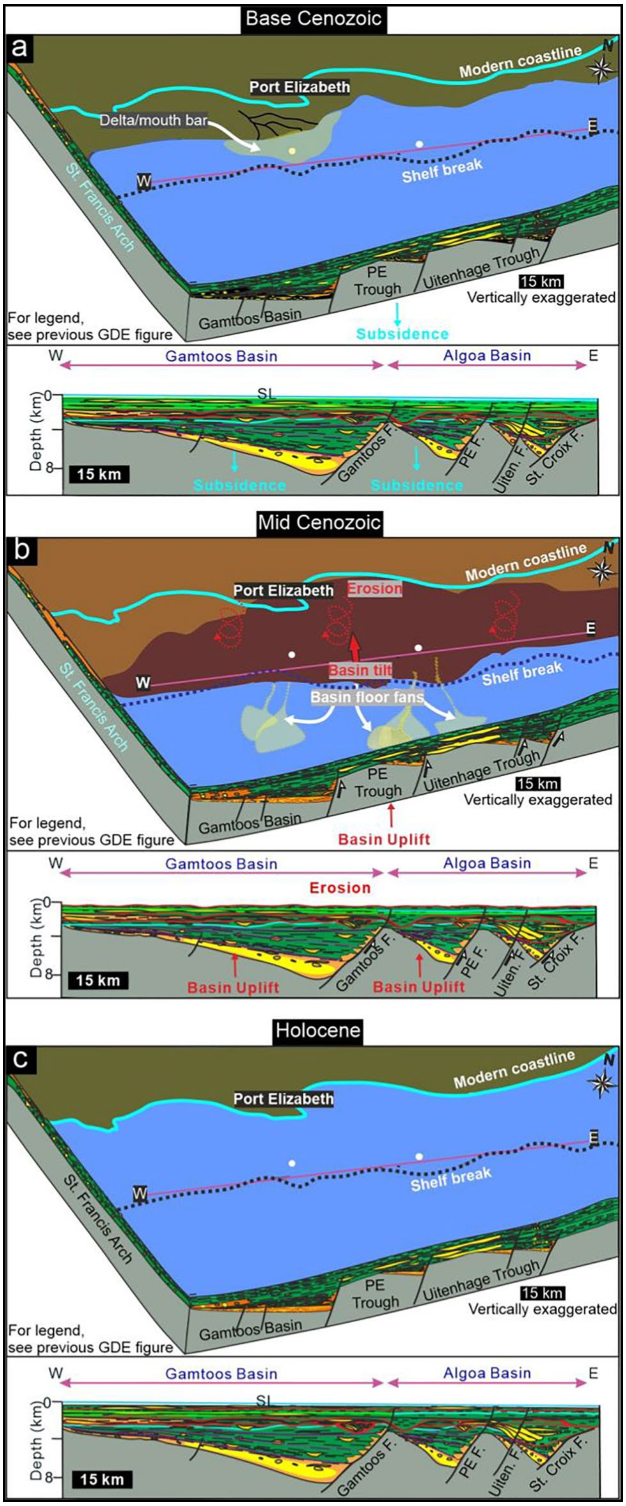


Fig. 17 **a, b, c** Upper Cenozoic gross depositional models, showing the basin evolution from syn-rift to transitional to drift phase (see Fig. 10 for legend)

regressive cycles in the marine sector and formed during the diachronous advancement (transgression) of relative sea level until the late Valanginian second-order maximum flooding surface. Well-established stratigraphic models are difficult to apply for the continental sector of the syn-rift sequence, and thus far, the best-fitting model for the current stratigraphic framework is a modified version of the genetic sequence model. The second regional succession is the post-rift low-order sequence 1, which is bound at the base by a major third-order Hauterivian unconformity (surface 13At1; in some places the basal boundary is the 1At1 Top Valanginian boundary) at the base and the late third-order Cenomanian unconformity (surface 15At1) at the top. Unconformably overlying the post-rift sequence 1, the third and final regional succession is the post-rift order-order sequence 2 that is bound by the third-order Mid-Cenozoic (Eocene) unconformity at the top. All major forced regressive periods appear to be tectonically triggered. The post-rift sequence contains several high-order systems tracts that can be identified as FSST-LST-TST-HST (Hunt and Tucker 1992; 1995; Plint and Nummedal 2000; Catuneanu 2002, 2019a, b) contained within the low-order boundaries. Although these sequences are bound by subaerial unconformities, some intervals within them are bound by flooding and regressive surfaces (i.e., the Campanian to Lower Cenozoic succession; Galloway 1989; Catuneanu 2019a, b). In these flooding surface-bound third- or even fourth-order successions, the T-R sequence model (sensu Embry and Johannessen 1992; Embry 1993) is valid.

This shows, yet again, that these sequence models are more sensitive to depositional scale (also see the Sedimentation Rate Scale concept in Miall 2015; Catuneanu 2019a, b). Thus, this level of the stratigraphic framework can be explained with the concept of scale in sequence stratigraphy (Catuneanu 2019a), where (1) system tracts form at any scale (i.e., are independent of scale); (2) stratigraphic bounding surfaces should not be limited to just low-order subaerial unconformities (sensu depositional model II, III, IV), but to surfaces that bound genetically related successions (Catuneanu 2019a, 2020). This is because low-order flooding surfaces (MFS and MRS—sensu genetic and T-R sequence models) can be contained within subaerial unconformity bound depositional sequence models. Therefore, when applying sequence models, it is important to consider the resolution of the successions within the regional stratigraphic framework, because certain models are more scale dependent than others.

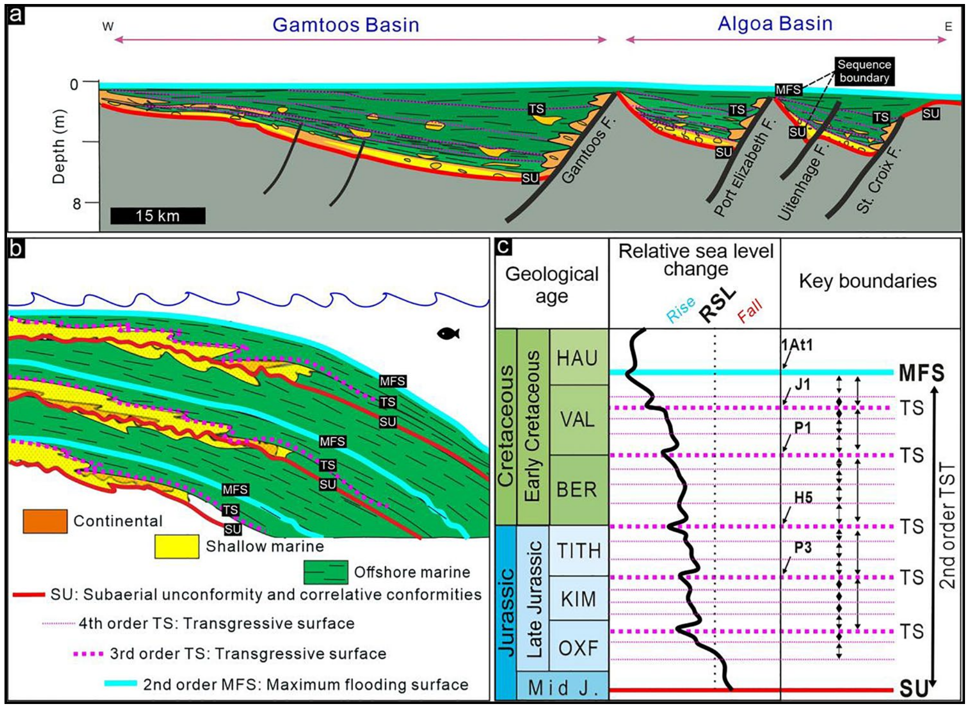


Fig. 18 **a** Simplified cross-section of the syn-rift sequence in the Algoa and Gamtoos basins, showing the main stratigraphic surfaces. **b** Summary of Galloway's model (1989), which is a genetic sequence approach that uses the maximum flooding surface (MFS) as sequence boundary (modified from Embry et al. 2007). **c** RSL curve and the associated system tracts and their bounding surfaces in the Algoa and Gamtoos basins

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Author contribution This paper was developed from the PhD thesis of MHM. EMB conceptualized idea for research, designed the project, and as the project leader, advised MHM during the study. MHM was responsible for data processing, analysis, and interpretation, and drafted the initial figures of the manuscript. Both authors performed critical writing and revision of the manuscript for important intellectual content and approved the final manuscript. Opinions expressed, and conclusions arrived at are solely our responsibility.

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Data availability All dataset generated for this study are included in the article.

Declarations

Conflict of interest The authors declare no competing interests.

References

Africa Energy Corp (2020) Oil and gas exploration in Africa, Operations, South Africa, Block 11b/12b https://www.africaenergycorp.com/operations/south-africa-block-11b-12b/ accessed 07 December 2020

Almond JE (2012) Proposed Jachtvlakte Precinct Human Settlement Plan, Nelson Mandela Bay Municipality, Eastern Cape. Natura Viva Palaeontological Assessment: Combined Desktop and Scoping Study: 22p

Ayodele O, Chatterjee T, Donker JVB (2020) Seismic stratigraphic analyses of early cretaceous (Valanginian) sediments of Gamtoos Basin, Offshore South Africa. Int J Sci 26(1):1–14

Baby G, Guillocheau F, Boulogne C, Robin C, Dall'Asta M (2018) Uplift history of a transform continental margin revealed by the stratigraphic record: the case of the Agulhas transform margin along the Southern African Plateau. Tectonophysics 731:104–130

Bate KJ, Malan JA (1992) Tectonostratigraphic evolution of the Algoa, Gamtoos and Pletmos Basins, offshore South Africa. In: De Wit MJ, Ransome IGD (eds) Inversion tectonics of the Cape Fold Belt, Karoo and Cretaceous Basins of Southern Africa. Balkema, Rotterdam, pp 61–73

Ben-Avraham Z, Hartnady CJH, Malan JA (1993) Early tectonic extension between the Agulhas Bank and the Falkland Plateau due to the rotation of the Lafonia microplate. Earth Planet Sci Lett 117:43–58

Bosence DWJ (1998) Stratigraphic and sedimentological models of rift basins. In: Purser BH, Bosence DWJ (eds) Sedimentation and tectonics of rift Basins Red Sea – Gulf of Aden. Springer, Dordrecht, p 630

Broad DS (1990) Petroleum geology of the Gamtoos and Algoa Basins. Geol Soc S Afr Geocongress 90:60–63

Broad DS, Jungslager EHA, McLachlan IR, Roux J, van der Spuy D (2012) South Africa's offshore Mesozoic basins. Phanerozoic Passive Margins, Cratonic Basins and Global Tectonic Maps. Elsevier: 535–560

Brown LF Jr, Benson JM, Brink GJ, Doherty S, Jollands A, Jungslager EHA, Keenan JHG, Muntingh A and Van Wyk NJS (1995) Sequence stratigraphy, in offshore South African divergent basins. An atlas on exploration for Cretaceous lowstand traps by Soekor (Pty) Ltd. Am Assoc Pet Geol Stud Geol: 41

Burgess PM, Allen PA, Steel RJ (2016) Introduction to the future of sequence stratigraphy: evolution or revolution? J Geol Soc 173:801–802

Caku N, Gwavava O, Liu K, Baiyegunhi C (2020) An integration of magnetic, gravity and seismic data in evaluating the Algoa Basin in the Eastern Cape Province of South Africa for stratigraphic and structural geodynamics. Pure Appl Geophys 177:4177–4205

Catuneanu O (2020) Sequence stratigraphy of deep-water systems. Mar Pet Geo 114:104238

Catuneanu O (2002) Sequence stratigraphy of clastic systems: concepts, merits, and pitfalls. J Afr Earth Sci 35:1–43

Catuneanu O (2006) Principles of sequence stratigraphy. Elsevier

Catuneanu O (2019a) Model-Independent Sequence Stratigraphy. Earth Sci Rev 188:312–388

Catuneanu O (2019b) Scale in sequence stratigraphy. Mar Pet Geo 106:128–159

Catuneanu O, Galloway WE, Kendall C, Miall A, Posamentier HW, Strasser A, Tucker ME (2011) Sequence stratigraphy: methodology and nomenclature. Newsl Stratigr 44(3):173–245

Catuneanu O, Zecchin M (2020) Parasequences: allostratigraphic misfits in sequence stratigraphy. Earth Sci Rev: 103289

Christie-Blick N (1991) Onlap, offlap, and the origin of unconformity-bounded depositional sequences. Mar Geo 97:35–56

Chorowicz J (2005) The East African rift system. J Afr Earth Sci 43:379–410

De Wit MJ (1992) The Cape Fold Belt: a challenge for an integrated approach to inversion tectonics. In: De Wit MJ, Ransome IGD (eds) Inversion tectonics of the Cape Fold Belt, Karoo ad Cretaceous Basins of Southern Africa. Balkema, Rotterdam, pp 3–14

Du Toit SR (1979) The Mesozoic history of the Agulhas Bank in terms of plate tectonic theory. Geokongres 77. Spec Publ Geol Soc S Afr 6:197–203

Dingle RV, Siesser WG, Newton AR (1983) Mesozoic and tertiary geology of Southern Africa. A.A. Balkema Rotterdam: 375 pp

Embry AF (1993) Transgressive-regressive (T–R) sequence analysisof the Jurassic succession of the Sverdrup Basin, Canadian Arctic Archipelago. Can J of Earth Sci 30:301–320

Embry AF (2009) Practical sequence stratigraphy. Can Soc Petroleum Geo Online at www.cspg.org, 81 (Accessed 02 Nov 2021)

Embry AF, Johannessen EP (1992) T–R sequence stratigraphy, facies analysis and reservoir distribution in the uppermost Triassic-Lower Jurassic succession, western Sverdrup Basin, Arctic Canada. In: Vorren TO, Bergsager E, Dahl-Stamnes OA, Holter E, Johansen B. Lie E, Lund TB (eds) Arctic geology and petroleum potential. Norw Petrol Soc Spec Pub 2: 121–146

Embry AF, Johannessen E, Owen D, Beauchamp B, Gianolla P (2007) Sequence stratigraphy as a "concrete" stratigraphic discipline. Report of the ISSC Task Group on Sequence Stratigraphy

Falvey DA (1974) The development of continental margins in plate tectonic theory. J Aust Pet Explor Ass 14:95–106

Feder J (2019) Offshore: making a comeback after the downturn. J Pet Technol 71:27–31

Frazier DE (1974) Depositional episodes: their relationship to the Quaternary stratigraphic framework in the north western portion of the Gulf basin. Geological Circular. University of Texas at Austin Bureau of Economic Geology 1:28

Galloway WE (1989) Genetic stratigraphic sequences in basin analysis. I. Architecture and genesis of flooding-surface bounded depositional units. Am Assoc Pet Geol Bull 73:125–142

Hattingh J (2001) Late Cenozoic drainage evolution in the Algoa Basin with special reference to the Sundays River Valley. Council for Geoscience 128:141

Haq BU, Hardenbol J, Vail PR (1987) Chronology of fluctuating sea levels since the Triassic. Science 235:1156–1166

Helland-Hansen W, Gjelberg JG (1994) Conceptual basis and variability in sequence stratigraphy: a different perspective. Sed Geo 92:31–52

Hodgson DM, Browning JV, Miller KG, Hesselbo SP, Poyatos-More M, Mountain GS (2018) Sedimentology, stratigraphic context, and implications of intrashelf bottomset deposits, offshore New Jersey. Geosphere 14:95–114

Holz M, Vilas-Boas DB, Troccoli EB, Santana VC, Vidigal-Souza PA (2017) Conceptual models for sequence stratigraphy of continental rift successions. Stratigr Timescales 2(119):186

Hong S, Bradshaw CJ, Brook BW (2015) Global zero-carbon energy pathways using viable mixes of nuclear and renewables. Appl Energy 143:451–459

Hunt D, Tucker ME (1992) Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall. Sed Geo 8:1–9

Hunt D, Tucker ME (1995) Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall – reply. Sed Geo 95:147–160

Illenberger WK (1992) Lithostratigraphy of the Schlemm Hoek formation (Algoa Group). Inst Coastal Research, University of Port Elizabeth

Jungslager EHA (1996) Geological evaluation of the remaining prospectivity for oil and gas of the pre-1At1 "Synrift" succession in Block 9, Republic of South Africa. Unpublished SOEKOR Rep: 63

Johnson JG, Murphy MA (1984) Time-rock model for Siluro-Devonian continental shelf, western United States. Geol Soc Am Bull 95:1349–1359

Koopmann H, Franke D, Schreckenberger B, Schulz H, Hartwig A, Stollhofen H, di Primio R (2014) Segmentation and volcano-tectonic characteristics along the SW African continental margin, South Atlantic, as derived from multichannel seismic and potential field data. Mar Pet Geo 50:22–39

Le Roux FG (1990) Palaeontological correlation of Cenozoic marine deposits of the southeastern, southern and western coasts Cape Province. S Afr J Geo 93(3):514–518

Le Roux FG (1989) The lithostratigraphy of Cenozoic deposits along the south-east Cape coast as related to sea-level changes. Doctoral dissertation, Stellenbosch: Stellenbosch University

Le Roux FG (1987) Lithostratigraphy of the Alexandria Formation. S Afr Committee Stratigraphy (SACS). Lithostratigraphic Ser 1:1–18

Lovecchio JP, Rohais S, Joseph P, Bolatti ND, Ramos VA (2020) Mesozoic rifting evolution of SW Gondwana: a poly-phased, subduction-related, extensional history responsible for basin formation along the Argentinean Atlantic margin. Earth Sci Rev 203:103138

Malan JA (1993) Geology, potential of Algoa, Gamtoos Basins of South Africa. Oil & Gas Journal. Soekor (Pty.) Ltd.

Malan JA, Martin AK, Cartwright JA (1990) The structural and stratigraphic development of the Gamtoos and Algoa Basins, offshore South Africa. Geol Soc of S Afr 90:328–331

Martin AK, Hartnady CJH, Goodlad SW (1981) A revised fit of South America and South-Central Africa. Earth Planet Sci Lett 54:293–305

Martin AK, Hartnady CJH (1986) Plate tectonic development of the south west Indian Ocean: a revised reconstruction of East Antarctica and Africa. J Geophys Res 91:4767–4786

Martins-Neto MA, Catuneanu O (2010) Rift Sequence Stratigraphy. Mar Pet Geo 27:247–253

McLachlan IR, McMillan IK (1976) Review and stratigraphic significance of southern Cape Mesozoic palaeontology. Trans Geol Soc S Afr 79:197–212

McMillan IK (1990) Foraminiferal definition and possible implications of the major mid-Cretaceous (Albian to Coniacian)

hiatuses of southernmost Africa. Geol Soc S Afr Abstr Vol 363–366
McMillan IK (2003) The Foraminifera of the Late Valanginian to Hauterivian (Early Cretaceous) Sundays River Formation of the Algoa Basin, Eastern Cape Province, South Africa. Ann S Afr Mus 106:1–274
McMillan IK, Brink GJ, Broad DS, Maier JJ (1997) Late Mesozoic sedimentary basins off the south coast of South Africa. In: Selly RC (ed) African basins, sedimentary basins of the world. Elsevier, Amsterdam, pp 319–376
McMillan IK (2010) The Foraminifera of the Portlandian (Late Jurassic) Bethelsdorp Formation of the Onshore Algoa Basin. Les Rosalines Press, Clovelly, Eastern Cape Province, p 176
Miall AD (2015) Updating uniformitarianism: stratigraphy as just a set of 'frozen accidents'. In: Smith DG, Bailey RJ, Burgess PM, Fraser AJ (eds) Strata and time: probing the gaps in our understanding. Geol Soc London Spec Publ 404: 11–36
Miall AD, Strasser A (2018) Standards for publications in the field of basin analysis. Earth Sci Rev 177:1
Muir RA (2019) Recalibrating the breakup history of SW Gondwana: the first U-Pb chronostratigraphy for the Uitenhage Group, South Africa. PhD thesis University of Cape Town
Muir R, Bordy EM, Prevec R (2015) Lower Cretaceous deposit reveals first evidence of a post-wildfire debris flow in the Kirkwood Formation, Algoa Basin, Eastern Cape, South Africa. Cret Res 56:161–179
Muir R, Bordy EM, Reddering JSV, Viljoen JHA (2017a) Lithostratigraphy of the Enon Formation (Uitenhage Group), South Africa. Geol Soc of S Afr 120:273–280
Muir R, Bordy EM, Reddering JSV, Viljoen JHA (2017b) Lithostratigraphy of the Kirkwood Formation (Uitenhage Group), including the Bethelsdorp, Colchester and Swartkops Members, South Africa. Geol Soc of S Afr 120:281–293
Muir R, Bordy EM, Mundi R, Frei D (2020) Recalibrating the breakup history of SW Gondwana: U-Pb radioisotopic age constraints from the southern Cape of South Africa. Gondwana Res 84:177–219
Nádor A, Sztanó O (2011) Lateral and vertical variability of channel belt stacking density as a function of subsidence and sediment supply: field evidence from the intramountaine Körös Basin, Hungary. SEPM Spec Publ 97:75–392
Neal JE, Risch D, Vail P (1993) Sequence stratigraphy-a global theory for local success. Oilfield Rev 5:51–62
Neal JE, Abreu V (2009) Sequence stratigraphy hierarchy and the accommodation succession method. Geology 37:779–782
Neal JE, Abreu V, Bohacs KM, Feldman HR, Pederson KH (2016) Accommodation succession (δA/δS) sequence stratigraphy: observational method, utility and insights into sequence boundary formation. J Geol Soc 173:803–816
Paton AD, Underhill JR (2004) Role of crustal anisotropy in modifying the structural and sedimentological evolution of extensional basins: the Gamtoos Basin, South Africa. Basin Res 16:339–359
Platon C (2017) Guyana-Suriname Basin, South America: hot ultradeepwater exploration opportunities and Liza Field: Worldwide Largest 2015–2016 Hydrocarbon Discovery. AAPG Annual Convention and Exhibition, Houston, Texas, April 2–5, 2017
Plint AG, Nummedal D (2000) The falling stage systems tract: recognition and importance in sequence stratigraphic analysis. In: D. Hunt and R. Gawthorpe (eds) Sedimentary responses to forced regressions. Geol Soc Spec Publ 172:1–17
Posamentier HW, Allen GP (1999) Siliciclastic sequence stratigraphy: concepts and applications. SEPM Concepts in Sedimentology and Paleontology 7:210
Posamentier HW, Jervey MT, Vail PR (1988) Eustatic controls on clastic deposition. I. Conceptual framework. In: Wilgus CK, Hastings BS, Kendall CGStC, Posamentier HW, Ross CA, Van Wagoner JC (eds) Sea level changes—an integrated approach. SEPM Spec Publ 42: 110–124
Prosser S (1993) Rift-related linked depositional systems and their seismic expression. In: Williams, G.D., Dobb, A. (eds) Tectonics and seismic sequence stratigraphy. Geol Soc London Spec Publ 71: 35–66
Schimschal CM, Jokat W (2019) The Falkland Plateau in the context of Gondwana breakup. Gondwana Res 68:108–115
Shone RW (2006) Onshore post-Karoo Mesozoic deposits. In: Johnson MR, Anhaeusser CR, Thomas RJ (eds) The Geology of South Africa. Geol Soc of S Afr, Johannesburg and CGS, Pretoria: 541–571
Shone RW (1978) A case for lateral gradation between the Kirkwood and Sundays River Formations, Algoa Basin. Trans Geol Soc S Afr 81:319–326
Shone RW (1976) The sedimentology of the Mesozoic Algoa Basin. Unpublished M.Sc. thesis, University of Port Elizabeth: 48p
Singh V, Brink GJ, Winter HDLR (2005) New interpretation reveals potential in onshore Algoa basin South Africa. Oil Gas J 103(1):34–39
Stevenson IR, McMillan IK (2004) Incised valley fill stratigraphy of the Upper Cretaceous succession, proximal Orange Basin, Atlantic margin of southern Africa. J Geol Soc Lond 161:185–208
Thomson K (1999) Role of continental break-up, mantle plume development and fault reactivation in the evolution of the Gamtoos Basin, South Africa. Mar Pet Geo 16:409–429
Thompson JO, Moulin M, Aslanian D, de Clarens P, Guillocheau F (2019) New starting point for the Indian Ocean: second phase of breakup for Gondwana. Earth-Sci Rev 191:26–56
Vail PR, Mitchum RM Jr, Thompson S (1977) Seismic stratigraphy and global changes of sea level, part four: global cycles of relative changes of sea level. Am Assoc Pet Geol 26:83–98
Vail PR (1991) The stratigraphic signatures of tectonics, eustasy and sedimentology – an overview. In: Einsele G, Ricken W, Seilacher A (eds), Cycles and events in stratigraphy. Springer–Verlag: 617–659
Van Wagoner J C, Posamentier HW, Mitchum RM Jr, Vail PR, Sarg JF, Loutit TS, Hardenbol J (1988) An overview of sequence stratigraphy and key definitions. In Sea level changes–an integrated approach. In: Wilgus CK, Hastings BS, Kendall CGStC, Posamentier HW, Ross CA, Van Wagoner JC (eds) Sea level changes—an integrated approach. SEPM Spec Publ 42: 39–45
Van Wagoner JC, Mitchum RM Jr, Campion KM, Rahmanian VD (1990) Siliciclastic sequence stratigraphy in well logs, core, and outcrops: concepts for high-resolution correlation of time and facies. APPG Methods Explor Ser 7:55