

**International Ocean Discovery Program  
Expedition 361 Preliminary Report  
South African Climates (Agulhas LGM Density Profile)**

**30 January–31 March 2016**

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## Publisher's notes

Core samples and the wider set of data from the science program covered in this report are under moratorium and accessible only to Science Party members until 30 September 2017.

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## Abstract

International Ocean Discovery Program (IODP) Expedition 361 drilled six sites on the southeast African margin and in the Indian-Atlantic ocean gateway, southwest Indian Ocean, from 30 January to 31 March 2016. In total, 5175 m of core was recovered, with an average recovery of 102%, during 29.7 days of on-site operations. The sites, situated in the Mozambique Channel at locations directly influenced by discharge from the Zambezi and Limpopo River catchments, the Natal Valley, the Agulhas Plateau, and Cape Basin, were targeted to reconstruct the history of the greater Agulhas Current system over the past ~5 my. The Agulhas Current is the strongest western boundary current in the Southern Hemisphere, transporting some 70 Sv of warm, saline surface water from the tropical Indian Ocean along the East African margin to the tip of Africa. Exchanges of heat and moisture with the atmosphere influence southern African climates, including individual weather systems such as extratropical cyclone formation in the region and rainfall patterns. Recent ocean model and paleoceanographic data further point at a potential role of the Agulhas Current in controlling the strength and mode of the Atlantic Meridional Overturning Circulation (AMOC) during the Late Pleistocene. Spillage of saline Agulhas water into the South Atlantic stimulates buoyancy anomalies that act as control mechanisms on the basin-wide AMOC, with implications for convective activity in the North Atlantic and global climate change. The main objectives of the expedition were to establish the sensitivity of the Agulhas Current to climatic changes during the Pliocene–Pleistocene, to determine the dynamics of the Indian-Atlantic gateway circulation during this time, to examine the connection of the Agulhas leakage and AMOC, and to address the influence of the Agulhas Current on African terrestrial climates and coincidences with human evolution. Additionally, the expedition set out to fulfill the needs of the Ancillary Project Letter, consisting of high-resolution interstitial water samples that will constrain the temperature and salinity profiles of the ocean during the Last Glacial Maximum.

The expedition made major strides toward fulfilling each of these objectives. The recovered sequences allowed generation of complete spliced stratigraphic sections that span from 0 to between ~0.13 and 7 Ma. This sediment will provide decadal- to millennial-scale climatic records that will allow answering the paleoceanographic and paleoclimatic questions set out in the drilling proposal.

## Introduction

The Agulhas Current of the South Indian Ocean is a fundamental part of the South Indian Ocean subtropical gyre circulation and constitutes the strongest western boundary current in the Southern Hemisphere oceans (Lutjeharms, 2006a) transporting ~70 Sv (1 Sv =  $10^6$  m<sup>3</sup>/s) of warm, saline tropical surface waters to the tip of Africa (Figure F1, F2). This volume transport is roughly twice that of the Gulf Stream in the North Atlantic (Cunningham et al., 2007), but like its northern counterpart the Agulhas Current fosters exchanges of heat and moisture with the atmosphere that influence regional climates and weather systems (Reason and Mulenga, 1999). A portion of the Agulhas waters invade the South Atlantic through the Agulhas rings (Arhan et al., 2011) that transport between 5–20 Sv of warm, saline water from the Indian Ocean to the South Atlantic—the so-called interocean “warm-water route” of the global oceanic thermohaline circulation (THC). Ocean models and paleoceanographic data strongly suggest that the “leakage” of saline Agulhas

water into the South Atlantic stimulates regional buoyancy anomalies that ultimately impact convective activity in the northern North Atlantic, plausibly acting as a contributor to the basin-wide Atlantic Meridional Overturning Circulation (AMOC) (Figure F1) (Weijer, 2000; Weijer et al., 2002; Knorr and Lohmann, 2003; Van Sebille et al., 2009; Biastoch et al., 2008, 2009a). The numerical simulations specifically point to Agulhas leakage as a potential modulator of the AMOC and a rheostat for the ventilation of the deep ocean. Hence the significance of the Agulhas Current is threefold:

The Agulhas Current is a significant component of the global THC; it carries surface water into the Atlantic that compensates for the export of deep water from the Atlantic Basin to the world ocean;

This Agulhas leakage transfer of salt to the South Atlantic variably impacts the buoyancy structure there and may contribute to mode changes and variability of the AMOC and thus climate variability in the North Atlantic region; and

Variations in Agulhas warm-water transports along the southeast African continental margin drive interannual variability connected with the Indian Ocean Dipole (IOD) mode with implications for southern Africa regional climate and weather systems.

Interest in the long-term evolution of ocean circulation off southern Africa, on Pliocene–Pleistocene timescales, has concentrated in the past on the Atlantic side of the continent. Deep Sea Drilling Project (DSDP) Legs 40 and 75 in 1974 and 1980 and Ocean Drilling Program (ODP) Legs 108 and 114 in 1985 and 1987 targeted the southwest African continental slope and rise north and south of Walvis Ridge in order to explore marine conditions during the opening of the South Atlantic, including the origin and paleoceanographic history of the Eastern Walvis Ridge and carbonate dissolution cycles. More recently, ODP Leg 175 in 1997 targeted the southeastern Atlantic margin between 5° and 32°S to assess the history of the Benguela Current and upwelling off Angola and Namibia. ODP Leg 208 in 2003 drilled a transect of six sites on Walvis Ridge to gain insight into paleoceanographic events such as the Paleocene/Eocene hyperthermals and the early Oligocene Oi1 cold event.

By contrast, the eastern continental margin off southern Africa is poorly represented in the database of scientific drill sites. Prior to International Ocean Discovery Program (IODP) Expedition 361, only one site, DSDP Leg 25 Site 244, has been drilled within the direct reaches of the South Indian western boundary current. The site is positioned on Davie Ridge, at the northern entrance of the Mozambique Channel, and was occupied during Leg 25 in 1972 (Simpson, Schlich, et al., 1974) to provide data on the structure and geological history of the East African margin and western Madagascar.

Expedition 361 fills this scientific/geographic gap by drilling targets in three sectors of the greater Agulhas Current system (Figure F3):

1. The northern sector in the Mozambique Channel that provides the source waters for the Agulhas Current;
2. The central sector in the confluence region where the southwestern extension of the East Madagascar Current converges with the Mozambique Channel throughflow to form the Agulhas Current; and
3. The southern sector in the Indian-Atlantic ocean gateway at the tip of Africa with Agulhas retroflexion, Agulhas Return Current, and Agulhas leakage.

Analysis of these sediments will help to address the scientific objectives outlined below.

## Background

### Motivation for drilling in the greater Agulhas Current system

#### The Agulhas Current system—modern oceanographic circulation

The Agulhas Current constitutes the largest ocean western boundary jet current in the Southern Hemisphere. This current is involved in the warm-water return flow that feeds the renewal of North Atlantic Deep Water (NADW) and is a key component of the global oceanic thermohaline “conveyor belt” circulation (Gordon, 1986; Weijer et al., 1999; Lutjeharms, 2006a). The Agulhas Current carries thermocline waters from the South Indian subtropical gyre with contributions of Red Sea and Arabian Sea Waters and from the Indonesian Throughflow (Lutjeharms, 2006a) (Figure F4). Driven by the anticyclonic wind field over the South Indian Ocean, these water types are advected through eddies and meanders from the equatorial Indian Ocean through the Mozambique Channel and the East Madagascar Current (EMC) (Song et al., 2004; Beal et al., 2006). Interaction between Madagascar and westward-traveling Rossby waves from the tropical Indian Ocean contribute to the formation of eddies (Schouten et al., 2002a) east of Madagascar (Bjastoch and Krauss, 1999). Four to five of these eddies, as wide as 350 km, drift southward through the Mozambique Channel per year, carrying a mean transport of 17 Sv (Ridderinkhof et al., 2010), imposing short-term modulation over the whole depth range and width of the channel (de Ruijter et al., 2002) and imparting an interannual variability of ~9 Sv into the Agulhas Current (Bjastoch et al., 2009a). A coupled ocean (sea-surface temperature [SST])–atmosphere oscillator in the tropical Indian Ocean, the IOD, provides important upstream forcing of the Agulhas Current (Ridderinkhof et al., 2010). The EMC has an estimated transport of 20 Sv (Donohue et al., 2003; Schott et al., 1988), increasing to 35 Sv at the southern tip of Madagascar (Nauw et al., 2008). At the latitude of Durban (30°S), the westward-flowing southern extension of the EMC converges with the southward-flowing train of Mozambique Channel eddies to form the Agulhas Current as a narrow jet-type current that is steered by the steep South African continental margin. By the time it passes 32°S, the Agulhas Current carries ~70 Sv of warm (24°–17°C) and saline (35.5–35.2) (Gordon et al., 1990, 1992; Beal and Bryden, 1999; Bryden and Beal, 2001) waters of the South Indian thermocline (Bryden et al., 2005). In its deeper reaches, the current also includes saline Red Sea Water (Gordon et al., 1987) and other waters derived from far-distant sources in the Pacific (Gordon and Fine, 1996; Speich et al., 2002).

The Agulhas Current's mean trajectory is steered by the bathymetry of the narrow southeast African shelf where its steep continental slope provides for maximum barotropic and baroclinic guidance (de Ruijter et al., 1999b; Lutjeharms and de Ruijter, 1996; Goschen and Schuman, 1990). Instabilities of the current are caused by the downstream migration of eddies and meanders that interact with the bathymetry and morphology of the continental margin. An example is solitary meanders that form in the Natal Bight, the so-called Natal Pulses (Figure F5) (e.g., Lutjeharms and Roberts, 1988; Beal and Bryden, 1999; de Ruijter et al., 1999b; van Leeuwen et al., 2000; Bryden et al., 2005; Bjastoch et al., 2008; Tsugawa and Hasumi, 2010; Rouault and Penven, 2011). At the tip of Africa, the current turns west, driven by its own inertia, and retroflects back to the east into the Indian Ocean as the Agulhas Return Current (Lutjeharms and Ballegooyen, 1988). Mozambique Channel and EMC eddies that propagate downstream with the Agulhas Current as

strongly barotropic solitary meanders (Bryden et al., 2005; Bjastoch et al., 2009a; Tsugawa and Hasumi, 2010) destabilize the retroflection to the extent that four to six up to 400 km wide anticyclonic eddies (Agulhas rings) form per year and spin off the retroflection area carrying between 2 and 20 Sv of thermocline water to the South Atlantic (de Ruijter et al., 1999a; Richardson, 2007). Some researchers have suggested that Agulhas leakage is linked with interannual modes of Indian and Pacific variability, thus proposing a connection with the IOD and Pacific La Niña/El Niño phases (Schouten et al., 2002b; Palastanga et al., 2006).

#### Agulhas leakage and the AMOC

The dynamics of the Agulhas leakage and its possible impact on the AMOC and global climate have been explored in a number of ocean and climate models. These studies suggest that (1) this exchange affects the buoyancy of Atlantic thermocline waters, potentially influencing NADW formation on multidecadal timescales (Weijer et al., 2002; Knorr and Lohmann, 2003; Bjastoch et al., 2009a) and (2) perturbations of planetary waves by mesoscale eddies influence decadal variability of the AMOC (Van Sebille and van Leeuwen, 2007; Bjastoch et al., 2008).

Saltwater entering the South Atlantic with Agulhas rings stimulates planetary (Kelvin and Rossby) waves that propagate across the Atlantic Basin and perturb the AMOC (Bjastoch et al., 2009a). Short-term variability that appears to be associated with Agulhas leakage is observed in the subtropical North Atlantic (de Ruijter et al., 1999a), whereas some of the interannual to decadal AMOC variability seen in the models plausibly stems from the frequency of Agulhas ring shedding that, in turn, is modulated by the IOD and El Niño Southern Oscillation (ENSO) modes (de Ruijter et al., 1999a; Gordon and Haxby, 1990). The basin-scale radiation of planetary waves triggered by Agulhas leakage hence constitutes a “fast-response” mechanism that operates on interannual to decadal timescales.

The advection of saltwater from the Agulhas region to the convection centers in the North Atlantic Ocean is the likely connection between the AMOC response and Agulhas leakage. Seeding numerical Lagrangian floats into the Agulhas retroflection area in high-resolution ocean general circulation models reveals an advective transit time of 30–40 y from the Agulhas Current to the North Atlantic (van Sebille et al., 2010). These time estimates are also consistent with those obtained with lower-resolution models (Weijer, 2000). Continuing heat exchange with the overlying atmosphere augments the density anomaly associated with leaked Agulhas saltwater parcels as they drift northward (Weijer, 2000; Haarsma et al., 2011). Agulhas leakage therefore stimulates an AMOC response with a time delay dictated by the advective timescale for the excess salt to reach the North Atlantic, whereas the new AMOC equilibrium state is achieved several hundred years later when buoyancy fluxes and mixing are in balance (Weijer, 2000; Hughes et al., 2009). Establishing the impact of wind forcing on Agulhas leakage and its subsequent effect on the AMOC is not straightforward because the strength and position of the Southern Hemisphere mid-latitude westerlies may affect the Agulhas leakage and AMOC simultaneously (Bjastoch et al., 2009b; Toggweiler and Samuels, 1995; Sijp and England, 2008), perhaps by shifting the position of the Subtropical Front (STF) south of Africa. The STF is thought by some to define the width of the Agulhas leakage corridor, hence the strength of the leakage, although recent modeling studies show a stronger dynamic relationship with the intensity of the Southern Hemisphere westerlies (Durgadoo et al., 2013). Nonetheless, the westerlies control the

northward Ekman transport in the Southern Ocean, which forces deep water to ascend to the upper ocean, conceivably “pulling” the deep branch of the AMOC (Toggweiler and Samuels, 1995; Visbeck, 2007). Through their influence on deep-water upwelling and AMOC strength, the westerly winds and Agulhas buoyancy fluxes likely play important roles in the regulation of the ocean's ability to store carbon (Watson and Garabato, 2006; Backeberg et al., 2012), which posits a further plausible link between Agulhas leakage and global climate variability.

### Paleoceanography of the Agulhas Current system

The Agulhas Current region is an area in which retrieval of high-quality sediment cores is difficult. The southeast African margin has a very narrow shelf and a steep continental slope, leading to frequent sediment instability and slumping. Further, the vigorous Agulhas Current and its mesoscale variability can cause sediment redistribution because meanders and eddies frequently reach the seafloor. Yet, a number of published studies and emerging work demonstrate that paleoceanographic records of excellent quality are in fact achievable for reconstructing both surface and deep-water variability in the region. A full synthesis of the paleoceanographic evidence is yet to emerge, but there appears to be several aspects of the Agulhas paleotime series about which different workers are in broad agreement. Based on published records, Agulhas leakage has been a persistent feature of the past 1.3 my, with less leakage during full glacial times than interglacial times and greatest leakage at the glacial terminations (Peeters et al., 2004; Caley et al., 2012; Petrick et al., 2015). There is also general agreement about evidence for a more northerly position of the STF during glacial times (Rau et al., 2002, 2006; Bard and Rickaby, 2009; Martínez-Méndez et al., 2010), and some suggestion that this may play a role in reducing Agulhas leakage. However, there is also evidence that the positions of the westerly wind belt and STF can be decoupled (Graham and De Boer, 2013; De Boer et al., 2013; Durgadoo et al., 2013), leading to some uncertainty in the exact mechanisms of changing Agulhas leakage.

At the tip of Africa, a spliced record composed of Cores GeoB-3603-2 and MD96-2081 (termed the Cape Basin Record [CBR]; Peeters et al., 2004) shows maximum abundance of the so-called “Agulhas leakage fauna” (ALF) that appears to be related to minima in precession (maxima in northern summer insolation), leading these authors to suggest a possible teleconnection to the monsoon system. Multiple-proxy data from planktonic foraminifers from sediment Core MD96-2080 on the Agulhas Bank provide a detailed reconstruction of surface-ocean paleoclimatology in the area. Continued warming across full-glacial stages (marine isotope Stages [MIS] 2 and 6) displayed in planktonic Mg/Ca data implies increased influence of warm Agulhas water in the region and/or reduced northward advection of cold subantarctic surface water (Martínez-Méndez et al., 2010) (Figure F6). This pattern is consistent with the hypothesis that peak Agulhas leakage occurred during glacial terminations and plausibly aided the AMOC to shift to its full-strength interglacial mode (Knorr and Lohmann, 2003, 2007; Peeters et al., 2004). A high-resolution faunal record of the accumulation rate of tropical species *Globorotalia menardii* at ODP Site 1087 in the southern Benguela region was used to infer that Agulhas leakage strengthened during every glacial termination of the past 1.3 my (Caley et al., 2012). The Caley et al. (2012) interpretation of increased leakage during terminations in the Late Pleistocene is also supported by combined alkenone ( $Uk^{37}$  and  $\delta D$ ) and dinoflagellate cyst assemblages, SST, and salinity estimates from Site 1087 (Petrick et al., 2015).

SST and salinity records at an upstream location along the southeast African margin (Core MD96-2048; 26°S) (Caley et al., 2011) display prominent 41 ky cyclicity that was interpreted to suggest that long-term Agulhas Current variations were associated with high-latitude (as opposed to regional tropical) climate forcing. However, the cyclicity also suggests that some of the apparent variability in Agulhas leakage could actually be changes in the Agulhas Current. Thus, to circumvent the potential problem that ALF (Peeters et al., 2004) and *G. menardii* (Rau et al., 2006; Caley et al., 2012) indexes might be sensitive to the changing composition of the Agulhas source assemblage upstream, Caley et al. (2014) proposed a new quantitative foraminiferal-based proxy index for Agulhas leakage, named Agulhas leakage efficiency, and suggested that Agulhas leakage efficiency represents the transfer of Agulhas water from the Indian Ocean to the Atlantic independent of the variations in the source assemblage. Using this approach, Caley et al. (2014) confirm substantial changes in Agulhas leakage volume transports at the termination of glacial periods (>10 Sv) and possibly a complete halt of leakage during MIS 12.

The composition of terrigenous sediment in core tops of marine sediment cores around South Africa shows significant and systematic provenance variations (Franzese et al., 2006, 2009). Provenance studies using  $^{87}Sr/^{86}Sr$ ,  $\epsilon Nd$ , and  $^{230}Th_{xs}$  flux estimates from Holocene and Last Glacial Maximum (LGM) samples from a number of cores near the tip of South Africa were used to suggest reduced advection of sediment derived from Agulhas water (and therefore possibly Agulhas leakage) during peak glacial times (Franzese et al., 2006). In a follow-up study, Franzese et al. (2009) made a more detailed geographic study of Holocene and LGM samples from a set of cores from the R/V *Charles Darwin* 154 site survey cruise as well as additional cores from the Lamont Doherty Earth Observatory repository from the Agulhas Plateau. The interpretations from these two studies support a weaker Agulhas Current and less leakage, as well as an Agulhas trajectory very similar to modern. These results are partly at odds with models that suggest over glacial–interglacial cycles, if the wind pattern is fixed but its strength reduced, a weaker Agulhas Current results in increased leakage (De Ruijter, 1982; Dijkstra and De Ruijter, 2001; Van Sebille et al., 2009). However, if the winds shift northward and weaken during glacial periods, a weaker Agulhas Current could combine with reduced leakage. The equivocal comparison between data and models call for further work including multiproxy analyses.

A key question concerning Agulhas leakage is: How important are the locations of the STF and westerly wind belts? For instance, early work from Core MD96-2080 from the western flank of the Agulhas Bank (Rau et al., 2006) showed the continuous presence of subtropical planktonic foraminifers (e.g., *G. menardii*); this observation implies persistent Indian-Atlantic surface water flow during the last 450 ky. On the other hand, transient occurrences of subpolar species (*Neogloboquadrina pachyderma* dextral) suggest intermittent incursions of cold subantarctic waters in the Agulhas corridor during glacial periods (Rau et al., 2002, 2006), perhaps the result of meridional shifts of the subtropical and subantarctic fronts. SST records and ocean productivity indicators near the eastern entrance of the Indian-Atlantic ocean gateway in Core MD96-2077 are tentatively taken to support such a scenario in that they suggest that during some full-glacial stages the STF moved northward by as much as 7° in latitude (Bard and Rickaby, 2009), thus potentially severely reducing Agulhas Current transports into the gateway and limiting leakage to the South Atlantic. However, this picture is contrasted by substantial increases of ALF (Peeters et al.,



2004) in the Agulhas corridor at the termination of glacial periods, alluding to an involvement of Agulhas leakage in interhemispheric ocean and climate change, notably the resumption of NADW formation (Peeters et al., 2004). Additionally, the records of Caley et al. (2014) and Petrick et al. (2015) also demonstrate Agulhas leakage was a persistent feature of the past 500 ky, including glacial MIS 10 (Caley et al., 2014), apparently at odds with a substantial effect on Agulhas leakage caused by the significant northward migration of the STF (Bard and Rickaby, 2009).

Multiple-species stable isotope and alkenone data from ODP Site 1085, slightly further north, also suggest that Agulhas leakage variability during MIS 11 was directly related to AMOC activity and wind forcing. Site 1085 shows evidence for strengthened leakage at the end of MIS 11 that may have contributed to renewed ice-sheet build-up and the demise of warm conditions (Dickson et al., 2010).

Recent reconstructions detailing the multicentennial- to millennial-timescale hydrographic variability in the Agulhas corridor have been published for the last glacial cycle (80 ka to present; Core MD02-2594) (Dyez et al., 2014), the previous two glacial–interglacial climate cycles of MIS 8–5 (Core MD96-2080; 265–77 ka) (Marino et al., 2013), and upstream in the Agulhas Current for the last glacial cycle (Core CD154 17-17K; Simon et al., 2013). These studies confirm a connection of leakage maxima with glacial–interglacial climate transitions and extend the connections to millennial-scale salinity anomalies that appear to systematically coincide with accelerated warming at the end of the North Atlantic cold phases (stadials). This finding lends credence to earlier hypothetical considerations (Lutjeharms, 2006a) and numerical models (Knorr and Lohmann, 2003; Weijer et al., 2002; Biastoch et al., 2008) pointing to Indian-Atlantic salt leakage as an essential modulator of abrupt climate change. However, reanalyses of a freshwater LGM hosing experiment using a fully coupled atmosphere–ocean general circulation model (Gong et al., 2013) has been recently used to suggest that the millennial-scale salinity increases in the Agulhas corridor are consistent with the presence of a quasi-interhemispheric salt seesaw. This salt seesaw is analogous to the thermal bipolar seesaw, responding to reduced cross-hemispheric heat and salt exchange during times of weakened AMOC (Simon et al., 2015a). Indeed, Simon et al. (2015a) suggest that although more upstream saline Agulhas water was propagated to the Indian-Atlantic ocean gateway during Heinrich Stadial 1, the salt flux into the South Atlantic, through the Indian-Atlantic ocean gateway, during that time was actually reduced. Accordingly, intervals with higher salinity in the Agulhas Current source region cannot necessarily be taken to indicate increased salt exchange through the Indian-Atlantic ocean gateway into the South Atlantic, thus calling for further study.

### **Agulhas Current links with southern African climates and rainfall patterns**

Southern Africa spans a significant range of climatic and vegetation zones (Figure F7) from the low-latitude tropical regime that is primarily under the influence of the Intertropical Convergence Zone (ITCZ) and Congo Air Boundary (CAB) to the high southern latitudes that are influenced by the northern extensions of the circum-Antarctic westerly wind belt (Tyson, 1986; Chase and Meadows, 2007). The ITCZ and CAB collectively form the divide between easterly winds arriving from the Indian Ocean and westerly winds from the Atlantic (Leroux, 1983). Presently, the southernmost extent of the seasonal migrations of the ITCZ and CAB is situated over the Zambezi Catchment during austral summer (December, January, and February [DJF]). The Zambezi Catchment is

the largest riverine catchment in southeastern Africa, with headwaters extending far into the continental interior. Because of the northern position of the African rainfall belt as well as the presence of mountain ranges of the East African Rift zone, annual rainfall amounts are higher across the Zambezi Catchment compared to the neighboring Limpopo Catchment to the south. Although directly connected with the ITCZ, the convergence zone over tropical southern Africa is decoupled on occasion from the divide between dry trade winds in the east and wet monsoon in the west, as occurring, for instance, over West Africa in summer. Rainfall intensity today in southeast Africa is correlated to SST variability in the southwest Indian Ocean and the Agulhas Current regime (Reason and Mulenga, 1999; Walker, 1990; Jury et al., 1993; Reason, 2002; Singleton and Reason, 2007). Additionally, today's interannual variability of precipitation in South Africa is also antiphased with that of tropical East Africa (Goddard and Graham, 1999). It is apparent from modern observations that terrestrial precipitation records have very regional patterns, and thus understanding past variability requires records from a range of archives that span this variability.

During the Late Pleistocene, shifts in African climate have been largely paced by regional insolation changes driven by orbital precession (deMenocal et al., 1993). These changes result in antiphased summer insolation maxima between the Northern and Southern Hemispheres, which drives an interhemispheric temperature contrast resulting in zonal shifts of the ITCZ and imprint of the summer monsoonal rainfall (Kutzbach et al., 2008). Additionally, African climate is impacted by high-latitude forcing predominantly varying on longer obliquity and eccentricity timescales (Tuenter et al., 2003; Weber and Tuenter, 2011). Although in the low-latitude tropics African climate is dominated by the influence of the ITCZ and associated rain belts, studies from central and eastern Africa document the increasing influence of the Atlantic and Indian Oceans (Castañeda et al., 2007; Schefuß et al., 2005; Tierney et al., 2008). Whereas longer term climate evolution of the African continent is documented by a variety of terrestrial and marine records, the history of the northeastern and southeastern tropical Africa (e.g., Schneider et al., 1997; Johnson et al., 2002; Schefuß et al., 2005; Castañeda et al., 2007; Weldeab et al., 2007; Tierney et al., 2008, 2011; Ziegler et al., 2010; Otto-Bliesner et al., 2014) is better constrained than southern Africa. Southern African records are sparse, fragmented, and often suffer from a lack of robust age frameworks (e.g., Gasse et al., 2001; Partidge et al., 1997, 2004; Chase et al., 2007; Collins et al., 2014). Such information is important because variability has significantly influenced African biomes during the Pleistocene, and this has in turn affected the distributions of species as well as human demography (Scott et al., 2008).

Lake Malawi, the southernmost of the East African Rift lakes in the southern tropics, provides the only available continuous continental record of the last 1.3 my of terrestrial climate in southern East Africa. Reconstruction of temperature (using the organic proxy TEX<sub>86</sub>) and aridity (using leaf wax  $\delta^{13}\text{C}$ ) indicates a variable and predominantly arid climate that has 40 ky periodicity prior to 900 ka (the mid-Pleistocene transition [MPT]), shifting to a more humid environment after the MPT. After the MPT, the record has strong 100 ky periodicity, with warmer and wetter conditions in interglacial intervals and relatively cool and dry glacial intervals (Johnson et al., submitted). The inferred shift in climate conditions across the MPT is supported by additional sedimentological proxies that indicate lower lake levels prior to the MPT followed by higher amplitude lake level variability and overfilled lake conditions until ~100 ka punctuated by intervals of short-lived extreme drought (Lyons et

al., 2015). A similar story for the MPT is also found in the record of African  $C_4$  plant abundance from ODP Site 1077 in the tropical South Atlantic, although this record does not exhibit the shift toward overall more humid conditions for the last ~900 ky (Schefuß et al., 2003).

Lake Malawi is located in northwestern part of the Zambezi Catchment, which drains into the Indian Ocean at ~20°S. A  $\delta D_{\text{leaf wax}}$  record in sediment Core GeoB 9307-3 off the Zambezi River documents brief and distinctly wetter intervals that correlate with the Younger Dryas and Heinrich Stadial 1 (Schefuß et al., 2011). Together with BIT index (the relative abundances of branched glycerol dialkyl glycerol tetraethers (GDGTs) and the isoprenoid GDGT, crenarchaeol (Hopmans et al., 2004; Huguet et al., 2007) and X-ray fluorescence data, this proxy record is taken to indicate that rainfall intensities and Zambezi sediment discharge increase because of a southward shift of the ITCZ during Northern Hemisphere cold events. However, in an apparent contradiction, the  $\delta^{13}C_{\text{leaf wax}}$  record of this core shows an increased abundance of drought-tolerant  $C_4$  grasses during these inferred wet intervals. This discrepancy in  $C_3$ - $C_4$  plants is probably attributed to shifts in source areas within the Zambezi subcatchments, as inferred from magnetic mineral inventories (Just et al., 2014), presumably due to changes in the locus of rainfall.

A more distal, deeper coring site ~200 km north of the Zambezi River mouth at ~1300 m water depth provides continuous sedimentary records spanning the last ~40 ky. A high-resolution record of neodymium isotopes ( $\epsilon Nd$ ) in the lithogenic clay fraction from one of the cores (64PE304-80) is interpreted to reflect changes in Zambezi sediment discharge relative to sediment transported from more northern sources by the strong net southward eddy-induced flow through the Mozambique Channel (van der Lubbe et al., 2016). The reconstructed intervals of enhanced Zambezi discharge are in agreement with the  $\delta D$  rainfall record obtained from a parallel core (GIK16160-30; Wang et al., 2013) after correction for the  $C_3$ - $C_4$  vegetation abundances.

Collectively, the evidence is consistent with the inference that the Zambezi Catchment experienced relatively wetter conditions during MIS 2 and the late Holocene, whereby Heinrich Stadial 1 and the Younger Dryas stand out as intervals of extreme wet conditions. More arid conditions occurred during MIS 3 and between ~15 and 5 ka. The later interval is synchronous with but opposite in sign to the African Humid Period in northern Africa. Altogether, Zambezi Catchment records document precession-paced changes in the African monsoonal rainfall belt with enhanced rainfall during periods of increased Southern Hemisphere summer insolation, superimposed by wet conditions during high-latitude Northern Hemisphere abrupt cold events.

Progressing south, a 342 ky long pollen record from marine sediment Core MD96-2048 from 660 m water depth ~120 km south of the Limpopo River mouth shows glacial–interglacial and precession-driven climate variations in the extent of the subtropical biome (Dupont et al., 2011). On land the sediment record from Tswaing Crater, a meteorite impact north of Pretoria, provides the longest terrestrial record of climate variability located directly in South Africa, spanning the last 200 ky. Clastic particle size variations from this site have been used to suggest that cyclic changes in precipitation were linked with the long-term effect of regional insolation changes driven by orbital precession (Partridge, et al., 1997, 2004).

Marine sediment Core CD154-10-06P located off the east coast of subtropical South Africa, KwaZulu-Natal (KZN), reveals shifts in river runoff at the southeast African margin spanning the past 270 ky that also strongly follow orbital precession pacing (Figure F8). X-

ray fluorescence elemental data from Simon et al. (2015b) show humid phases that can be plausibly connected with millennial-scale Northern Hemisphere cold events. These excursions extend those recently identified in similar data from Core CD154-17-17K, a little further south, that were linked periods of early modern human innovation during the middle Stone Age (Ziegler et al., 2013). Some of the millennial-scale events recorded in the eastern South Africa runoff records are coincident with periods of enhanced dune activity and mobility in the Kalahari and Namib Deserts and are consistent with the suggestion of shifted rainfall patterns and wind regimes (Stokes et al., 1999; Thomas et al., 2000; Stuut et al., 2002). Broadly, the conclusion drawn from the data is that past continental climate changes in southern Africa were linked with changes in ocean and atmospheric circulation, some directly associated with meridional shifts of the ITCZ, the Antarctic circumpolar ocean fronts, and the Southern Hemisphere mid-latitude westerlies.

A particularly intriguing feature of both emergent records from stalagmites in coastal caves in South Africa (Bar-Matthews et al., 2010) and marine sediment cores at the southeast African continental margin (Schefuß et al., 2011; Wang et al., 2013; Ziegler et al., 2013; Just et al., 2014; van der Lubbe et al., 2014, 2016; Weldeab et al., 2014; Simon et al., 2015b) is the indication of recurrent but spatially variable millennial oscillations of rainfall patterns.

Precession-only sensitivity experiments using a high-resolution fully coupled ocean-atmosphere model (altering the seasonal and latitudinal distribution of solar insolation) supports the proxy-based interpretations described from previous studies. These simulations show that during precession maxima (Pmax), higher Southern Hemisphere summer (DJF) insolation causes higher temperatures and lower surface pressure over the Southern Hemisphere, especially over land (Figure F9). Specifically, lower pressure during Pmax compared to precession minima (Pmin) over South Africa and higher surface pressure over the southern Indian Ocean results in stronger easterly surface winds blowing toward eastern South Africa (Figure F9). Over land, convection also increases, resulting in greater precipitation and greater net precipitation (precipitation minus evaporation) over nearly all of southern Africa during Pmax. The enhanced precipitation during Pmax is particularly pronounced in the KZN and Eastern Cape province region, compared to other regions further north or west, which results in higher surface runoff in the KZN and Eastern Cape province and explains the considerable spatial variability observed in different core sites adjacent to land in the southwest Indian Ocean.

### Density profile of the LGM ocean

The circulation of the deep ocean at the LGM is a crucial piece of the puzzle to understand past variations in  $CO_2$  and glacial–interglacial cycles more generally. Although the distribution of sedimentary deep-ocean circulation tracers ( $\delta^{13}C$ ,  $Cd/Ca$ ,  $\epsilon Nd$ , and  $\delta^{18}O$ ) indicate that LGM ocean circulation was likely different than that of the modern ocean (e.g., Rutberg et al., 2000; Piotrowski et al., 2004, 2005; Marchal and Curry, 2008; Lund et al., 2011), the distributions of these properties are inconclusive enough that they may also be consistent with modern circulation and differences in surface forcing (e.g., Gebbie, 2012; Gebbie and Huybers, 2006; LeGrand and Wunsch, 1995). Thus, to understand the role of the deep ocean in ice age climate variability, we require a more robust assessment of ice age deep-ocean variability, using a suite of tracers characterized by wide-ranging sensitivity to surface forcing.

In the modern ocean, we use the patterns of temperature and salinity to map the distribution of deep-water masses. In addition, these values inform the balance of air–sea exchange processes that

are required to create the negative buoyancy to form deep water; they are an integrated record of climate at high latitudes. It would be ideal to use the same strategy for the ice age ocean. However, there are few available means to develop a full temperature-salinity plot for the LGM. Schrag and DePaolo (1993) and Schrag et al. (1996, 2002) pioneered a strategy for quantifying the  $\delta^{18}\text{O}$  of seawater by sampling a profile of deep-ocean sediment, making highly precise measurements of  $\delta^{18}\text{O}$  and applying diffusion models to calculate the value of LGM water. This strategy has been expanded to include  $[\text{Cl}^-]$ , thus allowing an estimate of salinity (Adkins et al., 2002; Adkins, 2013; Miller et al., 2015). With local  $\delta^{18}\text{O}$  data from benthic foraminifers, pore water information can be turned into a single point on the LGM temperature-salinity diagram. The current version of this plot, from sampling IODP material, contains only four points (Figure F10) (Adkins et al., 2002). The relative scarcity of the observations stems from the requirements of the approach: sediment must be drilled to >150 m below seafloor to properly measure and model the diffusion profile; a well-behaved sediment column, free of complicated fluid flow and diagenesis, must be sampled; and an entire hole must be dedicated to the pursuit. Nevertheless, despite the stringent requirements this approach is currently the most direct way to estimate physical properties and structure of the ice age deep ocean.

In any case, the existing data imply that there were larger-than-modern density differences between deep-ocean water masses at the LGM and most of the ocean lies close to the freezing point and therefore differences in density were due primarily to salinity (see also discussion in Miller et al., 2012). Most surprisingly, the salt gradient in the modern Atlantic of fresh southern-sourced waters and salty northern-sourced waters appears to have been reversed at the LGM. This suggests the saltiest waters of the LGM ocean originated in the Southern Hemisphere. Adkins et al. (2002) concluded that Glacial Southern Source Bottom Water (GSSBW) was the densest due to its high salinity. Enhanced density differences between northern-sourced and southern-sourced bottom waters indicate greater vertical stratification. A stronger vertical stratification at the LGM would help explain indications that there was a physically isolated reservoir of  $\text{CO}_2$  in the deep ocean at this time (Broecker and Barker, 2007). In the years since this early work, analytical measurement of  $[\text{Cl}^-]$  has been improved, several new sampling strategies have targeted increasing throughput, and the data analysis tools used to model the data have been improved. The next most important step in constraining the temperature, salinity, and density structure of the LGM deep ocean is to obtain depth transects of these properties. To this end, samples taken during Expedition 361 spanning from 450 to 3040 m water depth will be used to help constrain the processes that could fill the LGM deep ocean and control its circulation.

## Scientific objectives

Expedition 361 Pliocene–Pleistocene objectives include the following:

- To establish the sensitivity of the Agulhas Current to changing climates of the Pliocene–Pleistocene in association with transient to long-term changes of high-latitude climates, tropical heat budgets, and the monsoon system.
- To determine the dynamics of the Indian–Atlantic ocean gateway circulation during such climate changes in association with changing wind fields and migrating ocean fronts.

- To examine the connection between Agulhas leakage and ensuing buoyancy transfer and shifts of the AMOC during major ocean and climate reorganizations during at least the last 5 my.
- To address the impact of Agulhas variability on southern Africa terrestrial climates and notably rainfall patterns and river runoff.

Specific scientific objectives include the following:

- To determine the variability of the greater Agulhas Current system under contrasting climatic regimes: Agulhas Current variability under early Pliocene warm conditions, during the mid-Pliocene expansion of Northern Hemisphere ice sheets, and through the MPT;
- To establish the role of Agulhas leakage in transient and long-term shifts of the AMOC during these climatic transitions: proxy records of mode/strength of the Agulhas leakage during periods of major climatic reorganizations and for AMOC variations through the same intervals;
- To establish the response of the Agulhas Current system to Antarctic climate variability and bipolar linkages: evidence for variation of the Agulhas leakage in highly resolved temporal records will be compared to Antarctic and bipolar climate changes, as well as with evidence for shifts of Southern Ocean fronts bordering the Agulhas corridor at the southern tip of Africa and strength of the westerlies;
- To understand the remote tropical origins of Agulhas Current variability: evidence for variation of the Agulhas leakage in highly resolved temporal records will be compared to records of Indonesian Throughflow and monsoon modulation on the Agulhas Current source region and impacts on warm and salt-water transports along the southeast African margin and Indian–Atlantic saltwater leakage;
- To better determine southern African climate sensitivity: comparison of varying Agulhas Current warm-water transports with rainfall patterns in southern Africa, in connection with the Pliocene–Pleistocene evolution of tropical climates, ITCZ migration, and tectonic history of eastern Africa; and
- To provide further verification of glacial–interglacial variations in the Southern Ocean's role in the carbon cycle: nutrient cycling, productivity, and  $p\text{CO}_2$  and their role in global biogeochemical cycles.

Additionally, Expedition 361 will complete an intensive interstitial fluids program aimed at constraining the temperature, salinity, and density structure of the LGM deep ocean, from the bottom of the ocean to the base of the main thermocline. High-resolution interstitial water samples will be utilized for  $\delta^{18}\text{O}$  and chloride measurements to characterize the salinity of the bottom water and to deconvolve the temperature and ice volume control on  $\delta^{18}\text{O}$  of benthic foraminifers.

## Principal results

### Site U1474

Site U1474 is located in the northernmost Natal Valley ( $31^\circ 13.00'\text{S}$ ;  $31^\circ 32.71'\text{E}$ ) ~88 nmi south-southeast of Durban, South Africa, in a water depth of 3045 m below sea level (msl). The north-south–trending Natal Valley is a sediment-filled basin between the coast of southeast Africa and Mozambique Ridge. At its northern end, the shoaling valley passes into the extensive coastal plains of Southern Mozambique (Dingle et al., 1978; Goodlad,



1986), whereas toward the south the deepening Natal Valley merges with Transkei Basin below 4500 mbsl. Terrigenous sediment supply into the basin is dominated by seasonal discharge from the numerous short but fast-flowing rivers that characterize the drainage system of the Natal coast (e.g., the Tugela River), as well as contributions from the Limpopo River and possibly the Zambezi River. Surface sediment dispersal is strongly affected by the ~100 km wide Agulhas Current flowing southward close to the continental shelf edge and transporting ~70 Sv at 32°S (Beal and Bryden, 1999) with surface velocities up to 1.5 m/s. At depth, the northward-flowing Agulhas Undercurrent hugs the continental slope, currently transporting NADW. The currents related to this northward flow have led to the formation of a network of elongate, north-south-orientated sediment drifts.

According to Lutjeharms (2006a), the Agulhas Current can be considered to be fully constituted at ~26°S, around Ponto do Ouro, close to the border between Mozambique and South Africa. Here, the East Madagascar Current converges with Mozambique Channel throughflow to form the Agulhas Current. The northern section of the Agulhas Current system, above Site U1474, is extraordinarily stable due to the steep, nearly rectilinear continental shelf that topographically steers the current flow southward (de Ruijter et al., 1999a; Lutjeharms, 2006a, 2007).

Several high-resolution orbital- to millennial-timescale records from shallow-penetration marine sediment cores located near Site U1474 (Ziegler et al., 2013; Simon et al., 2013, 2015a, 2015b) have provided multiproxy reconstruction of hydrographic variability within the main flow of the Agulhas Current as well as river discharge from the catchments of the Natal coast over the past 250 ky. In particular, Simon et al. (2013) demonstrated a strong connectivity between upstream Agulhas Current hydrographic variability and the phasing of temperature, salinity, and planktonic foraminiferal-based Agulhas leakage changes in the Agulhas leakage corridor, plausibly linked to the influence of recirculation within the southwest Indian Ocean subgyre, as predicted from physical oceanography (e.g., Gordon, 1985; Stramma and Lutjeharms, 1997). Additionally, it has been shown that changes in terrestrial climate (hydroclimate) are related to regional precession-paced insolation changes and the effects associated with high-latitude abrupt climate forcing (Simon et al., 2015b). When considered in combination with archaeological records, these records appear to provide evidence for links between climate and human settlement in South Africa during the middle Stone Age (Ziegler et al., 2013).

Our primary objective was to recover a key Pliocene–Pleistocene sedimentary succession, including the early Pliocene warm period, mid-Pliocene expansion of Northern Hemisphere ice sheets, and the MPT, formed under the influence of the upper reaches of the Agulhas Current. The site is ideally located to provide

- A reconstruction of Agulhas Current warm-water transports close to the start of the fully constituted Agulhas Current;
- An upstream record that may allow discerning connections between Agulhas leakage and its headwater variability;
- Evidence to understand the connections between southern African terrestrial climates and southeast Indian Ocean heat budgets, notably Agulhas Current warm-water transports and associated ocean-atmosphere heat and moisture transfer;
- A record of the vigor and hydrography of NADW (or its precursors) transported to the Circumpolar Deep Water (CDW) and the southwest Indian Ocean; and

- An interstitial water profile of  $\delta^{18}\text{O}$  and chloride ion concentration that can enhance the understanding of temperature, salinity, and density of the deep water bathing Site U1474 by providing an additional data point to the presently available pore water LGM temperature and salinity inventory.

Site U1474 consists of eight holes ranging in penetration depth from 3.1 to 254.1 m drilling depth below seafloor (DSF). Overall, 111 cores were recovered at this site. The advanced piston coring (APC) system penetrated 794.0 m and recovered 809.79 m of core (102% recovery). The half-length APC (HLAPC) system penetrated 102.4 m and recovered 100.96 m of core (99% recovery). A total of 910.75 m of sediment was recovered from the 896.4 m interval cored (102% recovery) at Site U1474. The total time spent at Site U1474 was 7.6 days.

### Sedimentology

The sediment at Site U1474 consists of two lithologic units. Unit I (0–0.5 m coring depth below seafloor [CSF-A]) is composed of brown foraminifer-bearing clay with nannofossils. Unit II (0.5–254.07 m CSF-A) is characterized by greenish gray foraminifer-bearing clay with nannofossils alternating with intervals of greenish gray nannofossil-rich clay with or without foraminifers. Nannofossil-rich clay is more common downhole. Dark gray foraminifer-bearing fine-sand layers ranging in thickness from a few centimeters to <2 m are common in Unit II (typically 1–3 per core). The composition of these sandy layers is predominantly quartz with carbonate, and many have erosional bases. Sediment in Unit II includes dark gray mottling that we interpret as bioturbation. The relative intensity of the bioturbation typically increases with depth throughout Unit II. Sediment in Unit II also includes millimeter- to centimeter-scale green layers that contain pyrite and glauconite based on X-ray diffraction (XRD) and smear slide observations. These layers represent diagenetic alterations.

Significant drilling disturbance was observed in the first section of most of the cores and in the base of partial-stroke APC cores.

### Physical properties

Despite the relatively homogeneous lithology, physical parameters vary along the entire sequence. Porosity increases with depth from 0 to 12.8 m core composite depth below seafloor (CCSF-A), reaching a maximum of 72% followed by a decrease to <50% at the bottom of the cored section. This decreasing trend toward the bottom is likely due to compaction. Variations in gamma ray attenuation (GRA) density reflect the same compaction pattern. Natural gamma radiation (NGR) and magnetic susceptibility markedly decrease in the upper 10 m CCSF-A and increase to 130 m CCSF-A. Below 130 m CCSF-A, NGR and magnetic susceptibility values decrease to the base of the section. This decreasing trend occurs in spite of compaction and thus likely reflects decreasing abundances of clay and magnetic minerals within the sediment. Superimposed on the general trends are cyclic variations in NGR of typically ~10–15 counts/s, which may be related to the variable mixtures of terrigenous and biogenic sediment components. Fine-sand layers found throughout the cored section are clearly identified by peaks in magnetic susceptibility and GRA density values. Spectral reflectance shows a marked cyclic pattern downhole and broadly corresponds with the trends in color spectrometry values.

### Micropaleontology

Analysis of calcareous nannofossils, planktonic and benthic foraminifers, and diatoms from core catcher and split-core samples



from Hole U1474A indicates that Site U1474 spans the Late Pleistocene to the latest Miocene (~6.2 Ma). Calcareous microfossils show good to moderate preservation in the upper 180 m CSF-A of the site. Below this depth, preservation and fossil group abundances decrease. A complete sequence of calcareous nannofossil zones was found from the late Miocene (Biozones NN11–NN21) to Late Pleistocene. Evidence for reworking of calcareous nannofossils is found throughout the entire sequence in the persistent presence of early Miocene species. The calcareous nannofossil assemblages are typical of tropical to subtropical settings, although the temperate species, *Coccolithus pelagicus*, is found throughout the cored interval. Planktonic foraminifers also record a complete sequence of tropical biozones that span Miocene Biozone M13 to Late Pleistocene Subbiozone Pt1b. The planktonic foraminifer fauna is dominated by *Globorotalia inflata*, which is indicative of transitional environments between subtropical and polar watermasses, and in deeper parts of the sequence the assemblage contains elements of the globocollid group that are typical of subtropical convergence zones. Benthic foraminifer fauna is diverse and includes numerous suboxic components characteristic of a lower bathyal to abyssal environment. Siliceous microfossils are characteristic of a modern Indian Ocean assemblage and make up a minor component of the mudline sample. Below the mudline sample, sponge spicules are rare to trace until they disappear completely below Sample 361-U1474A-10H-CC (90.19 m CSF-A).

The age model for Site U1474 is based on the biozonation of calcareous nannofossils, planktonic foraminifers, the extinction of the benthic foraminifer *Stilostomella*, and magnetostratigraphy (see below). These data reveal that sedimentation rates are nearly constant throughout the recovered sequence, without major hiatuses. A long-term linear sedimentation rate of ~3.7 cm/ky is estimated.

### Paleomagnetism

Paleomagnetic and rock magnetic analyses were carried out on sediment cores from Holes U1474A–U1474H. Analyses of discrete samples taken from Hole U1474A indicate that the magnetic mineralogy is dominated by magnetite. The relatively high saturation isothermal remanent magnetization (SIRM) and high and stable *S*-ratios further reveal that magnetic minerals are well preserved throughout the sequence. Below ~100 m CSF-A, an increase of magnetic minerals is expressed by high SIRM. Inclination and declination records were obtained by measuring and demagnetizing the natural remanent magnetization (NRM) of archive core halves and discrete samples. The majority of the APC cores were oriented using the Icefield MI-5 tool. The inclination record is of good quality, and nine polarity zones can be identified. The boundaries of the Brunhes, Matuyama, Jaramillo, Olduvai, Gauss, Gilbert, C3n, and C3r (sub)paleomagnetic chrons constrain the chronology of the sediment and are in good agreement with the biostratigraphic data.

### Stratigraphic correlation

Continuous and distinctive variations in magnetic susceptibility were used to make hole-to-hole correlations among Holes U1474A–U1474F. Confidence in these correlations is high because they can be cross-checked with continuous downcore measurements of color reflectance parameter *L\** and NGR. A complete affine table to the base of Hole U1474A was constructed to provide tabulated offsets for all cores relative to core depths (CSF-A). A continuous splice was constructed downhole to 234 m CCSF-D using cores from Holes U1474D–U1474F where possible. For some intervals, it was necessary to use sections from Hole U1474A, but sequences in

which whole-round samples had been removed were avoided. All sections of disturbed sediment were also avoided for construction of the splice. The continuity of the splice was confirmed with magnetic susceptibility, GRA density, NGR, and reflectance. Core intervals not included in the splice may be correlated to the CCSF-D depth scale using within-core variations of these data.

### Geochemistry

Interstitial water chemistry shows a moderate degree of early sediment diagenesis at Site U1474. Profiles of Mn and Fe indicate suboxic conditions from the seafloor to 5 m CSF-A. Sulfate reduction occurs throughout much of the sediment column. The overall low organic carbon content, on average <0.5 wt%, does not support complete removal of sulfate by 250 m CSF-A, and methane concentrations remain at background levels. Carbonate content of the pelagic sediment is moderate, averaging 40 wt%. The sandy layers contain significantly less carbonate than the nannofossil-rich clays, with values ranging between 20 and 30 wt%. Profiles of conservative elements (K and Mg) downhole suggest either fluid flow or clay mineral alteration reactions at depths below 250 m CSF-A.

## Site U1475

Site U1475 is located on the southwestern flank of Agulhas Plateau (41°25.61'S; 25°15.64'E) ~450 nmi south of Port Elizabeth, South Africa, in a water depth of 2669 mbsl. The Agulhas Plateau, which was formed during the early stages of the opening of the South Atlantic at ~90 Ma (Parsieglia et al., 2008), is a major bathymetric high that is variably coated with sediment (Uenzelmann-Neben, 2001). The 230,000 km<sup>2</sup> plateau, which ascends to ~2500 m above the adjacent seafloor, is bounded on the north by the 4700 m deep Agulhas Passage and is flanked by Agulhas Basin in the west and Transkei Basin in the northeast. The northern part of the plateau is characterized by rugged topography, whereas the central and southern parts of the plateau exhibit relatively smooth topography (Allen and Tucholke, 1981) and have greater sediment thickness (Uenzelmann-Neben, 2001).

A strong watermass transport flows across the Agulhas Plateau region (Macdonald, 1993), which involves the water column from the surface downward to the upper CDW. The hydrography of the upper ocean is dominated by the Agulhas Return Current, which comprises the component of the Agulhas Current that is not leaked to the South Atlantic Ocean but rather flows eastward from the retroflexion (Lutjeharms and Ansorge, 2001). Antarctic Intermediate Water, below the Agulhas Return Current, also follows the same flow path near South Africa as the Agulhas Current and shows a similar retroflexion (Lutjeharms, 1996). During its return to the southwest Indian Ocean, the Agulhas Return Current crosses the Agulhas Plateau, which deflects the deep-reaching current toward the Equator (Harris, 1970).

Site survey data collected during seismic cruises with the R/V *Petr Kottsov* in 1998 (Uenzelmann-Neben, 1998) and the R/V *Marion Dufresne* in 2002 show that Site U1475 is located on a sediment drift (Uenzelmann-Neben, 2001, 2002) that is deposited on the southwestern flank of Agulhas Plateau by NADW exiting the South Atlantic to the Indian Ocean. The wedge-shaped sediment drift thickens to the west, reaching a water depth of ~2510 m at its crest. The wavy character of the seafloor topography and the subsurface seismic reflection pattern are interpreted as sediment waves that document sedimentation by active deep-water flow. Site U1475 is located at 2669 mbsl, near the drift crest where minor buried depressions create a locally expanded sequence.

Millennial-scale multiproxy records covering the past 350 ky previously collected at this location highlight the synchrony of the regional ocean climatology and Antarctic climate variability. Evidence for regional ocean paleoclimatology includes latitudinal migrations of the regional Southern Ocean fronts and deposition of ice-rafted debris that document expansion of sub-Antarctic conditions to the plateau. These data serve as evidence for possible meridional shifts in the subantarctic frontal zone that borders the Agulhas leakage corridor and influences Agulhas leakage.

Paleoceanographic studies spanning the past 350 ky combined with seismic reflection data support the suitability of Site U1475 to achieve our primary objectives, which are to

- Recover a complete Pliocene–Pleistocene sedimentary succession from a high-accumulation sediment drift located within the southern Agulhas Return Current sector of the Indian-Atlantic ocean gateway;
- Assess the linking between Antarctic climate variations, circum-polar ocean front instability, and connections with Agulhas leakage into the South Atlantic;
- Assess the vigor and hydrography of NADW (or its precursors) exported to CDW and the southwest Indian Ocean at a location proximal to the entrance of NADW to the Southern Ocean and South Indian Ocean; and
- Evaluate the possibility of advective salinity feedbacks between Agulhas leakage and AMOC variability, notably the possible role of the leakage in modulating surface-to-deep ocean coupling in the North Atlantic during the transition between climatic states.

Site U1475 consists of six holes that penetrated from 1.5 to 277.0 m DSF. The APC system penetrated a total of 987.9 m and recovered 1015.92 m of core (103% core recovery). Six intervals advanced without coring to provide a continuous stratigraphic sequence penetrated a total of 86.0 m. The total time spent at Site U1475 was 5.7 days.

### Sedimentology

The sediment recovered at Site U1475 consists of two lithologic units. Unit I (0–4.75 m CSF-A) is composed of pale brown, light greenish or olive-gray, and white-gray nannofossil-rich foraminifer ooze. Unit II (4.75–277.22 m CSF-A) is composed of light greenish or pale gray to white-gray nannofossil ooze. Alternations between foraminifer-bearing or foraminifer-rich nannofossil ooze and nannofossil ooze with fine sand (foraminifers, quartz, and occasionally diatoms) were observed.

Sediment in both units includes dark gray mottling that we interpret as bioturbation (ichnofossil burrows [*Planolites*]). Thin darker bands commonly surround burrows, and macroscopic pyritized burrows are also common. Dropstones displaying coarse sand to granule grain sizes were observed in three different cores, which we interpret to represent ice-rafted debris. Sediment in both units also includes green layers that predominantly consist of pyrite and glauconite representing diagenetic alteration.

### Physical properties

Despite the homogeneous lithology, physical parameters show downhole trends as well as cyclic variations. A marked change in physical sediment properties occurs at ~110 m CSF-A. Above this depth, a change from quasi-regular short and lower amplitude variations to longer, higher amplitude and more irregular cyclic variation is observed. This change is most clearly displayed in NGR and color reflectance ( $a^*$ ) data. In addition,  $P$ -wave velocities decrease

and bulk densities increase at this depth, indicating a change in compaction trend. Prominent changes in  $P$ -wave velocity at Site U1475 can be clearly linked to seismic reflectors present in the site survey profiles.

### Micropaleontology

Analysis of calcareous nannofossils, planktonic foraminifers, and diatoms from core catchers and working-half core samples from Holes U1475B, U1475C, and U1475E reveals that the ~277 m section recovered at Site U1475 spans the latest Miocene (~6.91 Ma) to recent. Calcareous nannofossils show moderate to good preservation in all sequences with the consistent presence of well-preserved Eocene to middle Miocene (reworked) species. The nannofossil chronostratigraphy at Site U1475 spans from Biozones NN21 and CN15 to NN11 and the Subbiozone CN9d/CN9c boundary. Calcareous nannofossil assemblages are characterized by species typical of tropical to subtropical and temperate environments. Planktonic foraminifer biota at Site U1475 are moderately to well preserved and are mostly composed of subtropical convergence species mixed with polar species. The Pleistocene foraminifer assemblage is dominated by *G. inflata*, which typically constitutes 30%–50% of each sample. Diatoms show poor to moderate preservation and have a mixed assemblage of subtropical and Southern Ocean taxa. Diatom markers from both environmental settings are used to define datums; however, the Southern Ocean assemblage abundance is greatly reduced below 101.62 m CSF-A. Overall, the diatom chronostratigraphy spans from Biozone NTD17 to NTD12.

Sedimentation rates at Site U1475, based on biostratigraphy and paleomagnetic reversals during the Pleistocene and latest Pliocene are nearly linear at 2.8 cm/ky between 0 and 3.9 Ma. A notable increase in sedimentation rates to 9.6 cm/ky occurs between 3.9 and 5.3 Ma. Finally, older than 5.3 Ma, sedimentation rates decrease to 2.5 cm/ky.

### Paleomagnetism

All archive halves from Holes U1475B, U1475C, and U1475F and Cores 361-U1475E-1H through 15H were analyzed for NRM and demagnetized at 15 and 25 mT. In total, 98 discrete cube samples were taken from Holes U1475A, U1475B, and U1475D and subjected to NRM demagnetization. Cores from Site U1475 were not oriented because the relatively high latitude of the site means inclination data provide a reliable record of magnetic reversals. For most of the recovered interval, magnetic susceptibilities indicate that the sediment is diamagnetic in character and many results are below the detection limit of the whole-round and point magnetic susceptibility instruments. Nonetheless, taken together, the inclination records of all individual holes provide a consistent and detailed magnetostratigraphy for Site U1475. The boundaries of the Brunhes, Matuyama, Jaramillo, Olduvai, Gauss, Kaena, and Mammoth paleomagnetic chrons and subchrons constrain the chronology of the sediment and are in general agreement with the biostratigraphic data.

### Stratigraphic correlation

Select sequences from Holes U1475B, U1475C, U1475E, and U1475F were spliced together to create the most complete and representative section possible using RGB blue,  $b^*$  color reflectance, and NGR data. Sedimentological logs were consulted meticulously in the process of constructing the splice to avoid inclusion of any obviously disturbed sections or sections with completely unique features (relative to the other adjacent holes). The splice constitutes

a continuous sequence with a total length of ~292 m CCSF-D. However, confidence in the splice is low surrounding occasional problematic intervals, and further work on shore will be required to improve confidence.

### Geochemistry

Interstitial water chemistry shows a moderate degree of early sediment diagenesis at Site U1475. The nitrate profile indicates suboxic conditions in the upper 0.25 m CSF-A. Sulfate concentrations decrease throughout the sediment column, and sulfate is never completely consumed. Methane concentrations remain at background levels. Carbonate is the dominant sedimentary component, ranging from 75 to 85 wt%, with terrigenous material dominating the remaining fraction. Organic carbon contents range from 0.3 to 0.6 wt%, decreasing slightly downhole. Together, carbonate, organic carbon, and elemental biogenic indicator profiles suggest that export production increased into the Late Pleistocene.

### Site U1476

Site U1476 is located on Davie Ridge at the northern entrance of the Mozambique Channel (15°49.25'S; 41°46.12'E) at a water depth of 2165 mbsl. It is 3 nmi northwest of DSDP Site 242.

The Mozambique Channel is considered to be one of the most turbulent areas in the world ocean (Ternon et al., 2014), bordered by Madagascar to the east and Mozambique to the west. At its southern end, flow through the channel feeds into the greater Agulhas Current system. The Mozambique Channel is characterized by complex and variable surface and subsurface circulation. Several watermasses converge within the Mozambique Channel, and the circulation is dominated by activity related to the inflow of both Indonesian Throughflow and Tasman Strait Throughflow as well as the strength of the tropical and subtropical surface gyres in the Indian Ocean (Penven et al., 2006; Palastanga et al., 2006; Ridderinkhof et al., 2010; Schott et al., 2009; Backeberg and Reason, 2010). Satellite observations (e.g., Schouten et al., 2003; Quartly and Srokosz, 2004) and ocean models (Biaostoch and Krauss, 1999) have shown that mesoscale anticyclonic eddies generally form as the channel narrows close to Davie Ridge (at about 16°S), between the northern and central basin of the Mozambique Channel. These eddies typically maintain a high rotational velocity, often >1.5 m/s (Schouten et al., 2003; Ullgren et al., 2012) as they migrate southward through the channel at a mean rate of ~4–7 eddies a year. Accordingly, processes in the Mozambique Channel have downstream implications for the Agulhas Current including leakage into the South Atlantic Ocean (e.g., Bryden et al., 2005; Biaostoch et al., 2008, 2009b). Mozambique Channel eddies may also be linked with interannual modes of Indian and Pacific Ocean variability, implying a connection with the Indian Ocean Dipole and Pacific La Niña/El Niño phases (Schouten et al., 2002a; Palastanga et al., 2006).

Limited paleoceanographic evidence currently exists regarding the longer term linkage between variability in the northern source waters of the Agulhas Current and its eventual leakage into the South Atlantic Ocean. The primary objectives at Site U1476 are to

- Recover a complete Pliocene–Pleistocene sedimentary succession including the early Pliocene warm period, the mid-Pliocene expansion of Northern Hemisphere ice sheets, and the MPT;
- Reconstruct Mozambique Current warm-water transports during periods of orbitally modulated and suborbitally accelerated climate changes; and

- Assess the influence of remote upstream forcing on southeast African warm-water transport.

Specific questions that will be addressed include: Did the restriction of the Indonesian Seaway and the associated reduction of the Indonesian Throughflow in the Pliocene affect the Agulhas Current source region in the western tropical Indian Ocean and subsequently impact warm-water and saltwater transports along the southeast African margin? Did the Agulhas Current, by way of far-field controls on tropical–subtropical wind forcing, respond to the long-term development of tropical climates and the associated weakening of the monsoons in the course of the global cooling of the Pliocene?

Site U1476 consists of five holes that penetrated from 5.7 to 234.8 m DSF. The APC system penetrated a total of 841.1 m and recovered 873.85 m of core (104%). One interval was advanced 1.0 m without coring to adjust coring gaps to provide a continuous stratigraphic sequence. The total time spent at Site U1476 was 4.1 days.

### Sedimentology

Two lithologic units were described at Site U1476. Unit I (0–34.57 m CSF-A) is composed of light brown to greenish gray foraminifer ooze with nannofossils alternating with foraminifer-rich nannofossil ooze. Unit II (34.57–235.41 m CSF-A) is composed of greenish gray foraminifer-rich nannofossil ooze and nannofossil ooze with foraminifers, silt, and clay.

Sediment in both units includes dark gray mottling that we interpret as bioturbation. Thin darker bands commonly surround burrows, and macroscopic pyritized burrows are common. Sediment also includes green layers that predominantly consist of pyrite and glauconite, which are diagenetic alterations. Only minor coring disturbance is observed in the cores.

### Physical properties

Despite the relatively homogeneous lithology, different physical parameters show significant trends downhole as well as cyclic variations along the sediment column. High-amplitude cyclic changes occur in the uppermost 16 m CSF-A of all holes. These cyclic changes continue downward to the bottom of the holes with lower amplitude and higher frequency. Variations in color reflectance indicate sediment compositional changes and RGB data broadly correspond with color reflectance parameter  $L^*$ . Bulk densities increase downhole due to compaction, but there are large variations in the uppermost 16 m CSF-A that are also seen in the other physical properties.

### Micropaleontology

Calcareous nannofossil and planktonic foraminifer biostratigraphy indicates that Hole U1476A spans the Late Pleistocene to late Miocene. Diatoms are not included in the biostratigraphy because the record is barren of diatoms throughout except for tropical diatoms present in minor amounts in the mudline sample. Calcareous microfossils show very good preservation in Pliocene- to Pleistocene-age sediment; however, the late Miocene is characterized by an increase of fragmented planktonic foraminifers. Assemblages in both microfossil groups include tropical to subtropical forms with the periodic appearance of species typical of temperate environments. Sedimentation rates, based on calcareous nannofossil and planktonic foraminifer datums, increase from 2.3 to 3.5 cm/ky downhole. No hiatuses were observed; however, diachronous events were observed within the planktonic foraminifer biochronology.

These events might suggest that calibration of microfossil datums from the tropical western Indian Ocean need refinement.

### Paleomagnetism

Paleomagnetic and rock magnetic analyses were carried out on sediment cores from Holes U1476A, U1476B, U1476D, and U1476E. All together, the rock magnetic data imply that the concentration of high-coercivity minerals (e.g., hematite and titanomagnetite) is relatively stable, whereas magnetite concentrations decrease below ~150 m CSF-A. Demagnetization of NRM carried out on discrete samples and archive halves shows that the directional record carries a strong coring overprint. The uppermost two sections of each core reveal steep downward inclinations after demagnetization at maximum levels of 25 mT suggesting that the applied field was too weak to remove the overprint. More detailed demagnetization experiments on discrete samples show changes in inclination after demagnetization of 40 mT, suggesting that sediment has an early diagenetic overprint that might be removed by demagnetization at higher fields. Because the Icefield MI-5 orientation tool malfunctioned, the declination data could not be corrected for core orientation and can therefore not be used for assigning polarity zones. A more detailed investigation of demagnetization behavior will be needed to establish a more confident paleomagnetic stratigraphy for Site U1476.

### Stratigraphic correlation

Ideal coring conditions and good signal in the magnetic susceptibility measurements allowed for near-real time correlation at Site U1476. Coring offsets were applied in Holes U1476A and U1476D so that no gaps were present downhole to the full depth of the holes (229.0 m CSF-A). Hole U1476E provided similar offsets to Hole U1476A so that a splice could be constructed primarily between Holes U1476D and U1476E. The splice was constructed using magnetic susceptibility data and confirmed using NGR and RGB (blue) data.

### Geochemistry

Interstitial water chemistry shows mild early sediment diagenesis at Site U1476. Nitrate and sulfate, two species that disappear with progressively more intense microbial respiration, persist deeper into the sediment column and at higher concentrations than was documented at Sites U1474 or U1475. Methane concentrations remain at or near background levels. Decreasing concentrations of major elements, such as potassium and sodium, reflect uptake by clay minerals. Carbonate is variable (45–75 wt%), with terrigenous sediment making up the remainder of the sediment. The sediment is organic carbon poor, with average concentrations of 0.24 wt% total organic carbon (TOC).

## Site U1477

Site U1477 is located in the western Mozambique Channel on the upper continental slope (19°21.29'S; 36°54.90'E), ~65 nmi east of the Zambezi River delta region, at a water depth of 429.2 mbsl.

Site U1477 receives fluvial material exported from the Zambezi Catchment, which is in the southernmost reach of the African monsoonal precipitation belt and drains multiple subbasins. Collectively, these subbasins span ~1.385 million km<sup>2</sup> and the river itself extends more than 2500 km. Annual precipitation across the Zambezi Catchment varies spatially with ~150 cm in the northern catchment region, ~85 cm in the southern region, and 60–70 cm in the central region (Ronco et al., 2006). Peak precipitation in the Zam-

bezi Catchment occurs during the austral summer (DJF), when the ITCZ is located at its most southerly position.

The mean outflow of the Zambezi River is 3000 m<sup>3</sup>/s (Gammel-srød, 1992), which transports an annual sediment load of ~51 Mm<sup>3</sup>, making it the largest single source of suspended sediment supply to the Mozambique margin (Walford et al., 2005). This fluvial sediment mixes with current-transported and biogenic material and form a major component of the extensive current-controlled sedimentary deposits that characterize the Mozambique margin. This sediment has the potential to provide comprehensive proxy records of regional oceanographic changes as well as changes in hydrological conditions of the African precipitation belt in southeastern Africa (e.g., Just et al., 2014; Schefuß et al., 2011; Schulz et al., 2011; Wang et al., 2013; Weldeab et al., 2013, 2014; van der Lubbe et al., 2014, 2016).

Site U1477 is on a contourite drift deposited under the influence of the eddy-dominated water flow through the Mozambique Channel. The drift displays packages of parallel and laterally continuous subseafloor reflectors. Site U1477 is immediately southwest of the 6.51 m long sediment Core GeoB9307-3 (18°33.99'S, 37°22.89'E; 542 mbsl) (Schefuß et al., 2011), which is in an area with elevated sedimentation during the deglacial period to the Holocene. Existing data from Core GeoB9307-3 suggest the great potential of Site U1477 for providing a centennial-scale paleoceanographic record.

The Site U1477 primary objectives are to

- Recover a complete high-resolution sedimentary succession that spans the last 2 my, including the MPT, from the Mozambique margin close to the Zambezi River delta;
- Generate a high-resolution Pleistocene profile of southern African continental climate changes on orbital and suborbital time-scales;
- Establish linking between southern African terrestrial climates and southwest Indian Ocean heat budgets, notably warm-water transport along the southeast African margin and associated ocean–atmosphere heat and moisture transfer;
- Examine the relationship between such climate variability and early human evolution; and
- Reconstruct upstream control on Agulhas leakage through headwater variability during periods of orbitally modulated and suborbitally accelerated climate changes.

Specific questions that will be addressed include: Did the long-term climatic developments of the Pleistocene, through their impact on atmospheric circulation, alter the rainfall patterns over southeast Africa, notably in conjunction with far-field responses to East African uplift, monsoon dynamics, and migration of the ITCZ (Johnson et al., 2002; Schefuß et al., 2011; Trauth et al., 2009)? Did variable Agulhas Current warm-water transport contribute to and modulate the impacts of shifting air boundaries and rainfall patterns over southeast Africa, and possibly offset these patterns from those over southwest Africa and the Namib (Dupont et al., 2005, 2011; Maslin et al., 2012)?

The stratigraphic extent of Site U1477 was considerably shorter than anticipated, with a maximum age of ~200 ka. As a result, the paleoclimate site objectives will require adjustment to focus on high-temporal timescale variability (centennial–decadal) over the last glacial cycle. The remarkably high sedimentation rates at Site U1477 promise an unprecedented opportunity to investigate hydroclimate variability in southeastern Africa and its potential links to changes in the greater Agulhas Current system.



Site U1477 consists of three holes that penetrated from 119.4 to 181.2 m DSF. The APC system penetrated a total of 296.2 m and recovered 308.07 m of core (104%). The HLAPC recovered 174.00 m of sediment over a 169.2 m interval (103%). The extended core barrel (XCB) was deployed for one core resulting in 7.96 m of sediment (97%). One interval was advanced 1.0 m without coring to adjust coring gaps to provide a continuous stratigraphic sequence. The total time spent at Site U1477 was 1.9 days.

### Sedimentology

Sediment at Site U1477 consists of two lithologic units. Unit I (0–0.5 m CSF-A) is composed of very dark gray to dark greenish gray sandy clay with foraminifers and nannofossils. Unit II (0.5–254.07 m CSF-A) is composed of very dark gray to dark greenish gray silty clay with intermittent to frequent occurrences of sand layers. These sand layers contain quartz and clay, and thicknesses range from centimeter to meter scale.

Bioturbation is not apparent in either unit. Macrofossils, including bivalve and echinoderm fragments, are present throughout the cores. Many of the cores show disturbance related to gas expansion.

### Physical properties

Despite the relatively homogeneous lithology, physical parameters at Site U1477 show a complex pattern of high-amplitude changes that are likely caused by climate-related variations in terrigenous sediment supply or current sorting effects. However, some excursions to lower values in NGR and GRA bulk density data may be due to the voids caused by gas expansion. Also, the collection of reliable *P*-wave data below 16.9 m CSF-A in all of the holes was inhibited by strong signal attenuation resulting from the frequent occurrence of gas expansion voids. Porosities at Site U1477 decrease downhole, and average porosities are significantly lower when compared to the previous sites (U1474–U1476).

### Micropaleontology

Site U1477 spans the Holocene to the Late Pleistocene. Two biostratigraphic datums were observed: the abundance crossover from *Gephyrocapsa caribbeanica* to *Emiliana huxleyi* at ~90 ky and the top occurrence of *Globigerinoides ruber* (pink) at ~120 ky. Sedimentation rates, based on biostratigraphic datums as well as radiocarbon ages tied in from a nearby piston core, suggest deposition rates of ~1.5 m/ky from 0 to ~30 m CSF-A in Hole U1477A that decrease to ~83 cm/ky from ~30 m CSF-A to the base of the hole. Calcareous microfossils are generally well preserved, although abundance is typically low. Planktonic foraminifer tests compose <1% of sediment particles in most samples, whereas <50 nannofossils per field of view were observed throughout most of the section. The planktonic assemblage, which includes the regular occurrence of pteropods, is joined by benthic foraminifers, ostracods, sponge and gorgonian spicules, mollusks, echinoderm plates, and fish otoliths. Siliceous microfossils make up a minor component of the mudline and core catcher samples. Marine and freshwater diatoms, phytoliths, and sponge spicules are present, providing indications of both terrestrial and marine sources.

### Paleomagnetism

Paleomagnetic measurements at Site U1477 show a clear magnetic signal. For all holes, inclinations center around ~50° during the Brunhes Chron, which is expected for the site location. Rock-magnetic data acquired on discrete samples reveal phases of high ferromagnetic mineral content that largely match magnetic susceptibility data collected on archive section halves and whole

cores. Variations in magnetic minerals present reflect either a change in the composition of the terrigenous fraction or preferential mineral dissolution.

### Stratigraphic correlation

Real-time stratigraphic correlation was possible at Site U1477 using magnetic susceptibility data. Holes U1477A–U1477C were used for the splice from 0 to ~85 m CCSF-A. Below ~85 m CCSF-A, the splice consists primarily of sediment from Hole U1477B, with a couple of exceptions where intervals of Hole U1477A were used. A continuous stratigraphic splice was not possible at this site because of substantial gas expansion that led to core fracturing and variable core stretching between holes.

### Geochemistry

Interstitial water chemistry and headspace gas concentrations show relatively intense early sediment diagenesis at Site U1477. The sulfate–methane transition appears at ~16 m CSF-A, below which sulfate is completely consumed and methane concentrations increase rapidly to a peak of ~75,500 ppmv at ~35 m CSF-A. Other redox-sensitive elements, including iron, manganese, and barium, show enrichments caused by remobilization. Terrigenous sediment dominates the core. Carbonate contents average 5 wt%, with a few intermittent layers of shell material with carbonate contents as high as ~20 wt%. The average TOC content is 0.61 wt%.

## Site U1478

Site U1478 is located in the Delagoa Bight on the Inharrime Terrace (25°49.26'S; 34°46.16'E) ~75 nmi east of the Limpopo River at a water depth of 488 mbsl.

The Delagoa Bight is a distinct indentation of the continental margin (Lamont et al., 2010) into which the Limpopo River, the second largest eastward-draining river in Africa, deposits sediment. Its hydrography is influenced by the southerly flowing waters from the Mozambique Channel and the East Madagascar Current (Lutjeharms, 2006a, 2006b), the confluence of which forms the Agulhas Current. The Limpopo Catchment is a little over 410,000 km<sup>2</sup>, considerably smaller than that of the neighboring Zambezi. The Limpopo River has a mean annual discharge of ~170 m<sup>3</sup>/s and delivers annual sediment loads of 33 Mt/y (Milliman and Meade, 1983) to the Delagoa Bight.

The Site U1478 primary objectives are to

- Recover a complete high-resolution sedimentary succession that spans the last 2 my;
- Generate a high-resolution Pleistocene profile of southern African continental climate changes on orbital and suborbital time-scales;
- Establish linking between southern African terrestrial climates and southwest Indian Ocean heat budgets, notably warm-water transports along the southeast African margin and associated ocean–atmosphere heat and moisture transfer;
- Examine the relationship between such climate variability and early human evolution; and
- Reconstruct upstream control on Agulhas leakage through headwater variability during periods of orbitally modulated and suborbitally accelerated climate changes.

Specific questions that will be addressed include: Did the long-term climatic developments of the Pleistocene, through their impact on atmospheric circulation, alter the rainfall patterns over southeast Africa? Did variable Agulhas Current warm-water trans-

ports contribute to and modulate the impacts of shifting air boundaries and rainfall patterns over southeast Africa and possibly offset these patterns from those over southwest Africa and the Namib (Dupont et al., 2005; Maslin et al., 2012)?

Site U1478 consists of four holes that penetrated from 216.0 to 248.4 m DSF. The APC system penetrated a total of 698.9 m and recovered 708.66 m of core (101%). The HLAPC recovered a total of 213.4 m of sediment over a 206.8 m cored interval (103%). Five intervals were advanced 54.3 m without coring to adjust coring gaps to provide a continuous stratigraphic sequence. The total time spent at Site U1478 was 2.7 days.

### Sedimentology

Sediment at Site U1478 consists of one lithologic unit. Unit I (0–248.59 m CSF-A) is composed of dark olive-gray and dark greenish gray sand with foraminifers and nannofossils that alternate with clayey or sandy silt with foraminifers and nannofossils. The sand is predominantly composed of quartz.

Bioturbation is rare; however, the coarser grained sediment at Site U1478 may obscure sedimentary structures, such as bioturbation and diagenetic alterations. Macrofossils, including bivalves, gastropods, and echinoderms, are present throughout the cores.

### Physical properties

The physical properties measured at Site U1478 show a complex pattern of amplitude changes and trends. All high-resolution records derived by physical properties core logging (magnetic susceptibility, NGR, GRA bulk density, RGB color, and spectral reflectance) show cyclic changes that are likely related to the variable lithologic alternations between silt-rich and sand-rich intervals. These cyclic changes are pervasive throughout the sequence and probably reflect complex interactions between ocean circulation, sea-level fluctuations, and fluvial discharges recorded at Site U1478. Two zones of very low magnetic susceptibility values at ~89–92 and ~164–168 m CSF-A may be related to sediment diagenesis as indicated by elevated iron and manganese concentrations in the interstitial water. Porosities decrease downhole, and average porosities are similar to those at Site U1477 but are significantly lower compared to the deeper water Sites U1474–U1476.

### Micropaleontology

Biostratigraphy of calcareous nannofossils and planktonic foraminifers indicates that Hole U1478A spans the Upper Pleistocene to the middle Pliocene with a basal age of ~4 Ma. Calcareous microfossil assemblages include warm subtropical to tropical species in combination with coastal- to slope-water taxa. Planktonic foraminifers and calcareous nannofossils are abundant throughout Site U1478. Foraminifers dominate sandy beds, whereas calcareous nannofossils are typically more abundant in silty and clay-rich intervals. Glassy and translucent foraminifers are found throughout most of the recovered sequence, although fragmentation increases in the oldest parts of the sequence. Calcareous nannofossils are mostly well preserved, but the *Discoaster* group commonly exhibits fragmentation of the delicate arms. Diatoms are present only in surface sediment, and sponge spicules and phytoliths are scarce in the lower parts of the sequence. Low levels of reworking are evident in planktonic foraminifer records. The biochronology for both calcareous microfossil groups reveals sedimentation rates of ~9 cm/ky between the Late Pleistocene and ~2.1 Ma and lower rates of 2.9–5.3 cm/ky older than 2.1 Ma. Planktonic foraminifers and calcareous nannofossils give diverging age-depth relationships between 1.9 and

3 Ma, which is possibly linked to sedimentological processes. The two fossil groups are in agreement in the lowermost ~25 m of Site U1478 and predict a basal age of 4–4.1 Ma.

### Paleomagnetism

Rock magnetic and paleomagnetic analyses were carried out on discrete samples from Hole U1478A and archive-half sections from Holes U1478A–U1478D. SIRM and hard isothermal remanent magnetization (HIRM) measured on discrete samples largely follow downcore patterns in magnetic susceptibility. The S-ratio is mostly stable; however, distinct minima at ~90, 165, and 245 m CSF-A indicate a strong depletion of low-coercivity minerals. These intervals coincide with minima in the magnetic susceptibility and SIRM records. The minimum in magnetic susceptibility at ~90 m CSF-A lies below the sulfate–methane transition, and the minimum at ~165 m CSF-A is located just below an interval of elevated dissolved Fe and Mn concentrations, suggesting that in these zones early diagenetic processes affected the magnetic mineral record.

Inclination data appear to be of good quality, and the Brunhes/Matuyama Chron boundary and the Jaramillo Subchron were identified. According to biostratigraphy, the sedimentary sequence dates to ~4 Ma; however, the Matuyama–Gauss Chron transition was not identified in the paleomagnetic data.

### Stratigraphic correlation

Four holes were drilled at Site U1478 using the APC and HLAPC. Generally good core quality and clear magnetic susceptibility signals resulted in robust and unambiguous stratigraphic ties between holes. We have high confidence that these holes constitute a nearly complete section spanning the full length of the longest hole (244 m recovered in Hole U1478A), with the exception of one probable gap at ~195 m CSF-A. The objective of obtaining a complete section was aided by the fact that the magnetic susceptibility from whole-round physical property loggers could be used for real-time correlation in Holes U1478B–U1478D; adjustments to the drilling depth were made in these holes for the purpose of avoiding potential core gap alignment. A continuous splice was constructed for the uppermost ~200 m CCSF-D, and a floating splice of another ~50 m of section is appended below the coring gap. In general, the clarity of the stratigraphic ties and the multiple cross-checks available from several different data sets gives us high confidence in the integrity of these two separate spliced sequences.

### Geochemistry

Interstitial water chemistry and headspace gas concentrations show relatively intense early sediment diagenesis at Site U1478. The sulfate–methane transition zone occurs at ~70 m CSF-A, below which sulfate is completely consumed and methane concentrations increase rapidly. Several methane peaks occur below the sulfate–methane transition, with the largest of ~65,000 ppmv at ~214 m CSF-A. Other redox-sensitive elements, including iron and manganese, also show multiple peaks at depth. These pulses of iron and manganese and associated lows in magnetic susceptibility are interpreted as paleoredox horizons related to repeated fluctuations in sedimentation. Detrital material is the most important sedimentary component. Carbonate contents average 28 wt%, and TOC contents average 0.5 wt%; neither show any trend with depth.

## Site U1479

Site U1479 is located on a 30 km wide morphological high, rising ~200 m above the regional seafloor, on the mid-to-lower west-

ern slope of the Agulhas Bank in Cape Basin (35°03.53'S; 17°24.06'E), ~85 nmi southwest of Cape Town, South Africa, at a water depth of 2615 mbsl.

This region has been the focus of numerous oceanographic studies and a growing number of paleoceanographic studies (e.g., Beal et al., 2011, and references therein) in order to describe the present hydrography within the so-called Indian-Atlantic ocean gateway (or “Agulhas ring corridor”; Gordon, 2003) and also to gain a better understanding of past oceanographic variations in the area and how they may be related with global climate changes. Several studies have highlighted the Agulhas Current's sensitivity to climate changes and reorganizations of atmospheric and the ocean circulation at large.

As the Agulhas Current separates from the Agulhas Bank at the southern tip of Africa, it retroflects, shedding rings, eddies, and filaments to the South Atlantic. This leads to leakage of between 2 and 20 Sv of Indian Ocean water into the Atlantic and affects the water column to depths of <2000 mbsl (Gordon et al., 1987; de Ruijter et al., 1999a; Richardson, 2007).

The Agulhas ring corridor is an area in which retrieval of high-quality sediment cores is difficult. The southeast African margin has a very narrow shelf and a steep continental slope, leading to frequent sediment instability and slumping. Furthermore, the vigorous Agulhas Current and its variability can cause sediment redistribution because meanders and eddies frequently reach the seafloor. Yet, a number of published studies and emerging work demonstrate that paleoceanographic records of excellent quality are in fact achievable for reconstructing both surface and deep-water variability in the region (e.g., Rau et al., 2002, 2006; Peeters et al., 2004; Martínez-Méndez et al., 2010; Dickson et al., 2010; Caley et al., 2011, 2012, 2014; Marino et al., 2013; Dyez et al., 2014; Petrick et al., 2015).

The Site U1479 primary objectives are to

- Recover a complete Pliocene–Pleistocene sedimentary succession, including the early Pliocene warm period, mid-Pliocene expansion of Northern Hemisphere ice sheets, and the MPT, from a high-accumulation site located within the Agulhas ring corridor;
- Reconstruct Agulhas Current warm-water transports during orbitally modulated and suborbitally accelerated climatic changes;
- Assess the linking between Antarctic climate variations, circum-polar ocean front instability, and connections with Agulhas leakage into the South Atlantic;
- Assess the vigor and hydrography of NADW, or its precursors, exported to CDW and the southwest Indian Ocean; and
- Evaluate the possibility of advective salinity feedbacks between Agulhas leakage and AMOC variability, notably the possible role of the leakage in modulating surface-to-deep ocean coupling in the North Atlantic during the transition between climatic states.

Site U1479 consisted of nine holes, ranging in depth from 1.0 to 300.7 m DSF. Overall, 105 cores were recorded for the site. A total of 963.21 m of core over a 975.3 m interval was recovered using the APC system (99% core recovery). Seven intervals were advanced without coring over 175.7 m. The total time spent at Site U1479 was 6.0 days.

### Sedimentology

Sediment at Site U1479 consists of one lithologic unit. Unit I (0–301.03 m CSF-A) is composed of light greenish gray, greenish gray,

and light olive-gray (5Y 6/2) nannofossil ooze with or without foraminifers.

Moderate to strong bioturbation is the only secondary sedimentary structure observed and is widespread throughout the sequence. Discrete ichnofossil burrows were commonly observed, often surrounded by thin darker bands. The occurrence of intervals rich in sand-sized quartz and foraminifers further suggests the deposition of contourites and/or turbidites.

### Physical properties

At Site U1479, the lithology is homogeneous and has been classified as one lithologic unit. All high-resolution physical property records derived by core logging show similar cyclic changes that are likely related to the lithologic alternations within this nannofossil ooze between intervals of more or less terrigenous content and thus may reflect changes in ocean circulation and/or terrigenous supply. Also, the changes in general physical property trends broadly correlate between the parameters. A slump in the lowermost part of Site U1479 is characterized by physical properties that are distinctly different from the rest of the cored section.

### Micropaleontology

Biostratigraphy of calcareous nannofossils, planktonic foraminifers, and diatoms indicates that Hole U1479B spans the late Pleistocene to the late Miocene with a bottom age of ~7 Ma. Calcareous microfossils include primarily subtropical convergence and coastal-to slope-water taxa with minor abundances of warm subtropical and subpolar taxa. Diatoms are mostly composed of subtropical taxa with a minor presence of Southern Ocean taxa in the Pleistocene and subtropical taxa in the early Pliocene and latest Miocene. Planktonic foraminifers and calcareous nannofossils are abundant throughout Site U1479, whereas diatoms make episodic appearances, particularly in the upper and lower parts of the record. Preservation is good to moderate for calcareous taxa and moderate to poor for diatoms. The biochronology for both calcareous microfossil groups and diatoms is consistent with an average sedimentation rate of ~4.9 cm/ky.

### Paleomagnetism

Paleomagnetic analyses were carried out on archive halves from Site U1479 and on discrete samples from Hole U1479B. The inclination and declination data from the archive halves are relatively noisy, which might be partially explained by the alteration of magnetic minerals as suggested by downhole records of various rock magnetic parameters including the Sr ratio, HIRM, and SIRM. Additionally, magnetic susceptibility is very low for most of the downhole record. Inclinations and declinations show an interval of normal polarity in the uppermost ~55 m CSF-A (Brunhes Chron), although the lower boundary is deeper than would be anticipated from the biostratigraphy. A distinct interval of reversed polarity between ~55 and ~125 m CSF-A is probably the Matuyama Chron, which spans from ~2.6 to 3.6 Ma. Unlike the Brunhes/Matuyama Chron boundary, the inferred Matuyama/Gauss Chron boundary is in agreement with ages derived from the biostratigraphy. Additional paleomagnetic analyses on rock magnetic properties and directional data are necessary to constrain and eventually refine the magnetostratigraphy for Site U1479.

### Stratigraphic correlation

Stratigraphic correlation of Holes U1479B–U1479I was complicated by very low magnetic susceptibility and adverse weather con-

ditions resulting in several partial core recoveries in all the holes, as well as soupy top sections that were generally unusable for stratigraphy. Notwithstanding, the NGR and color (e.g., RGB green) records display clear variability in all undisturbed core sections, making the alignment of cores relatively straightforward once all scanning was complete. Furthermore, comparatively constant offsets between cores in Holes U1479B and U1479C led to the development of a robust and nearly complete splice from just below the mudline to the bottom of Hole U1479B at ~300 m CSF-A. The generally clear stratigraphic relationship between Holes U1479B and U1479C only needed refinement and supplementation in scattered discrete intervals.

### Geochemistry

Interstitial water chemistry and headspace gas concentrations indicate moderate early sediment diagenesis. Major element concentrations show some evidence of uptake into clay minerals and precipitation of authigenic carbonates. There is no clear sulfate–methane transition zone in Hole U1479B—sulfate concentrations are zero at ~185 m CSF-A, but methane concentrations are never above ~50 ppmv. Other redox-sensitive elements, such as iron and barium, show more dramatic enrichments, with iron reaching ~15  $\mu\text{M}$  at ~60 m CSF-A and barium reaching ~600  $\mu\text{M}$  at ~150 m CSF-A. Calcium carbonate ranges from ~51 to 91 wt%, with an average value of 67 wt% and no distinct trend downhole. Organic carbon ranges between 0.15 and 1.93 wt% with an average value of 0.62 wt%.

## Expedition synthesis and preliminary scientific assessment

The greater Agulhas Current system is a key location to study past ocean circulation and climate, as it represents a significant component of the global thermohaline circulation, carrying surface water into the Atlantic that compensates for the export of deep water from the Atlantic Basin to the world ocean. This Agulhas leakage transfer of salt to the South Atlantic variably impacts the buoyancy structure there and likely contributes to mode changes and variability of the AMOC and thus climate variability in the North Atlantic region and beyond. Additionally, variations in Agulhas warm-water transports along the southeast African continental margin foster exchanges of heat and moisture with the atmosphere that influence southern Africa regional climates.

Operations during Expedition 361 drilled six sites in the southwest Indian Ocean from February to March 2016 (Figure F3). In total, we recovered 5175 m of core, with an average recovery of 102%, during 29.7 days of on-site operations, from a region poorly represented in the database of drill sites for scientific purposes. No holes were logged. This is considerably less than the initially planned campaign targeting 5811 m of section, including downhole logging at four sites (Hall et al., 2015). The difference amounts to ~11 days of lost operational time. A medical evacuation accounted for 1.8 days and weather a further 1.5 days of lost operations. The remainder of the lost operational time was due to delays in attaining the necessary permissions to operate in Mozambique exclusive economic zone (EEZ) waters, which necessitated a revision of the drill plan and 2840 nmi of additional transit to Expedition 361.

Expedition 361 South African Climates (Agulhas LGM Density Profile) had the following five fundamental objectives:

- To establish the sensitivity of the Agulhas Current to changing climates of the Pliocene–Pleistocene in association with transient to long-term changes of high-latitude climates, tropical heat budgets, and the monsoon system;
- To determine the dynamics of the Indian–Atlantic ocean gateway circulation during such climate changes in association with changing wind fields and migrating ocean fronts;
- To examine the connection between Agulhas leakage and ensuing buoyancy transfer and shifts of the AMOC during major ocean and climate reorganizations during at least the last 5 my;
- To address the impact of Agulhas variability on southern Africa terrestrial climates and, notably, rainfall patterns and river runoff; and
- To constrain the temperature, salinity, and density structure of the LGM deep ocean from the bottom of the ocean to the base of the main thermocline.

The expedition made major strides toward fulfilling each of these objectives. The recovered sequences allowed complete spliced sections to be generated that span the interval of 0 to between ~0.13 and 7 Ma (Figure F11). The sedimentological characteristics (Figures F12, F13, F14) range from highly terrigenous near the Zambezi (Site U1477) and Limpopo (Site U1478) Rivers and in the Natal Valley (Site U1474) to very carbonate rich in the northern Mozambique Channel (Site U1476), the Agulhas Plateau (Site U1475), and Cape Basin (Site U1479). The carbonate fossil preservation is good in the Pleistocene and mostly good to moderate, tending to be a little worse near the bottoms of each sequence (Figures F15, F16). Biostratigraphies from nannofossils and foraminifers are quite good (Figures F17, F18). At Sites U1475 and U1479, diatoms are abundant enough to provide further biostratigraphic constraints, and at these sites there is potential for future paleoenvironmental work with diatoms (Figure F19). All the fossils showed a mixture of tropical and subtropical convergence and temperate or subpolar species in the southernmost sites (Figures F19, F20, F21), and changes through time in these assemblages will provide important constraints on the dynamics of the Agulhas Current system. For Sites U1475, U1476, U1478, and U1479, sea conditions and time were sufficient that geochemical compositions were measured on a suite of solid bulk samples from the carbonate sample residue. As Ba/Al ratios may be a good X-ray fluorescence proxy for productivity, Figure F22 displays the Ba/Al ratios of bulk samples against TOC. Site U1477, with an extremely high terrigenous load, shows no correlation and has Ba/Al ratios of typical silicate detritus. Site U1478 also has mostly terrigenous Ba/Al ratios, but a few samples stand above. Site U1476 is in an area of low productivity, so the range of Ba/Al ratios is low and not correlated with TOC. However, it is elevated above terrigenous, indicating at least 50% of the Ba is probably from biogenic sources. Site U1475, located on the Agulhas Plateau where we would expect variations with the position of the STF, has high Ba/Al ratios and has a generally strong positive trend with TOC with the exception of a couple of samples.

Early sediment diagenesis, driven by microbial respiration of organic matter in sediment, defines many dissolved elemental profiles. One of the characteristic profiles that indicates the extent and intensity of these reactions is dissolved sulfate (Figure F23). Where microbial respiration is intense as a result organic matter availability sulfate is rapidly consumed. Where microbial respiration is more moderate sulfate decreases at a slower rate and sometimes persists to the base of the measured interval. We see a range of diagenetic



intensities across the Expedition 361 sites, with the most intense microbial activity and diagenesis at Site U1477 (Zambezi) and the least activity at Site U1476 (Mozambique Channel). It is likely that the observed differences between sites are driven by location and sedimentation rate rather than organic carbon content because TOC does not vary between sites (Figure F14).

Operations at Site U1474 (Natal Valley; Figure F3) were scheduled to produce three APC/XCB holes to 300 m below seafloor (mbsf), with logging in one of the deep holes and a single hole to 150 mbsf for interstitial water samples. This drilling objective was largely accomplished with the exception of logging and a reduction in the target section depth to 254 m CSF-A because of loss of operational time as noted above. Recovery was excellent, and triple coring allowed compilation of a complete spliced record extending to the latest Miocene (~6.2 Ma). The site boasts an excellent paleomagnetic timescale (Figure F23) that is in good agreement with the biostratigraphy, and these together suggest uniform sedimentation rates of ~4.1 cm/ky over most of the sequence and an apparent increase near the bottom (Figure F11). This record represents the only site situated beneath the main flow of the fully constituted Agulhas Current and will therefore provide the opportunity for high-resolution climate reconstructions of Agulhas Current warm-water transports and upstream variability that may allow the identification of connections between Agulhas leakage and its headwater variability. The site also holds significant potential to investigate the connections between southern African terrestrial climates and southeast Indian Ocean heat budgets and thermocline and deep-water variability with likely links to the development of the Indonesian Throughflow as well as aridification of east Africa. Foraminifers show excellent preservation, thus also making this an ideal site for a long record of surface-ocean pH from boron isotopes. A high-resolution program of interstitial water samples collected from a 150 m CSF-A section, will provide an additional data point to the presently available pore water LGM temperature and salinity inventory.

Operations at Site U1475 (Agulhas Plateau; Figure F3) were scheduled for three APC/XCB holes to 300 mbsf with logging and a single hole to 150 mbsf for interstitial water samples. This drilling objective was largely accomplished with the exception of logging. Recovery was excellent, and multiple coring, including some spot coring caused by weather-related disturbances, allowed compilation of a complete spliced record extending to the late Miocene (~7 Ma). The paleomagnetic timescale is robust to the base of the Mammoth Chron (C2An.2r at 99 m CCSF-A) (Figure F23) and is in good agreement with the biostratigraphy, but the overprint was too much to take the paleomagnetic timescale to the bottom. Age estimates suggest sedimentation rates of ~2.9 cm/ky in the uppermost 115 m CCSF-A, 10.3 cm/ky between 115 and 255 m CCSF-A, and 2.8 cm/ky between 255 m CCSF-A and the bottom of the section (Figure F11). This record will provide the opportunity for high-resolution climate reconstructions of the Agulhas Return Current and connections with the STF, productivity, and deep-water circulation. A high-resolution program of interstitial water samples, collected from a 150 m CSF-A section, will provide an additional data point to the presently available interstitial water LGM temperature and salinity inventory.

Operations at Site U1476 (Mozambique Channel; Figure F3) were scheduled for three APC/XCB holes to 300 mbsf with logging and a single hole to 150 mbsf for interstitial water samples. This drilling objective was largely accomplished with the exception of logging and a reduction in the target depth to 220 m CSF-A because of loss of operational time as noted above. Recovery was excellent, and triple coring allowed compilation of a complete spliced record extending to the late Miocene (~6.9 Ma). The site boasts excellent biostratigraphy and notably cyclic physical properties. The paleo-

magnetic reversal signal was complicated by apparent cyclically varying magnetic mineralogy and will require shore-based work to try to extract a paleomagnetic timescale at this site (Figure F23). The sedimentation rate is ~2.2 cm/ky from the mudline to ~50 m CCSF-A and 3.8 cm/ky from ~50 m CCSF-A to the bottom (Figure F11). This site is located on Davie Ridge at the northern end of the Mozambique Channel in a region with low productivity and with equilibrium ocean-atmosphere CO<sub>2</sub>. The site will therefore provide the opportunity for high-resolution reconstructions of tropical faunal assemblages that will allow identification of connections between Agulhas leakage and its headwater variability. The site also holds significant potential to investigate the connections between southern African terrestrial climates and southeast Indian Ocean heat budgets and thermocline and deep-water variability with likely links to the development of the Indonesian Throughflow as well as aridification of east Africa. Foraminifers show excellent preservation, thus also making this an ideal site for a long record of surface-ocean pH from boron isotopes. A high-resolution program of interstitial water samples collected from a 150 m CSF-A section will provide an additional data point to the presently available interstitial water LGM temperature and salinity inventory.

Operations at Site U1477 (Zambezi Catchment; Figure F3) were scheduled for three APC/XCB holes to 207 mbsf. This drilling objective was modified to end at APC refusal, which led to recovering ~166 m. Recovery was excellent, and triple coring allowed compilation of a complete spliced record to ~85 m CCSF-A. The magnetic susceptibility signal is strong and could be matched to nearby <sup>14</sup>C-dated cores, and two biostratigraphic markers, in agreement, pointed to sediment accumulation rates of ~1 m/ky at this site (Figure F11). This extreme accumulation rate was a surprise and led to only recovering ~120 ky of sediment record from the Zambezi Catchment. Therefore, the sediment record will not allow a 2 my record as planned, but will instead, for example, provide the opportunity for extremely high resolution reconstructions of terrestrial climate and thermocline characteristics during the last glacial cycle. The site also holds significant potential to investigate the connections between southern African terrestrial climates and southeast Indian Ocean heat budgets and notably the links to the cultural evolution of modern humans.

Operations at Site U1478 (Limpopo Catchment; Figure F3) were scheduled to be three APC/XCB holes to 180 mbsf, with a permitted depth to 250 mbsf, and a single hole to 150 mbsf for interstitial waters. This drilling objective was successfully accomplished, and coring was taken to the maximum allowed depth of 250 m CSF-A with APC, until refusal, followed by HLAPC coring. Recovery was excellent, and triple coring allowed compilation of a complete spliced record extending to ~4 Ma. The paleomagnetic timescale was robust for the uppermost ~100 m CSF-A, below which the signal appears to be badly modified by diagenesis (Figure F23). The magnetic reversal positions are in good agreement with the biostratigraphy, and these together suggest a sedimentation rate of ~9.3 cm/ky from the mudline to ~200 m CCSF-A and rate of 2.8 cm/ky from ~200 m CSF-A to the bottom of the site (Figure F11). This record will provide the opportunity for high-resolution climate reconstructions of faunal, biogeochemical, and terrigenous tracers that are characteristic of the upper reaches of the Agulhas Current warm-water transports that will allow connections between Agulhas leakage and its headwater variability. The site also holds significant potential to investigate the connections between southern African terrestrial climates and southeast Indian Ocean heat budgets and notably the links to the cultural evolution of early modern

humans. A high-resolution program of interstitial water samples collected from a 150 m CSF-A section will provide an additional data point to the presently available interstitial water LGM temperature and salinity inventory.

Operations at Site U1479 (Cape Basin; Figure F3) were scheduled for three APC/XCB holes to 350 mbsf with logging. This drilling objective was largely accomplished with the exception of logging and a reduction in the target section depth to ~300 m CSF-A because of time constraints and the biostratigraphy indication that we had achieved the temporal goal. Recovery was excellent, and multiple coring (with extra cores taken because of messy intervals related to large ocean swells) allowed compilation of a complete spliced record extending to ~7 Ma. Although the signal is low and therefore will need future work on shore, the paleomagnetic timescale (Figure F23) is in good agreement with the biostratigraphy, and these together suggest uniform sedimentation rates of ~4.3 cm/ky through the sequence (Figure F11). This record represents the only site situated in the immediate Agulhas leakage pathway. It will therefore provide the opportunity for high-resolution climate reconstructions of the leakage and temporal comparisons with deep-water circulation.

The following specific scientific objectives of the expedition are expected to be highly achievable with the materials covered:

- To determine the variability of the greater Agulhas Current system under contrasting climatic regimes: early Pliocene warm conditions, during the mid-Pliocene expansion of Northern Hemisphere ice sheets, and through the MPT;
- To establish the role of Agulhas leakage in transient and long-term shifts of the AMOC during these climatic transitions: proxy records of mode/strength of Agulhas leakage during periods of major climatic reorganizations and for AMOC variations through the same intervals;
- To establish the response of the Agulhas Current system to Antarctic climate variability and bipolar linkages: evidence for variation of the Agulhas leakage in highly resolved temporal records will be compared to Antarctic and bipolar climate changes as well as with evidence for shifts of Southern Ocean fronts bordering the Agulhas corridor at the southern tip of Africa and strength of the westerlies;
- To understand the remote tropical origins of Agulhas Current variability: evidence for variation of Agulhas leakage in highly resolved temporal records will be compared to records of Indonesian Throughflow and monsoon modulation on the Agulhas Current source region and impacts on warm-water and saltwater transports along the southeast African margin and Indian-Atlantic saltwater leakage;
- To better determine southern African climate sensitivity: comparison of varying Agulhas Current warm-water transports with rainfall patterns in southern Africa in connection with the Pliocene–Pleistocene evolution of tropical climates, ITCZ migration, and tectonic history of eastern Africa; and
- To provide further verification of glacial–interglacial variations in the Southern Ocean's role in the carbon cycle: nutrient cycling, productivity, and  $p\text{CO}_2$  and their role in global biogeochemical cycles.

## Drilling operations and core handling

Drilling operations and core handling were performed, as is widely acknowledged for IODP, with total professionalism and with

outstanding commitment to achieving the expedition scientific objectives. As a result, materials recovered during Expedition 361 were accordingly astonishing and promise significant future scientific research, including full-recovery APC coring to deeper than 300 m CSF-A at Site U1479; complete APC records through the late Miocene/early Pliocene to recent at Sites U1474–U1476, U1478, and U1479; and 382 interstitial water samples from Sites U1474–U1476 and U1478 to help constrain the temperature, salinity, and density structure of the LGM spanning from 488 to 3045 mbsl. At Site U1477, where degassing within the core barrel was experienced, appropriate core handling adjustments were implemented rapidly, preserving the scientific value of the cored sections. In summary, the exceptional skills of the drillers and core technicians were the main reason why, despite setbacks, the scientific objectives of Expedition 361 could be accomplished.

## Critical aspects

### Administrative preparation for operations within Mozambique EEZ waters

The majority of the lost operational time was due to delays in attaining the necessary permissions to operate in Mozambique EEZ waters (received some 48 days after the expedition start). These issues should be addressed and resolved prior to an expedition so as not to impact operational time and thereby jeopardize the scientific impact of the recovered material. Although such issues are relatively rare, in this case Expedition 361 had to compensate by dropping all of the planned logging operations and shortening holes (i.e., exclude XCB drilling) to ensure complete APC spliced records to target stratigraphic depths were obtained at all sites for the palaeoceanographic objectives and the interstitial water program, in support of the APL (Agulhas LGM Density Profile), were met. Fortunately, smooth coring operations, sequence characteristics, and a clement sea state for much of the expedition worked in our favor to produce 100% recovery. This will serve to reduce the negative impact of lost operational time.

## Operations

During Expedition 361, we conducted coring operations in 35 holes at 6 sites. A total of 422.0 m was drilled without recovery, 5080.4 m was cored, and 5175.69 m of core was recovered (102% total core recovery) (Table T1). The overall time distribution included 4.9 days in port, 26.3 days in transit, and 29.7 days on site. The vessel transited a total of 6752 nmi.

### Port Louis port call

IODP Expedition 361 began at 1014 h (UTC + 4) on 30 January 2016 with the first line ashore at Quay A Mer Rouge in Port Louis, Mauritius. The IODP staff and chief scientists boarded the vessel at 1100 h, and the off-going science party departed at 1300 h. Port call activities started with the IODP staff crew change and crossover; off-going staff departed the vessel at 1500 h. The Siem crew crossover took place on 31 January, and the science party boarded the vessel that morning.

On 4 February the vessel was made ready for the sea passage. The port call ended with last line away at 0736 h. With the assistance from two harbor tugs, the vessel left Port Louis. The pilot departed the vessel at 0808 h. The propeller speed was increased to 140 rpm, and the R/V *JOIDES Resolution* began the sea passage to the first site (proposed Site MZC-01C) of Expedition 361.

## Transit to Site U1474

The original operations plan called for the ship to transit to proposed Site MZC-01C (Site U1476) to begin coring operations. However, the ship had not been cleared to operate within the Mozambique EEZ, and on 6 February 2016 the decision was made to go to Site U1474 (proposed Site NV-02C), which is located within the South Africa EEZ. After a 1563 nmi transit from Port Louis averaging 11.3 kt, the vessel arrived at Site U1474 at 2330 h (UTC + 2 h) on 9 February. Given the location of Site U1474 within the Agulhas Current, surface current speeds were high throughout operations, averaging ~1.5 m/s.

## Site U1474

Site U1474 consisted of 8 holes, ranging in depth from 3.1 to 254.1 m DSE. Overall, 111 cores were recorded for the site. A total of 809.79 m of core over a 794.0 m interval was recovered using the APC system (102% core recovery). The HLAPC system was used to core a 102.4 m interval, and 100.96 m of core was recovered (99% core recovery). A total of 910.75 m of sediment was recovered from a 896.4 m interval at Site U1474 (102% core recovery). The total time spent at Site U1474 was 7.6 days.

### Hole U1474A

The drill string was run to a depth of 3025.2 mbsl. The top drive was picked up and the bit was placed at 3042.6 mbsl for the first APC core. The core barrel was retrieved completely full, missing the sediment/water interface at the seafloor. The bit was raised 7.9 m to 3034.7 mbsl for a second coring attempt. This also yielded a full core barrel. These two cores were later curated as Cores 361-U1474G-1H and 361-U1474H-1H. The bit was raised 5 m to 3029.7 mbsl for a third coring attempt at 1525 h. This core retrieved a good mudline core.

Cores 361-U1474A-1H through 27H were successfully recovered using the APC. After four partial strokes using the APC, the HLAPC was deployed for Cores 28F through 29F. After reaching the HLAPC refusal depth at 254.1 mbsf, the drill string was pulled out of the hole. The bit cleared the seafloor at 1040 h on 12 February, ending Hole U1474A.

A total of 27 APC cores were taken over a 244.9 m interval with a total recovery of 256.11 m of core (105% core recovery). Two HLAPC cores were retrieved over a 9.2 m interval with 8.72 m recovered (95%). Total core recovery for Hole U1474A was 104%.

### Hole U1474B

The vessel was offset 20 m north of Hole U1474A, and coring in Hole U1474B started at 1320 h on 12 February. Cores 361-U1474B-1H through 16H penetrated to 147.3 m and recovered 142.09 m of sediment (96% core recovery). One interstitial water whole-round sample was taken from each core section for high-resolution geochemistry. After reaching the total depth at 147.3 m DSE, the drill string was pulled out of the hole. The bit cleared the seafloor at 0835 h on 13 February.

### Hole U1474C

The vessel was offset 20 m east of Hole U1474A, and coring in Hole U1474C started at 0935 h on 13 February. Core 361-U1474C-1H was recovered with 3.07 m of sediment. The stratigraphic correlation specialists determined that a longer first core was needed to span stratigraphic gaps, and Hole U1474C was terminated.

### Hole U1474D

The ship maintained its position 20 m east of Hole U1474A, and coring started in Hole U1474D at 1100 h on 13 February. Hole U1474D was cored to 124.5 m DSE using the APC system. At 0215h on 14 February, winds increased to 50 kt, gusting up to 58 kt, and combined with a ~2 kt surface current led to the dynamic positioning system (DPS) operating at 100% capacity. The drill string was pulled out of the hole, and the bit cleared the seafloor at 0305 h on 14 February, ending Hole U1474D. The final depth of Hole U1474D was 124.5 m DSE. Cores 361-U1474D-1H through 14H were taken over a 124.5 m interval and recovered 126.04 m of sediment (101% core recovery).

### Hole U1474E

The vessel drifted at 0.9 kt southward after ending Hole U1474D. At 1900 h on 14 February, the thrusters were raised to transit back to Site U1474. Hole U1474E was spudded 20 m east of Hole U1474A at 0725 h on 15 February. The hole was drilled without coring to 105.5 m DSE. Cores 361-U1474E-2H through 9H were recovered using the APC system to 172.0 m. One drilled interval between 124.5 and 126.0 mbsf was used to aid in stratigraphic correlation. The HLAPC was deployed for Cores 10F through 19F. After recovering Core 19F, the drill string was pulled out of the hole. The bit cleared the seafloor at 0630 h on 16 February, ending Hole U1474E. The final depth of Hole U1474E was 219.0 m DSE.

A total of 7 APC cores were taken over a 65.0 m interval with a total recovery of 67.93 m of core (105% core recovery). Ten HLAPC cores were retrieved over a 47.0 m interval with 46.51 m recovered (99% core recovery). Two drilled intervals over 107 m were logged. The total core recovery for Hole U1474E was 102%.

### Hole U1474F

The vessel was offset 20 m south of Hole U1474A and Hole U1474F started at 0845 h on 16 February. Cores 361-U1474F-1H through 21H were retrieved using the APC system. After experiencing partial strokes while taking Cores 20H and 21H, the HLAPC system was deployed for Cores 22F through 24F. Following Core 24F, the stratigraphic correlation specialists requested a 2.0 m drilled interval (361-U1474F-251) to offset the coring gaps. Coring operations with the HLAPC continued through Core 33F, where APC refusal depth was reached at 238.4 m DSE. The drill string was pulled out of the hole, and the bit cleared the seafloor at 0400 h and cleared the rotary table at 0745 h on 18 February. The rig was then secured for transit. Permission to drill in the Mozambique EEZ had still not been received, so the decision was made to sail south. The vessel began the transit to proposed Site APT-01B (U1475) at 0948 h on 18 February, ending Hole U1474F and Site U1474.

A total of 21 APC cores were taken over a 190.2 m interval with a total recovery of 194.76 m of core (102% core recovery). Eleven HLAPC cores were retrieved over a 46.2 m interval with 45.73 m recovered (99% core recovery). One interval of 2.0 m was drilled without coring. A total of 241.3 m of sediment was recovered over a 236.4 m cored interval (102% core recovery) in Hole U1474F.

### Holes U1474G and U1474H

Cores 361-U1474G-1H and 361-U1474H-1H were retrieved prior to the start of Hole U1474A. Core 361-U1474G-1H was shot ~13 m below the sediment/water interface and recovered 9.97 m of sediment. Core 361-U1474H-1H was shot 0.3 m below the sedi-

ment/water interface and recovered 9.82 m of sediment. The science leadership decided that the greatest scientific value of Core 361-U1474G-1H would come from leaving it on the vessel for future science parties to train with.

### Transit to Site U1475

The vessel was under way at full speed for Site U1475 (proposed Site APT-01B) when the ship's doctor informed the Captain of a medical emergency requiring evacuation. The ship's heading was changed at 0820 h on 20 February 2016 to meet a helicopter for evacuation near Port Elizabeth, South Africa. At ~1200 h on 21 February, the vessel was in position for a helicopter transfer. By 1230 h, the helicopter departed with the patient and the vessel resumed the transit to Site U1475. After a 433 nmi transit from the medical evacuation point, the vessel arrived at Site U1475 at 1500 h on 23 February.

### Site U1475

Site U1475 consisted of 6 holes, ranging in depth from 1.5 to 277.0 m DSF. Overall, 107 cores were recorded for the site. A total of 1015.92 m of core over a 987.9 m interval was recovered using the APC system (103% core recovery). Six intervals were advanced without coring over 86.0 m. The total time spent at Site U1475 was 5.7 days.

#### Hole U1475A

The vessel arrived at Site U1475 at 1500 h on 23 February 2016. Core 361-U1475A-1H was recovered with 1.48 m of sediment, and sea level was determined to be 2670.4 m above the sediment surface. The science party decided that a longer, well-preserved mudline core was necessary, and Hole U1475A was concluded. One APC core was taken over a 1.5 m interval with a total recovery of 1.48 m of core (99% core recovery).

#### Hole U1475B

Hole U1475B began at 0330 h on 24 February. The APC was deployed for Cores 361-U1475B-1H through 26H from the seafloor to 243.9 m DSF. The drill string was pulled out of the hole, and operations in Hole U1475B ended when the bit cleared the seafloor at 0430 h on 25 February. A total of 26 APC cores were taken over a 243.9 m interval with 250.31 m of sediment recovered (103%). Cores 1H through 6H (0–54.13 m CSF-A) are extremely disturbed as a result of the high seas.

#### Hole U1475C

The vessel was moved 20 m north of Hole U1475B. APC coring in Hole U1475C started at 0625 h on 25 February and extended from the seafloor (2669.3 mbsl) to 275.0 m DSF. Cores 361-U1475C-1H through 30H were taken over a 272.0 m cored interval with 280.7 m of sediment recovered (103%). While taking Cores 3H and 12H, the shear pins on the core barrel sheared early due to rough sea conditions. A short interval from 148.5 to 151.5 m DSF was advanced without coring as requested by the stratigraphic correlation specialists to cover coring gaps. After reaching 275.0 m DSF, the drill string was pulled out of the hole and operations in Hole U1475C ended when the bit cleared the seafloor at 0935 h on 26 February.

#### Hole U1475D

The vessel was moved 20 m east of Hole U1475B. Coring in Hole U1475D began at 1155 h on 26 February and extended from the sea-

floor to 143.0 m DSF. Cores 361-U1475D-1H through 16H were taken over a 143.0 m interval with 150.86 m of sediment recovered (105%). Interstitial water samples were collected from every core section for postcruise research. After concluding coring operations in Hole U1475D, the drill string was pulled out of the hole, with the bit clearing the seafloor at 0425 h on 27 February.

#### Hole U1475E

The vessel was offset 20 m south of Hole U1475B, and Hole U1475E began at 0550 h on 27 February. APC coring in Hole U1475E extended from the seafloor (2671.8 mbsl) to 277.0 m DSF. Cores 361-U1475E-1H through 30H were taken over a 270.5 m interval with 277.20 m of sediment recovered (102%). One interval was advanced without coring from 119.0 to 125.5 m DSF as was requested by the stratigraphic correlation specialists to offset coring gaps. After reaching 277.0 m DSF, the drill string was pulled out of the hole, and operations in Hole U1475E ended when the bit cleared the seafloor at 1335 h on 28 February.

#### Hole U1475F

The vessel was offset 20 m west of Hole U1475B, and operations in Hole U1475F began at 1450 h on 28 February. The stratigraphic correlation specialists devised a spot-coring plan in Hole U1475F to cover large coring gaps. The hole was washed down from the seafloor (2669.3 mbsl) to 20 m DSF. Hole U1475F contained four intervals that were advanced without coring over 76.5 m. Six APC cores were recovered over a 57.0 m interval using nonmagnetic core barrels in Hole U1475F, with 55.37 m of sediment recovered (97% core recovery). After reaching 133.5 m DSF, the drill string was pulled from the hole, with the bit clearing the seafloor at 0235 h on 29 February. The beacon was recovered at 0451 h, and the drill floor was secured for transit. At 0930 h the vessel began the voyage to proposed Site ZAM-05A (U1477), ending Site U1475.

### Transit to Site U1476

After completing operations at Site U1475, the vessel initially transited toward proposed Site ZAM-05A. However, after not receiving clearance to operate within the Mozambique EEZ by the end of the day on 2 March 2016, the decision was made at 1730 h to halt the transit to Site U1477 and abandon the Mozambique sites. Rather, an alternative operations plan consisting of proposed Site CAPE-01C (U1479) and alternate proposed Site SubSAT-01D (re-drill of ODP Site 1089) would be carried out.

At 1313 h on 3 March, the vessel received news that the clearance documents had been signed by Mozambique officials (35 days after the start of the expedition) and the diplomatic note would be sent to the vessel and the *JOIDES Resolution* Science Operator (JRSO) when it was received by the embassy. The decision was made to transit to the northernmost site (proposed Site MZC-01C; U1476) so that reduced coring operations could be attempted at all of the primary proposed sites within the remaining expedition days. The vessel changed course and was under way to Site U1476 at 1318 h on 3 March. After an 1888 nmi transit from Site U1475, the vessel arrived on site at 0048 h on 8 March.

### Site U1476

Site U1476 consisted of 5 holes, ranging in depth from 5.7 to 234.8 m DSF. Overall, 90 cores were recorded for the site. A total of 873.85 m of core over an 841.1 m interval was recovered using the APC system (104% core recovery). One interval was advanced with-



out coring over 1.0 m. The total time spent at Site U1476 was 4.1 days.

#### Hole U1476A

The vessel arrived at Site U1476 at 0048 h on 8 March 2016. The first APC core was filled with water, and the bit was lowered 7 m for a second attempt. Hole U1476A was spudded at 0935 h, and a 5.72 m core was retrieved (Core 361-U1476A-1H). Seafloor depth was calculated at 2165.7 mbsl. Cores 1H through 24H (0–224.2 m DSF) were taken with 104% core recovery. Hole U1476A was terminated after reaching APC refusal depth. The drill string was pulled out of the hole, with the bit clearing the seafloor at 0705 h on 9 March, ending Hole U1476A.

#### Hole U1476B

The vessel was offset 20 m north of Hole U1476A, and Hole U1476B was spudded at 0815 h on 9 March. Seafloor was calculated at 2166.5 mbsl based on recovery from Core 361-U1476B-1H. Cores 1H through 16H (0–148.4 m DSF) were recovered with 154.42 m of sediment (104%). Interstitial water whole-round samples were taken from every core section for postcruise research. The drill string was pulled from the hole and cleared the seafloor at 2115 h on 9 March, ending Hole U1476B.

#### Hole U1476C

The vessel was offset 20 m east of Hole U1476A. Hole U1476C was spudded at 2225 h on 9 March, and Core 361-U1476C-1H recovered 5.72 m of sediment. The stratigraphic correlation specialists determined that the coring gaps were aligned, and Hole U1476C was ended at 2245 h.

#### Hole U1476D

Hole U1476D was spudded at 2330 h with a 1.0 m drilled interval. This was done to ensure offset coring gaps between holes. Cores 361-U1476D-2H through 25H (1.0–229.0 m DSF) were taken using nonmagnetic core barrels. After reaching 229.0 m DSF, the drill string was pulled from the hole, and the bit cleared the seafloor at 2015 h on 10 March, ending Hole U1476D. At total of 237.02 m of core was retrieved over a 228.0 m cored interval (103% core recovery).

#### Hole U1476E

The vessel was offset 20 m south of Hole U1476A, and Hole U1475E was spudded at 2125 h on 10 March. Cores 361-U1476E-1H through 25H (0–234.8 m DSF) recovered 243.79 m of sediment (104% core recovery). After reaching 234.8 m DSF, the drill string was pulled from the hole, and the bit cleared the seafloor at 2050 h on 11 March. The positioning beacon was recovered at 0102 h on 12 March. The rig floor was secured for transit at 0335 h, and the thrusters were raised at 0349 h. The vessel began the transit to Site U1477 at 0400 h, ending Site U1476.

### Transit to Site U1477

After a 350 nmi transit from Site U1476, the vessel arrived at Site U1477 at 0942 h on 13 March 2016, and the thrusters were lowered at 1015 h.

### Site U1477

Site U1477 (proposed Site ZAM-05A) consisted of 3 holes, ranging in depth from 119.4 to 181.2 m DSF. Overall, 69 cores were recorded for the site. A total of 308.07 m of core over a 296.2 m interval was recovered using the APC system (104% core recovery).

The HLAPC recovered 174.00 m of sediment over a 169.2 m interval (103% core recovery). The XCB was deployed for one core resulting in 7.96 m of sediment (97% core recovery). One interval was advanced without coring over 1.0 m. Overall, at total of 490.03 m of core was retrieved from a 474.0 m cored interval at Site U1477 (103% core recovery). The total time spent at Site U1477 was 1.9 days.

#### Hole U1477A

The APC/XCB bottom-hole assembly (BHA) and drill string were deployed to 412.2 mbsl. The first two coring attempts resulted in water cores and, after lowering the bit a total of 15 m, Hole U1477A was spudded at 1535 h on 13 March 2016. Core 361-U1477A-1H recovered 7.52 m of sediment, and the water depth was calculated at 429.2 mbsl. The hole was cored to 102.5 m DSF (Cores 1H through 11H) using the APC system. After partial strokes with the APC on Cores 10H and 11H, the HLAPC was deployed, and piston coring continued to 173.0 m DSF (Cores 12F through 26F). The XCB was deployed for Core 27X (173.0–181.2 m DSF). Coring was terminated in Hole U1477A at a total depth of 181.2 m DSF. The drill string was removed from the hole, with the bit clearing the seafloor at 0615 h on 14 March, ending Hole U1477A. The total core recovery for Hole U1477A was 182.53 m over a 181.2 m cored interval (101%).

#### Hole U1477B

The vessel was offset 20 m north of Hole U1477A, and Hole U1477B was spudded at 0705 h on 14 March. The APC system was deployed for Cores 361-U1477B-1H through 12H (0–108.6 m DSF). After two partial strokes with the APC, the HLAPC was used for Cores 13F through 26F (108.6–174.4 m DSF). A total of 185.73 m of core was recovered over a 174.4 m cored interval in Hole U1477B (106%). The drill string was pulled from the hole, and the bit cleared the seafloor at 1910 h on 14 March, ending Hole U1477B.

#### Hole U1477C

The vessel was offset 20 m east of Hole U1477A, and Hole U1477C was spudded at 1950 h on 14 March with a 1.0 m drilled interval. The APC system was used for Cores 361-U1477C-2H through 10H. After partial strokes on Cores 9H and 10H, the HLAPC was deployed for Cores 11F through 17F. Coring was terminated at a total depth of 119.4 m DSF. One partial stroke was recorded while using the HLAPC (Core 12F). A total of 121.7 m of core was recovered from a 118.4 m cored interval (103%). The drill string was pulled from the hole, with the bit clearing the seafloor at 0415 h and the rotary table at 0555 h on 15 March. The rig floor was secured for transit at 0630 h, and the vessel was underway to Site U1478 at 0642 h, ending Site U1477.

### Transit to Site U1478

After a 422 nmi transit from Site U1477, the vessel arrived at Site U1478 (proposed Site LIM-01B) at 2215 h on 16 March 2016. The thrusters lowered at 2215 h, and a positioning beacon was deployed at 2315 h. The vessel stabilized over the site coordinates at 2324 h, starting the site and Hole U1478A.

### Site U1478

Site U1478 consisted of 4 holes, ranging in depth from 216.0 to 248.4 m DSF. Overall, 119 cores were recorded for the site. A total of 708.66 m of core over a 698.9 m interval was recovered using the APC system (101% core recovery). The HLAPC recovered 213.44 m

of sediment over a 206.8 m interval (103% core recovery). Nine intervals were advanced without coring over 54.3 m. Overall, at total of 922.1 m of core was retrieved from a 905.7 m cored interval at Site U1478 (102% core recovery). The total time spent at Site U1478 was 2.7 days.

#### Hole U1478A

An APC/XCB BHA was made up, and the drill string was deployed to 484.3 mbsl. Hole U1478A was spudded at 0320 h on 17 March 2016. The APC system was used on Cores 361-U1478A-1H through 21H (0–196.7 m DSF). The HLAPC was then deployed after significant overpull (70,000 lb) was recorded while removing Core 21H, and Cores 22F through 32F (196.7–248.4 m DSF) were retrieved.

The APC system was deployed 21 times over a 196.7 m interval, with a recovery of 202.22 m (102.8% recovery). The HLAPC was deployed 11 times over a 51.7 m interval, with a recovery of 54.74 m (105.9% recovery). A total of 256.96 m of sediment was recovered over a 248.4 m cored interval in Hole U1478A (103% recovery). The drill pipe was pulled from the hole and the bit cleared the seafloor at 1805 h on 17 March, ending Hole U1478A.

#### Hole U1478B

The vessel was offset 20 m north of Hole U1478A, and Hole U1478B was spudded at 1840 h on 17 March. Hole U1478B was drilled without recovery from 0 to 1.0 mbsf to ensure offset coring gaps between Holes U1478A and U1478B. The APC system was used on Cores 361-U1478B-2H through 19H (1.0–172.0 m DSF), and the HLAPC was deployed for Cores 20F and 21F (172.0–181.4 m DSF). The coring system was switched back to the APC for Core 22H, which recorded a partial stroke. The HLAPC was used for the remaining cores in Hole U1478B (Cores 23F through 34F). After reaching 247.3 mbsf, the drill string was pulled from the hole, and operations in Hole U1478B ended with the bit clearing the seafloor at 1015 h on 18 March.

The APC was used for a total of 19 cores over a cored interval of 180.5 m with a recovery of 180.31 m (100% recovery). The HLAPC was used for 14 cores over a 65.8 m interval with a recovery of 66.54 m (101% recovery). A total of 246.85 m of core was recovered over a 246.3 m cored interval at Hole U1478B with 100% core recovery. Each core section from 0 to 150 m CSF-A was sampled for interstitial water for postcruise research.

#### Hole U1478C

The vessel was moved 20 m east of Hole U1478A, and Hole U1478C was spudded at 1110 h on 18 March. The hole was washed down without recovery to 3.0 m DSF in order to offset coring gaps between holes for stratigraphic correlation. APC coring continued for Cores 361-U1478C-3H through 21H (3.0–178.5 m DSF). Interval 361-U1478C-202 was drilled without recovery from 164.5 to 169.0 m DSF. The HLAPC was deployed for Cores 21F through 38F (178.5–248.3 m DSF). Within the HLAPC cored section, three intervals were drilled without coring over a total of 4.0 m. After completing coring operations, the drill string was pulled from the hole, with the bit clearing the seafloor at 0219 h on 19 March.

The APC system was deployed for a total of 19 cores over an interval of 172.5 m with a recovery of 173.25 m (100% recovery). The HLAPC was deployed for 14 cores over a 65.8 m interval with a recovery of 69.07 m (105% recovery). A total of 238.3 m of core was recovered over a 248.3 m cored interval (102% recovery). There

were a total of five intervals drilled without coring covering a total of 10 m.

#### Hole U1478D

The vessel was offset 20 m south of Hole U1478A, and Hole U1478D was spudded at 0310 h on 19 March. Core 361-U1478D-1H recovered 6.7 m of sediment, and the seafloor was estimated at 490.7 mbsl. Hole U1478D was drilled without recovery from 6.7 to 8.7 m DSF to offset coring gaps for stratigraphic correlation. The APC system was deployed for Cores 3H through 17H (8.7–151.2 m DSF). A center bit was installed, and the hole was drilled without recovery over 39.3 m (151.2–190.5 m DSF) to target gaps in the stratigraphy. The HLAPC was deployed for Cores 19F and 20F (190.5–199.9 m DSF). The drill string was then advanced without recovery 2.0 m and Cores 22F through 24F (201.9–211.3 m DSF) were retrieved.

The APC system was deployed for 16 cores over 149.2 m with a recovery of 152.88 m (102.5% recovery). The HLAPC system was deployed for 5 cores over a 23.5 m interval with 23.09 m recovered (98.3%). A total of 175.97 m of core was recovered over a 172.7 m cored section (102% core recovery). There were 3 intervals drilled without coring for covering a total of 43.3 m.

After completing coring operations at Hole U1478D, the drill string was pulled from the hole. The bit cleared the seafloor at 1350 h on 19 March and the rig floor at 1540 h. The rig floor was secured for transit, and the vessel began the transit to Site U1479 at 1630 h, ending Site U1478.

### Transit to Site U1479

After a 1196 nmi transit from Site U1478, the vessel arrived at Site U1479 (proposed Site CAPE-01C) at 0342 h on 24 March 2016. The thrusters lowered at 0414 h, and a positioning beacon was deployed at 0609 h. The vessel stabilized over the site coordinates at 0624 h, starting the site and Hole U1479A.

#### Site U1479

Site U1479 consisted of 9 holes, ranging in depth from 1.0 to 300.7 m DSF. Overall, 105 cores were recorded for the site. A total of 963.21 m of core over a 975.3 m interval was recovered using the APC system (99% core recovery). Seven intervals were advanced without coring over 175.7 m. The total time spent at Site U1479 was 6.0 days.

#### Hole U1479A

The APC/XCB BHA and drill string were made up and deployed to 2610 mbsl. Hole U1479A was spudded at 1150 h on 24 March 2016 and recovered 1.0 m of sediment. The seafloor was measured at 2618.5 mbsl. The science team decided that a longer, more pristine mudline core was desired, and Hole U1479A was abandoned.

#### Hole U1479B

The bit was lowered 5 m to 2615 mbsl, and Hole U1479B was spudded at 1255 h on 24 March. A water depth of 2618.3 mbsl was calculated based on recovery from Core 361-U1479B-1H. APC coring recovered Cores 1H through 32H (0–300.7 m DSF). A total of 296.73 m of sediment was recovered in Hole U1479B over a 300.7 m cored interval (99%). After completing coring operations in Hole U1479B, the drill string was pulled out of the hole, and the bit cleared the seafloor at 1920 h on 25 March. Sea conditions affected the core quality and recovery in the upper 82.5 m of the hole.

### Hole U1479C

The vessel was offset 20 m north of Hole U1479B, and a water depth of 2618.3 mbsl was assumed. Hole U1479C began at 2100 h on 25 March with a 1.0 m washed interval to offset coring gaps. Cores 361-U1479C-2H through 32H (1.0–295.5 m DSF) were retrieved using the APC system. A total of 303.69 m of sediment was recovered over a 294.5 m cored interval (103%). After completing coring operations in Hole U1479C, the drill string was pulled out of the hole, with the bit clearing the seafloor at 0250 h on 27 March.

### Hole U1479D

The vessel was offset 20 m east of Hole U1479B, and Hole U1479D was spudded at 0450 h on 27 March with the bit at 2615 mbsl. Cores 361-U1479D-1H through 3H (0–25.4 m CSF-A) were retrieved and followed by a 2.0 m washed interval to offset coring gaps for stratigraphic correlation. Cores 5H through 12H (27.4–103.4 m DSF) were recovered. After retrieving Core 12H, the drill string was pulled from the hole because of deteriorating sea conditions. The bit cleared the seafloor at 1510 h on 27 March, ending Hole U1479D. A total of 102.15 m of sediment was taken over a 101.4 m cored interval (101%).

### Hole U1479E

After waiting on weather for 12 h, the vessel was offset 20 m south of Hole U1479B. Hole U1479E was spudded at 0325 h on 28 March using an estimated seafloor depth of 2615.1 mbsl. Hole U1479E was drilled without recovery from 0 to 90 m DSF. The APC system was used on Cores 361-U1479E-2H through 8H (90.0–156.5 m DSF) followed by a 2.0 m drilled interval, employed to offset coring gaps for stratigraphic correlation. Cores 10H through 12H (158.5–187.0 m DSF) were recovered. Core 361-U1479E-133 was drilled without recovery over 42.0 m. Cores 14H through 18H were taken from 229.0 to 276.5 m DSF. After reaching total depth, the drill string was pulled from the hole with the bit clearing the seafloor at 2335 h on 28 March. A total of 15 APC cores recovered 148.17 m of sediment over a 142.5 m cored interval (104%). Three drilled intervals spanning 134.0 m were recorded for the hole.

### Hole U1479F

The vessel was offset 20 m west of Hole U1479B. Hole U1479F was spudded at 0125 h on 29 March. Core 361-U1479F-1H did not recover a mudline and instead had a full core barrel. Hole U1479F was abandoned for a second mudline attempt. Core 1H recovered 9.5 m of sediment with 100% core recovery.

### Hole U1479G

The drill string was pulled up 3.0 m, and Hole U1479G was spudded at 0225 h on 29 March. Core 361-U1479G-1H recovered 9.29 m of sediment, including the mudline. After calculating the seafloor at 2613.2 mbsl, the decision was made to core another mudline and then continue to core down.

### Hole U1479H

The drill string was pulled up 4.0 m, and Hole U1479H was spudded at 0325 h on 29 March. Core 361-U1479H-1H recovered a 5.57 m mudline. Cores 2H through 5H were taken from 5.6 to 43.6 m DSF followed by a 4.0 m interval that was advanced without recovery to offset coring gaps for stratigraphic correlation. Cores 7H through 10H (47.6–85.6 m DSF) were retrieved with poor APC recovery (75%). While taking Cores 7H and 9H, the flap-style core catcher failed to close and several meters of core was lost. Because of this, a critical stratigraphic interval was not cored, and the sci-

ence leadership decided to terminate the hole. The drill string was pulled out of the hole, with the bit clearing the seafloor at 1130 h on 29 March, ending Hole U1479H.

A total of 9 APC cores recovered 70.75 m of core over an 81.6 m cored interval (87%). APC cores were not oriented and used non-magnetic core barrels.

### Hole U1479I

Hole U1479I was spudded at 1200 h on 29 March, and Core 361-U1479I-1H recovered a 6.3 m mudline core. The hole was advanced without recovery to 41.0 m DSF. The flapper-style core catcher failed to close while taking Core 3H, and only 2.35 m was recovered. Core 4H recovered a full core barrel, but Core 5H misfired when the shear pins on the core barrel sheared early because of rough sea conditions. The decision was made to stop coring operations until weather conditions improved. The drill string was pulled from the hole, and the bit cleared the seafloor at 1820 h on 29 March. Four APC cores recovered 21.79 m of sediment over a 34.8 m cored interval (63% core recovery). One drilled interval of 34.7 m was recorded. The APC cores were taken using unoriented nonmagnetic core barrels.

The vessel spent the remaining operational time waiting on weather. At 0400 h on 30 March the drill pipe was tripped, and the bit cleared the rig floor at 1215 h. The positioning beacon was recovered at 0754 h. The rig floor was secured for transit at 1335 h, the thrusters were raised at 1415 h, and the vessel was under way to Cape Town, South Africa, at 1436 h, ending Hole U1479I and Site U1479.

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Table T1. Expedition 361 hole summary.

| Site, hole             | Latitude     | Longitude    | Seafloor depth (mbrf) | Cores (N) | Cored (m) | Recovered (m) | Recovery (%) | Drilled (m) | Total penetration (m) | Total depth (mbrf) | Time on hole (h) | Time on site (days) |
|------------------------|--------------|--------------|-----------------------|-----------|-----------|---------------|--------------|-------------|-----------------------|--------------------|------------------|---------------------|
| 361-                   |              |              |                       |           |           |               |              |             |                       |                    |                  |                     |
| U1474A                 | 31°12.9995'S | 31°32.7080'E | 3044.6                | 29        | 254.1     | 264.83        | 104          | 0.0         | 254.1                 | 3298.7             | 57.25            | 2.4                 |
| U1474B                 | 31°12.9882'S | 31°32.7083'E | 3045.2                | 16        | 147.3     | 142.09        | 96           | 0.0         | 147.3                 | 3192.5             | 21.75            | 0.9                 |
| U1474C                 | 31°12.9999'S | 31°32.7215'E | 3050.0                | 1         | 3.1       | 3.07          | 99           | 0.0         | 3.1                   | 3053.1             | 1.75             | 0.1                 |
| U1474D                 | 31°12.9999'S | 31°32.7213'E | 3045.2                | 14        | 124.5     | 126.04        | 101          | 0.0         | 124.5                 | 3169.7             | 16.75            | 0.7                 |
| U1474E                 | 31°12.9995'S | 31°32.7208'E | 3045.2                | 17        | 112.0     | 114.44        | 102          | 107.0       | 219.0                 | 3264.2             | 34.00            | 1.4                 |
| U1474F                 | 31°13.0105'S | 31°32.7078'E | 3046.8                | 32        | 236.4     | 240.49        | 102          | 2.0         | 238.4                 | 3285.2             | 51.25            | 2.1                 |
| U1474G                 | 31°12.9995'S | 31°32.7080'E | 3044.6                | 1         | 9.5       | 9.97          | 105          | 0.0         | 9.5                   | 3054.1             | 1.50             | 0.0                 |
| U1474H                 | 31°12.9995'S | 31°32.7080'E | 3044.6                | 1         | 9.5       | 9.82          | 103          | 0.0         | 9.5                   | 3054.1             | 1.50             | 0.0                 |
| Site U1474 totals:     |              |              |                       | 111       | 896.4     | 910.75        | 102          | 109.0       | 1005.4                | NA                 | 185.83           | 7.6                 |
| U1475A                 | 41°25.6052'S | 25°15.6440'E | 2681.4                | 1         | 1.5       | 1.48          | 99           | 0.0         | 1.5                   | 2682.9             | 11.25            | 0.5                 |
| U1475B                 | 41°25.6052'S | 25°15.6441'E | 2680.5                | 26        | 243.9     | 250.31        | 103          | 0.0         | 243.9                 | 2924.4             | 25.50            | 1.1                 |
| U1475C                 | 41°25.5941'S | 25°15.6439'E | 2680.4                | 29        | 272.0     | 280.70        | 103          | 3.0         | 275.0                 | 2955.4             | 29.00            | 1.2                 |
| U1475D                 | 41°25.6055'S | 25°15.6586'E | 2679.3                | 16        | 143.0     | 150.86        | 105          | 0.0         | 143.0                 | 2822.4             | 19.00            | 0.8                 |
| U1475E                 | 41°25.6162'S | 25°15.6439'E | 2682.9                | 29        | 270.5     | 277.20        | 102          | 6.5         | 277.0                 | 2959.9             | 33.00            | 1.4                 |
| U1475F                 | 41°25.6054'S | 25°15.6299'E | 2680.4                | 6         | 57.0      | 55.37         | 97           | 76.5        | 133.5                 | 2813.9             | 20.00            | 0.8                 |
| Site U1475 totals:     |              |              |                       | 107       | 987.9     | 1015.92       | 103          | 86.0        | 1073.9                | NA                 | 137.75           | 5.7                 |
| U1476A                 | 15°49.2535'S | 41°46.1242'E | 2176.8                | 24        | 224.2     | 232.90        | 104          | 0.0         | 224.2                 | 2401.0             | 29.50            | 1.2                 |
| U1476B                 | 15°49.2421'S | 41°46.1234'E | 2177.6                | 16        | 148.4     | 154.42        | 104          | 0.0         | 148.4                 | 2326.0             | 14.25            | 0.6                 |
| U1476C                 | 15°49.2526'S | 41°46.1355'E | 2176.6                | 1         | 5.7       | 5.72          | 100          | 0.0         | 5.7                   | 2182.3             | 1.50             | 0.1                 |
| U1476D                 | 15°49.2525'S | 41°46.1358'E | 2176.6                | 24        | 228.0     | 237.02        | 104          | 1.0         | 229.0                 | 2405.6             | 21.50            | 0.9                 |
| U1476E                 | 15°49.2635'S | 41°46.1236'E | 2176.3                | 25        | 234.8     | 243.77        | 104          | 0.0         | 234.8                 | 2411.1             | 31.75            | 1.3                 |
| Site U1476 totals:     |              |              |                       | 90        | 841.1     | 873.83        | 104          | 1.0         | 842.1                 | NA                 | 98.25            | 4.1                 |
| U1477A                 | 19°21.2930'S | 36°54.8962'E | 440.4                 | 27        | 181.2     | 182.53        | 101          | 0.0         | 181.2                 | 621.6              | 20.00            | 0.8                 |
| U1477B                 | 19°21.2822'S | 36°54.8958'E | 440.8                 | 26        | 174.4     | 185.73        | 106          | 0.0         | 174.4                 | 615.2              | 13.00            | 0.5                 |
| U1477C                 | 19°21.2928'S | 36°54.9066'E | 440.4                 | 16        | 118.4     | 121.75        | 103          | 1.0         | 119.4                 | 559.8              | 11.50            | 0.5                 |
| Site U1477 totals:     |              |              |                       | 69        | 474.0     | 490.01        | 103          | 1.0         | 475.0                 | NA                 | 44.50            | 1.8                 |
| U1478A                 | 25°49.2600'S | 34°46.1593'E | 499.2                 | 32        | 248.4     | 256.96        | 103          | 0.0         | 248.4                 | 747.6              | 19.25            | 0.8                 |
| U1478B                 | 25°49.2500'S | 34°46.1589'E | 499.2                 | 33        | 246.3     | 246.85        | 100          | 1.0         | 247.3                 | 746.5              | 16.25            | 0.7                 |
| U1478C                 | 25°49.2604'S | 34°46.1705'E | 501.2                 | 33        | 238.3     | 242.32        | 102          | 10.0        | 248.3                 | 749.5              | 16.00            | 0.7                 |
| U1478D                 | 25°49.2706'S | 34°46.1592'E | 502.0                 | 21        | 172.7     | 175.97        | 102          | 43.3        | 216.0                 | 718.0              | 14.25            | 0.6                 |
| Site U1478 Totals:     |              |              |                       | 119       | 905.7     | 922.10        | 102          | 54.3        | 960.0                 | NA                 | 65.75            | 2.7                 |
| U1479A                 | 35°03.5290'S | 17°24.0620'E | 2629.9                | 1         | 1.0       | 1.01          | 101          | 0.0         | 1.0                   | 2630.9             | 8.00             | 0.3                 |
| U1479B                 | 35°03.5289'S | 17°24.0621'E | 2629.7                | 32        | 300.7     | 296.73        | 99           | 0.0         | 300.7                 | 2930.4             | 31.00            | 1.3                 |
| U1479C                 | 35°03.5183'S | 17°24.0621'E | 2629.7                | 31        | 294.5     | 303.69        | 103          | 1.0         | 295.5                 | 2925.2             | 31.50            | 1.3                 |
| U1479D                 | 35°03.5286'S | 17°24.0754'E | 2626.5                | 11        | 101.4     | 102.15        | 101          | 2.0         | 103.4                 | 2729.9             | 12.50            | 0.5                 |
| U1479E                 | 35°03.5402'S | 17°24.0623'E | 2626.5                | 15        | 142.5     | 148.17        | 104          | 134.0       | 276.5                 | 2903.0             | 21.50            | 0.9                 |
| U1479F                 | 35°03.5290'S | 17°24.0493'E | 2626.7                | 1         | 9.5       | 9.50          | 100          | 0.0         | 9.5                   | 2636.2             | 2.25             | 0.1                 |
| U1479G                 | 35°03.5290'S | 17°24.0493'E | 2623.9                | 1         | 9.3       | 9.29          | 100          | 0.0         | 9.3                   | 2633.2             | 1.00             | 0.0                 |
| U1479H                 | 35°03.5289'S | 17°24.0489'E | 2624.6                | 9         | 81.6      | 70.75         | 87           | 4.0         | 85.6                  | 2710.2             | 8.75             | 0.4                 |
| U1479I                 | 35°03.5286'S | 17°24.0493'E | 2624.8                | 4         | 34.8      | 21.79         | 63           | 34.7        | 69.5                  | 2694.3             | 27.00            | 1.1                 |
| Site U1479 totals:     |              |              |                       | 105       | 975.3     | 963.08        | 99           | 175.7       | 1151.0                | NA                 | 143.50           | 6.0                 |
| Expedition 361 totals: |              |              |                       | 601       | 5080.4    | 5175.69       | 102          | 427.0       | 5507.4                | NA                 | 675.75           | 28.0                |



Figure F1. Global composite of land surface reflectance and sea-surface temperature (credit: Jacques Descloitres, MODIS Land Science Team, NASA) with schematic representation of the greater Agulhas Current system and its links to the Atlantic Meridional Overturning Circulation. The greater Agulhas Current system around South Africa consists of the Agulhas Current flowing south along the African shelf. Off the southern tip of Africa, the Agulhas Current abruptly retroflects and feeds back into the Indian Ocean. During this process, huge rings of water (Agulhas rings) are separated, drifting into the Atlantic. Upstream of the Agulhas Current, eddies around Madagascar insert short-term variability into the Agulhas Current, leading to short-term offshore meanders of the main current by several 100 km.

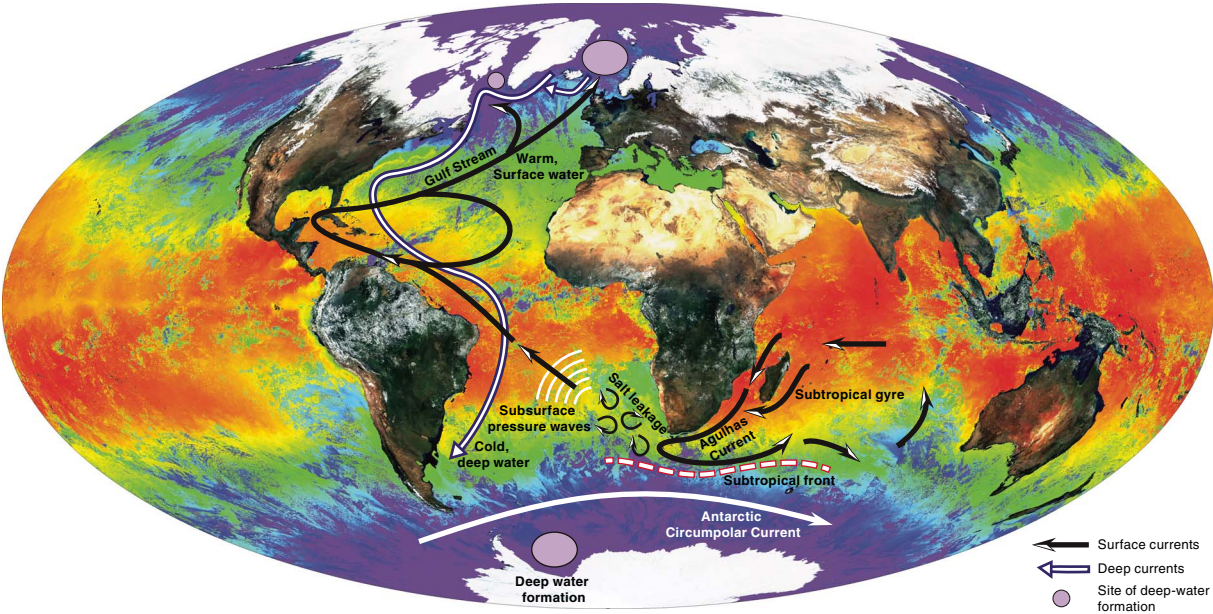


Figure F2. Surface currents of the greater Agulhas Current system represented in a high-resolution ocean model (snapshot). Credit: Professor Dr. Arne Biastoch, GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany.

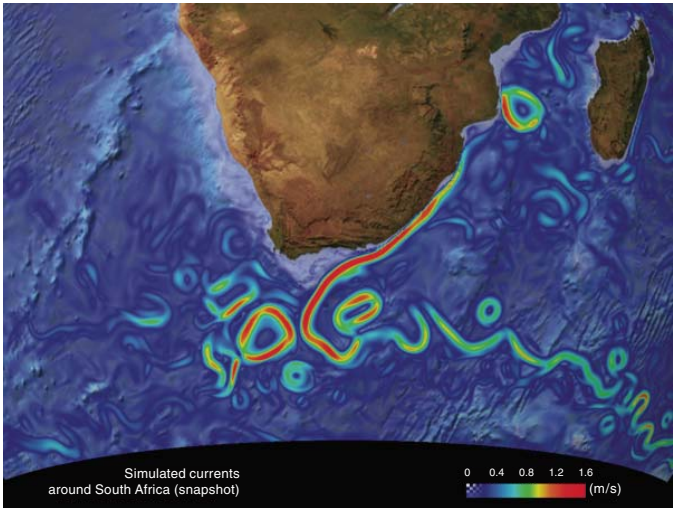


Figure F3. Expedition 361 site locations. Yellow and orange arrows = main surface ocean currents, gray arrows = main pathways of moisture supply to the African continent from the northwest Atlantic (via Congo) and the northwest and southwest Indian Ocean, dashed lines = approximate position of the Intertropical Convergence Zone (ITCZ) and Congo Air Boundary (CAB) (adapted from Reason et al., 2006), purple shaded area = Zambezi Catchment, green shaded area = Limpopo Catchment. AC = Agulhas Current, SEC = South Equatorial Current, SEMC = South East Madagascar Current, NEMC = North East Madagascar Current, EACC = East Africa Coastal Current.

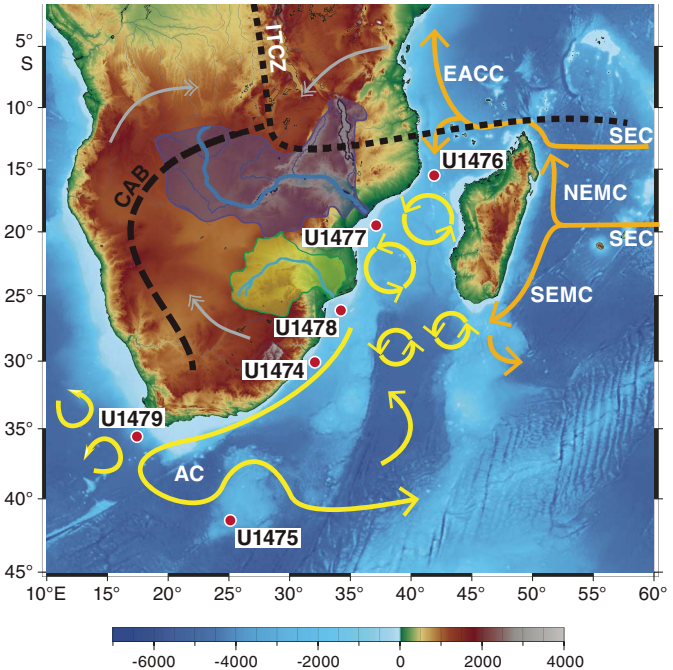


Figure F4. Potential temperature vs. salinity for the western Indian Ocean (adapted from Gordon et al., 1987). SICW = South Indian Central Water, SAMW = Subantarctic Mode Water, NADW = North Atlantic Deep Water, AABW = Antarctic Bottom Water, AAIW = Antarctic Intermediate Water, AASW = Antarctic Surface Water, SAASW = Subantarctic Surface Water.

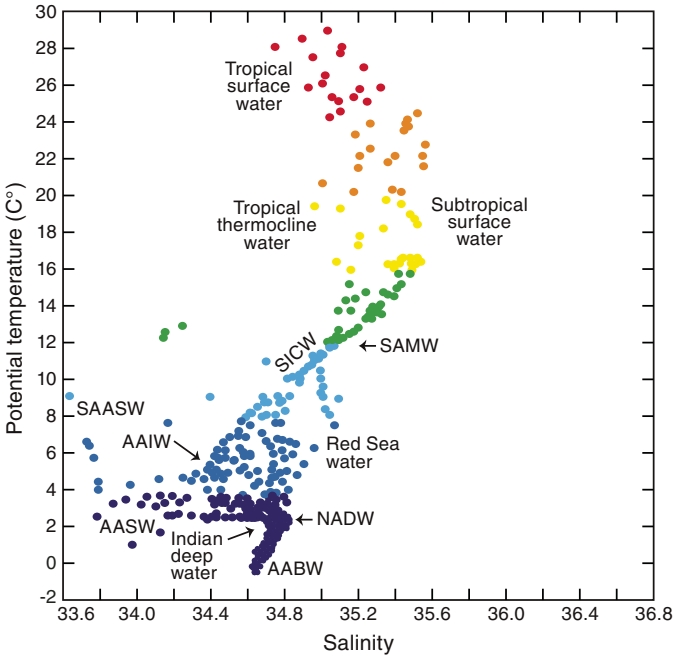


Figure F5. Example SST map overlaid with geostrophic current vectors. The satellite products used consist of the daily Odyssey SST analysis provided by the CERSAT and the Ssalto/Duacs absolute geostrophic velocities. Flow speeds <30 cm/s were not plotted. The loop or meander in the current shows a well-developed Natal Pulse just north of Algoa Bay. Image courtesy of Marjolaine Krug (CSIR-NRE).

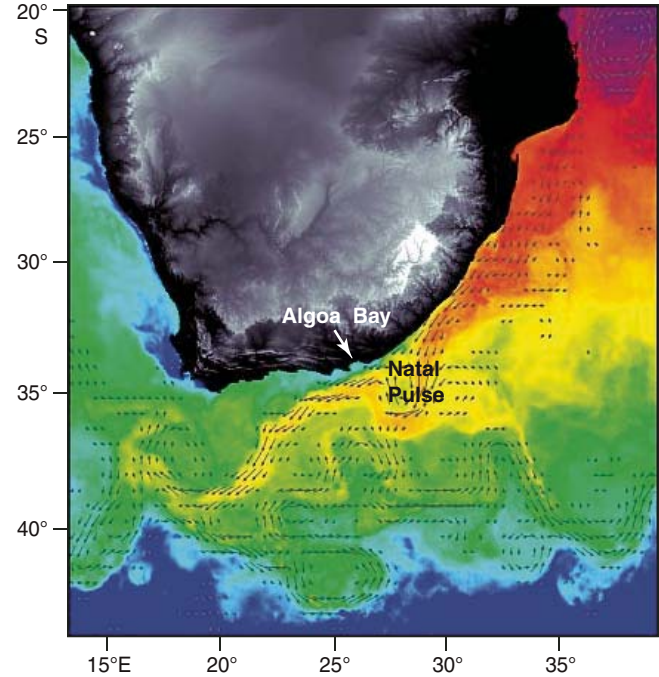


Figure F6. Paleoceanographic profiles from sediment Core MD96-2080 (close to Site U1479). A. Planktonic  $\delta^{18}\text{O}$  showing glacial-interglacial climates. B. Distribution of ALF in neighboring Core MD96-2081. C. SST variation along Core MD96-2080 from planktonic Mg/Ca ratios. Insert displays ALF section from the same core. D. Sea-surface salinity (SSS) estimated from paleothermometry combining data from A and C. Data from Peeters et al. (2004) and Martínez-Méndez et al. (2010).

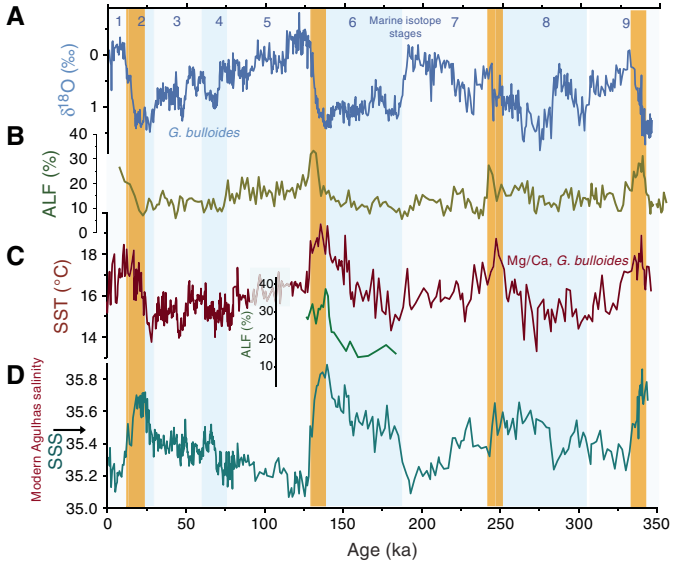


Figure F7. Global land cover map of Africa (Mayaux et al., 2004).

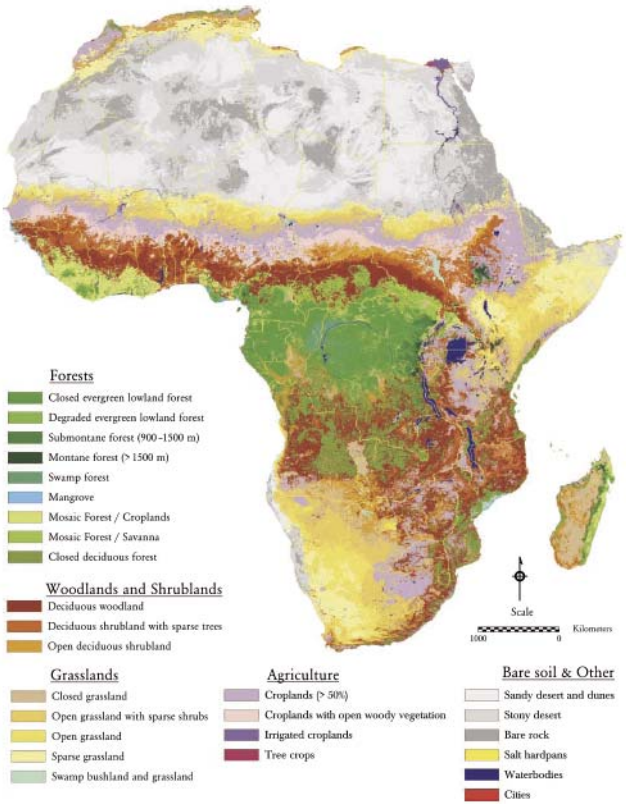




Figure F8. Long-term climate variability in eastern South Africa over the past 270,000 y from Simon et al. (2015b). A.  $\delta^{18}\text{O}$  splice from Chinese speleothems (green line) (Wang et al., 2001, 2008; Cheng et al., 2009) as presented in Barker et al. (2011) showing synchronous variability of the East Asian Monsoon with Northern Hemisphere summer insolation at  $65^\circ\text{N}$ . Underlying gray bars indicate glacial–interglacial terminations (T). B. Fe/K ratios from Core CD154-10-06P (black line; five-point running mean, fine-tuned age model) indicating more humid KwaZulu-Natal climate in accordance with varying austral (December–January) summer insolation at  $30^\circ\text{S}$ . Light orange line shows initial age model based on global benthic Stack LR04 tuning. C. Pretoria Saltpan Rainfall record (Partridge et al. 1997) with December insolation at  $30^\circ\text{S}$ . D. Benthic foraminiferal (*Cibicides* spp.)  $\delta^{18}\text{O}$  record from Core CD154-10-06P (black = fine-tuned age model, light orange = initial age model) reflecting global ice volume variability and local deep-water conditions in comparison with global benthic Stack LR04 (blue) (Lisiecki and Raymo, 2005). MIS = marine isotope stages. E. Age control points for Core CD154-10-06P including radiocarbon dates (black), tuning of the foraminiferal  $\delta^{18}\text{O}$  record (light orange), and  $\delta^{18}\text{O}$  splice from Chinese speleothems on precession phase (green).

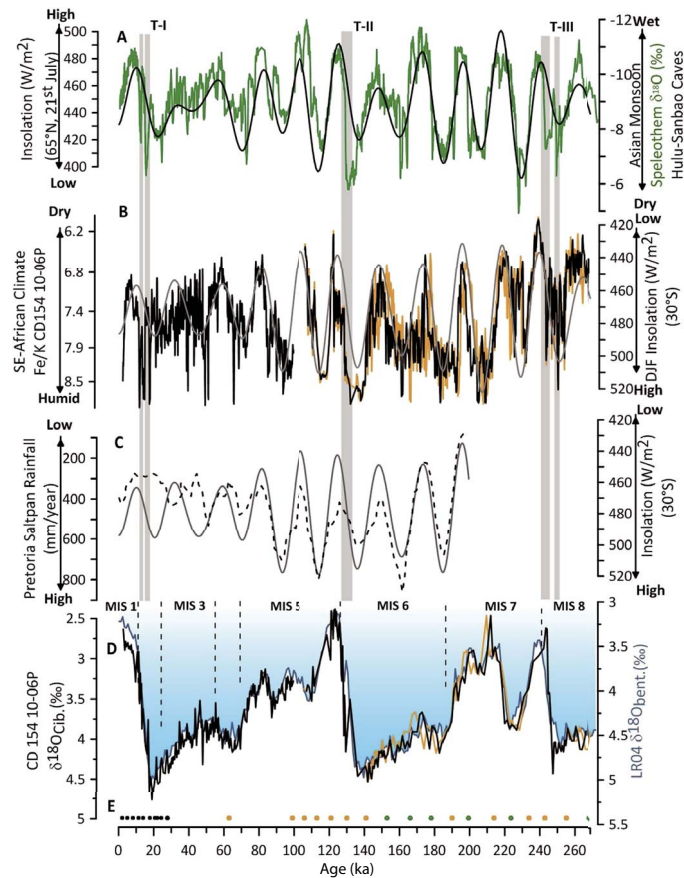


Figure F9. Results of idealized sensitivity precession showing the differences between maximum and minimum precession for DJF from experiments using high-resolution fully coupled ocean atmosphere model EC-Earth from Simon et al. (2015b). Figures were created using the model output and the Ferret program (version 6.82) for Macintosh (<http://www.ferret.noaa.gov/Ferret/>). A. Temperature. B. Precipitation. C. Vertical motion at 500 hPa (roughly 5 km). Negative values indicate upward motion, positive values indicate downward motion. D. Surface runoff over land.

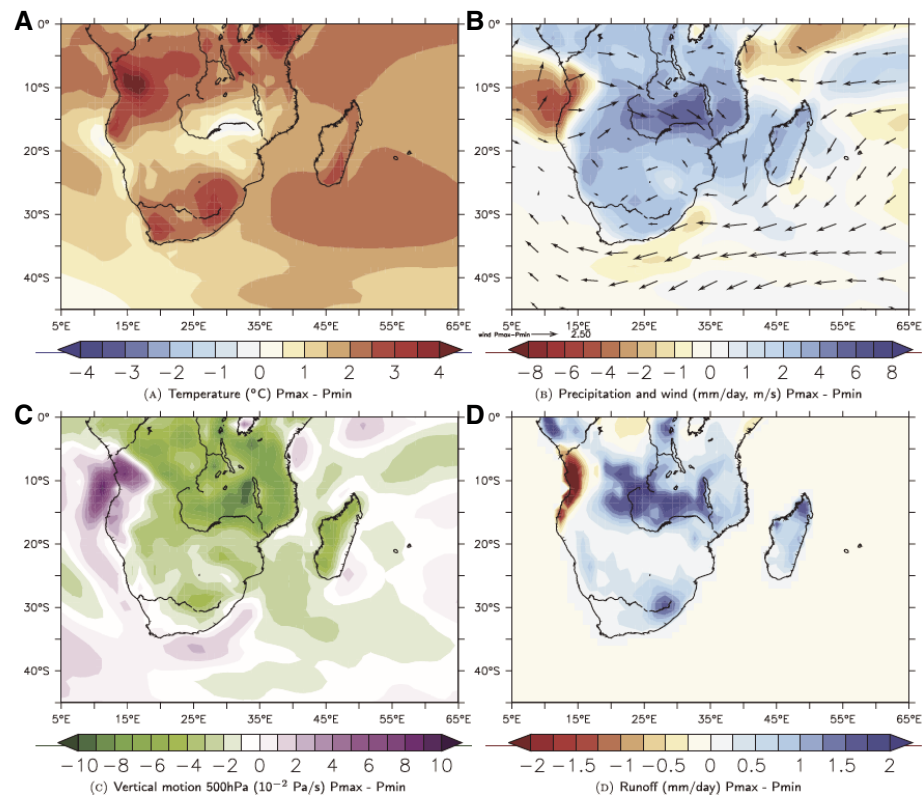


Figure F10. Temperature and salinity plot for the LGM. Based on the type of interstitial water data, this plot shows several differences with modern values. Yellow circles = modern bottom water where the cores for the blue LGM points were collected.

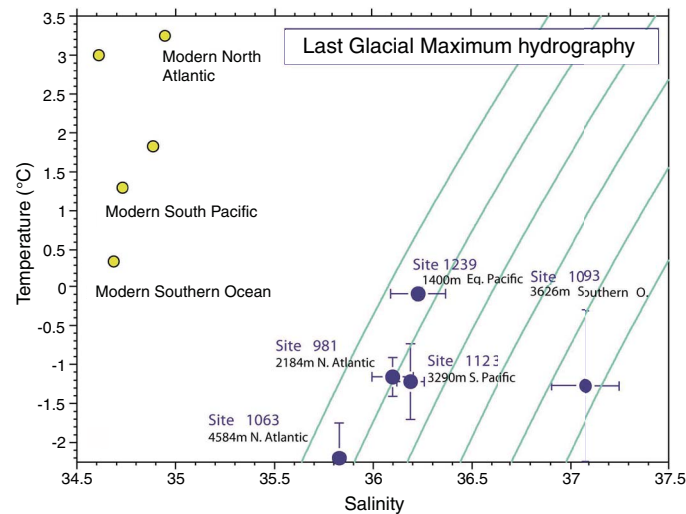




Figure F11. Age-depth relationships, Sites U1474–U1479. A. Time estimates based on a mixture of major planktonic foraminifer, calcareous nannoplankton, diatom, and paleomagnetic datums. B. Implied sedimentation rates.

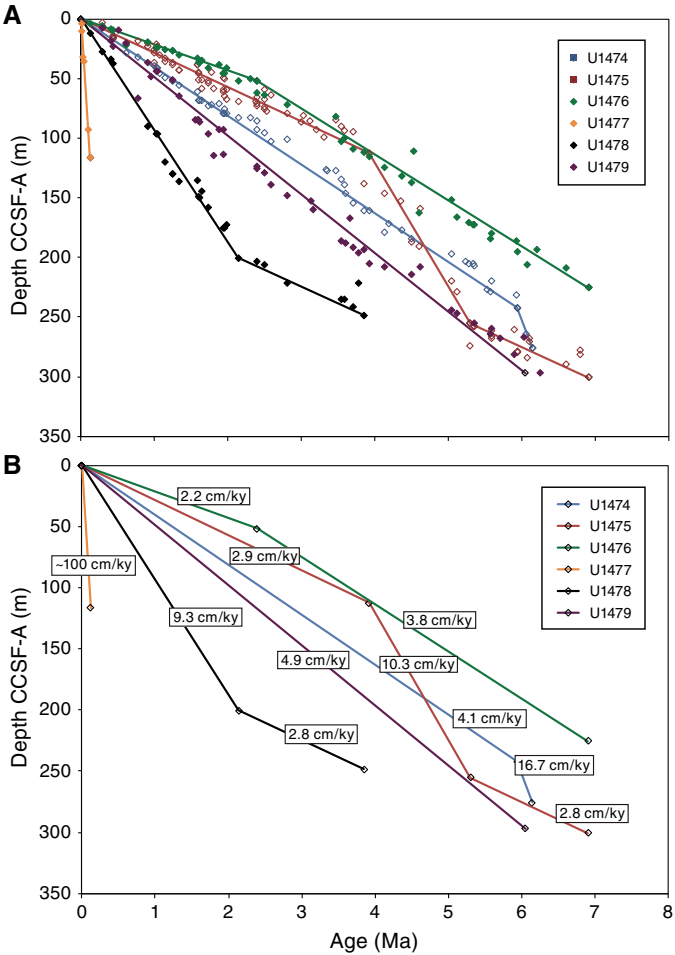


Figure F12. Summary of major lithologic characteristics of sediment cores, Sites U1474–U1479. Sites U1474, U1477, and U1478 are characterized by terrigenous sedimentation with carbonate content between 5 and 37.5 wt%. Sites U1475, U1476, and U1479 are characterized by pelagic sedimentation with carbonate content between 58 and 80 wt%. Sediment color ranges from white-gray (Site U1475) to greenish gray (Sites U1474, U1476, and U1479) and dark gray (Sites U1477 and U1478). Slight to moderate bioturbation occurs at Sites U1476–U1478, whereas strong bioturbation marks the sediment at Sites U1474, U1475, and U1479. Sandy layers (~0.5 cm to ~2 m thick) at Sites U1474, U1478, and U1479 are interpreted as contourite and/or turbidite deposits.

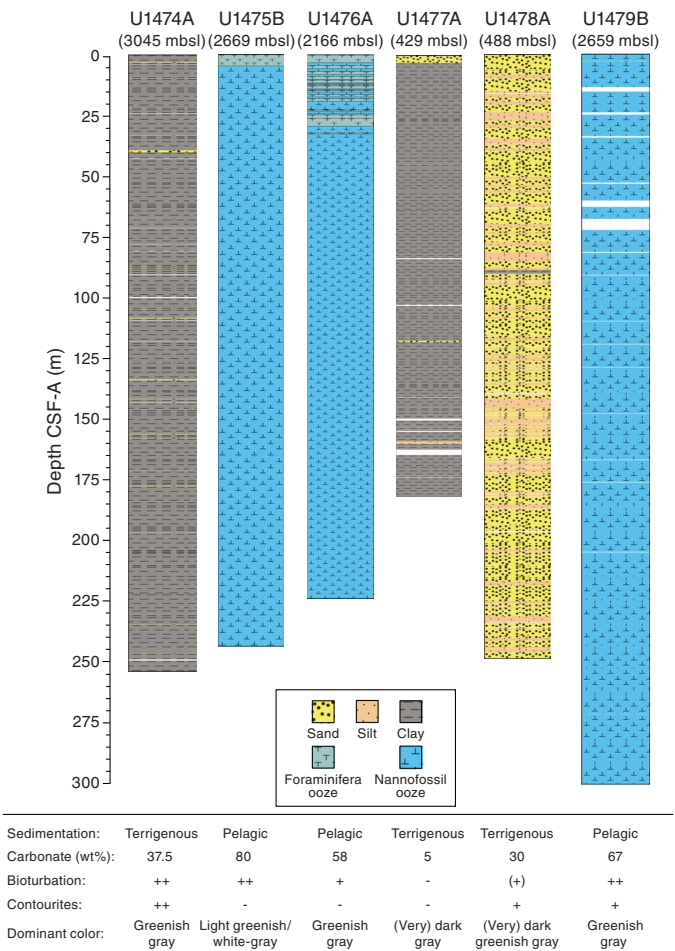


Figure F13. A, B. Summary of major lithologic characteristics based on smear slide observations of sediment cores, Sites U1474–U1479.

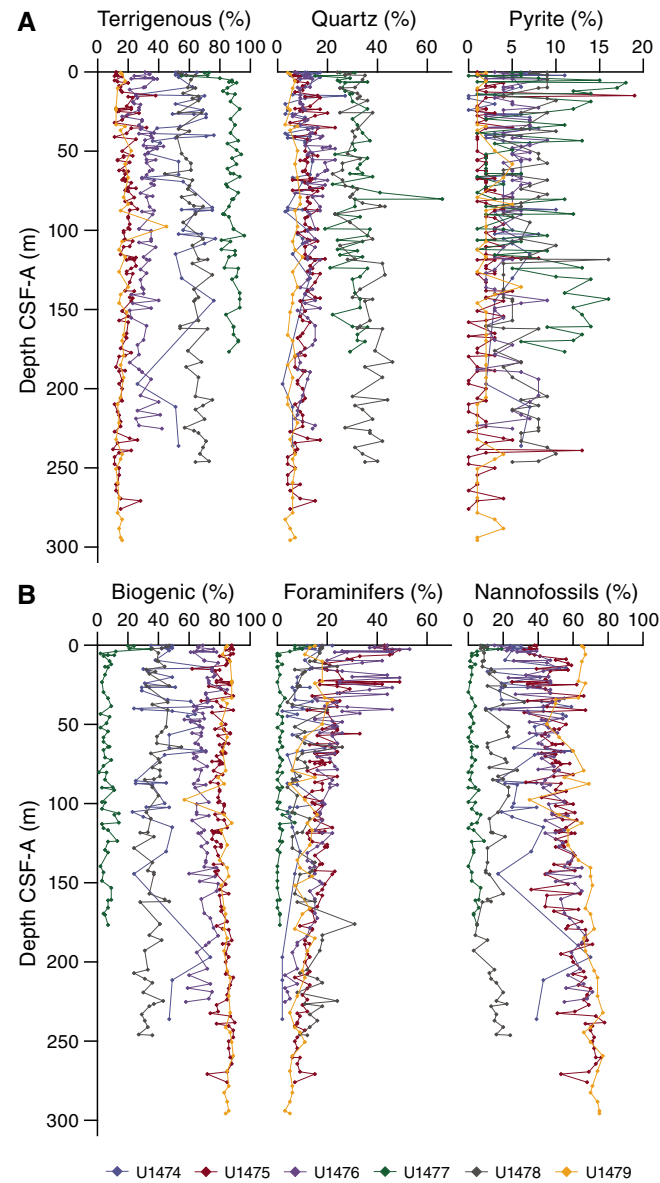


Figure F14. Calcium carbonate and total organic carbon (TOC) profiles, Sites U1474–U1479. TC = total carbon, TIC = total inorganic carbon.

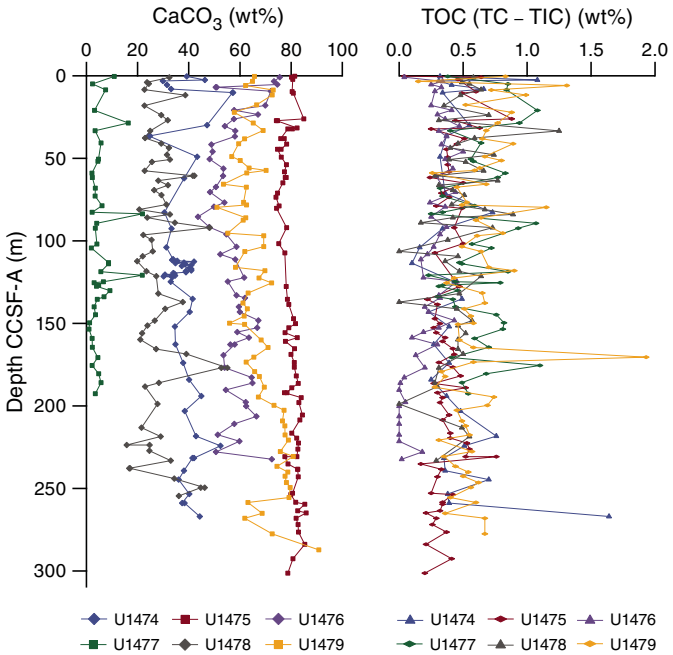


Figure F15. Summary of calcareous nannofossil preservation and reworking at Expedition 361 drill sites for the Pleistocene, Pliocene, and Miocene. Nannofossil preservation score is based on ratings of good, moderate, and poor to illustrate changes in preservation through time. Qualitative percentages of nannofossil group (red) and reworked species (green) abundances are indicated on the right with relative latitudinal and longitudinal coordinates for each site. Missing charts from different time periods are due to the negligible number of reworked species at that site. Site U1477 sequence covers only the Pleistocene; reworked species are sparsely recorded and nannofossil abundance varies throughout the site and increases latitudinally within time intervals. The group abundances for the other sites are high during the three time intervals.

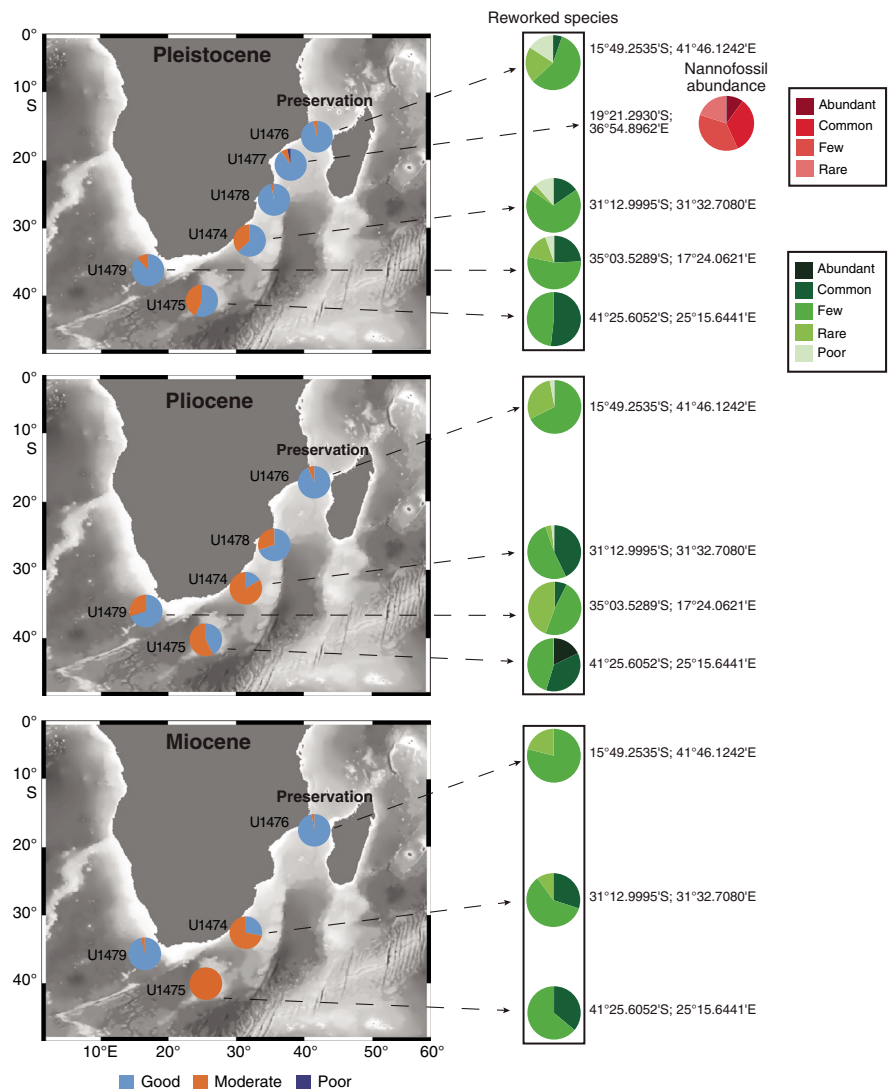


Figure F16. Summary of planktonic foraminifer preservation through time, Sites U1474–U1479. Qualitative preservation ratings were tracked through four time intervals: the Pleistocene, late Pliocene, middle Pliocene, and early Pliocene. Foraminifer preservation score is based on ratings of good, moderate, and poor to illustrate changes in preservation through time.

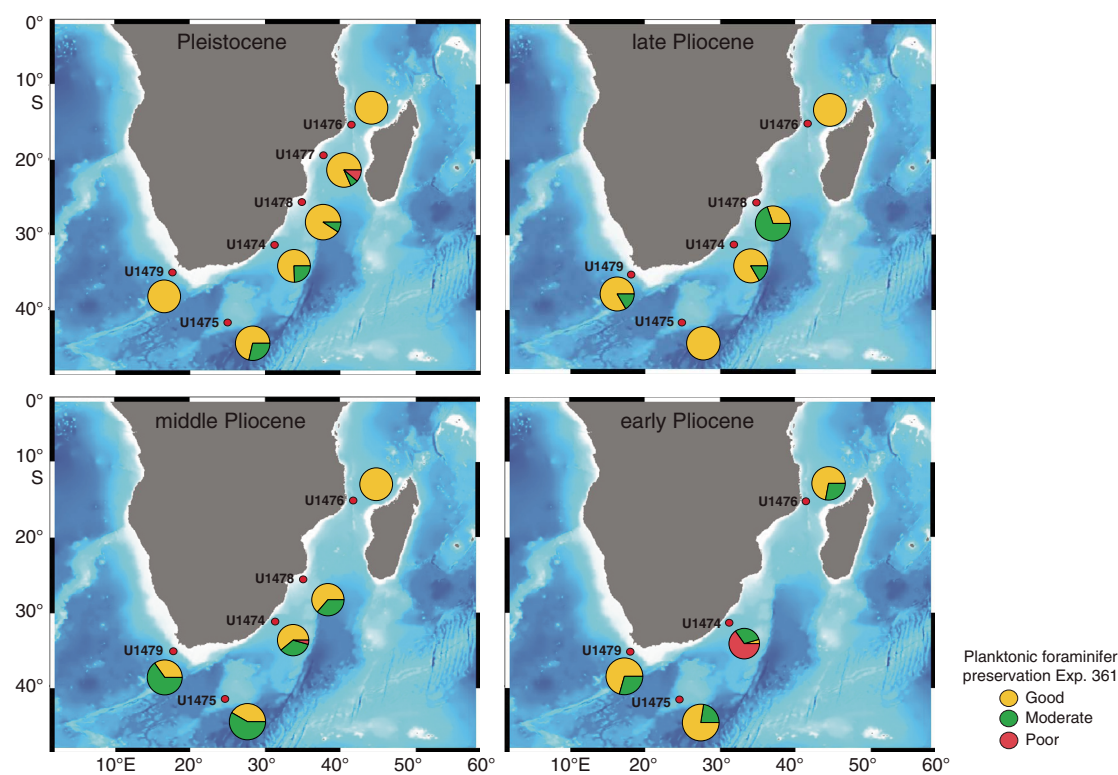




Figure F17. Calcareous nannofossil comparative biostratigraphic chart, Sites U1474–U1479.

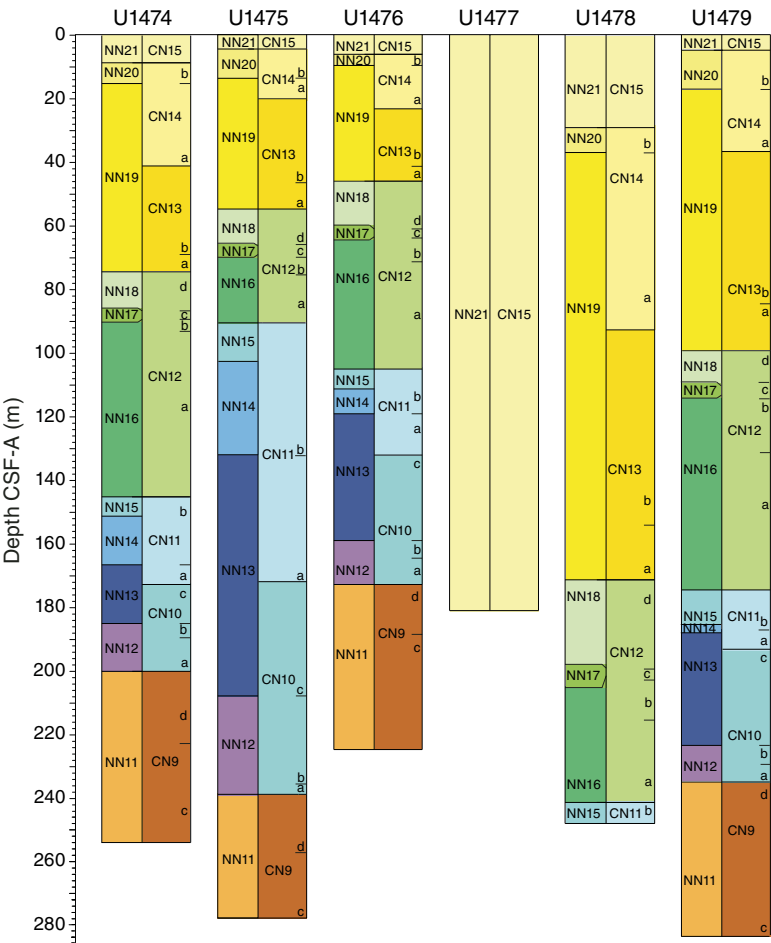


Figure F18. Planktonic foraminifer comparative biostratigraphic chart, Sites U1474–U1479.

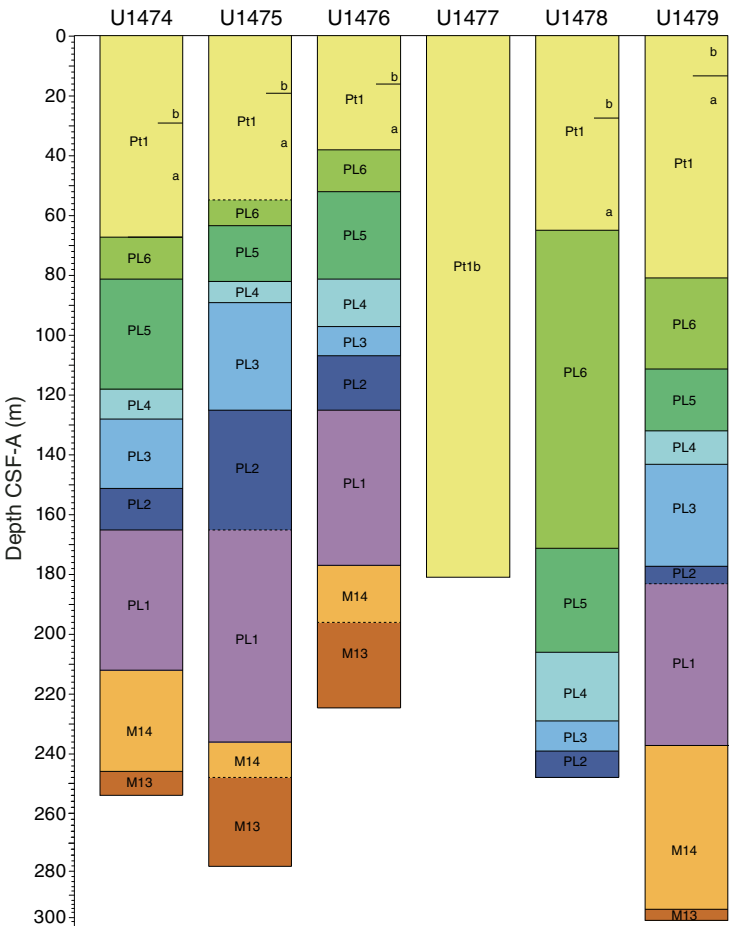


Figure F19. Summary of diatom and other siliceous microfossil groups through time, Sites U1474–U1479. Qualitative estimated percentages were used to track changes in siliceous microfossil assemblage through time spanning the Holocene to the late Miocene.

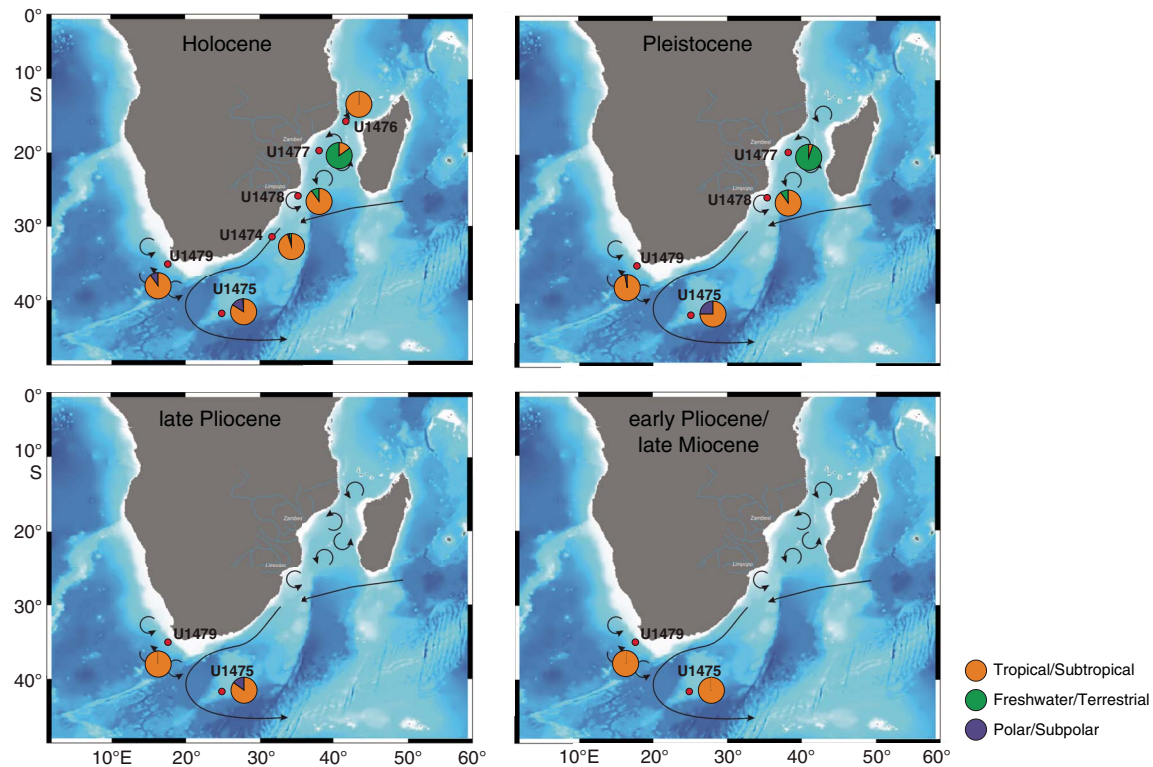


Figure F20. Summary of qualitative estimated percentages of calcareous nannofossil assemblages in sediment recovered from Sites U1474–U1479 spanning the late Miocene to Holocene (mudlines).

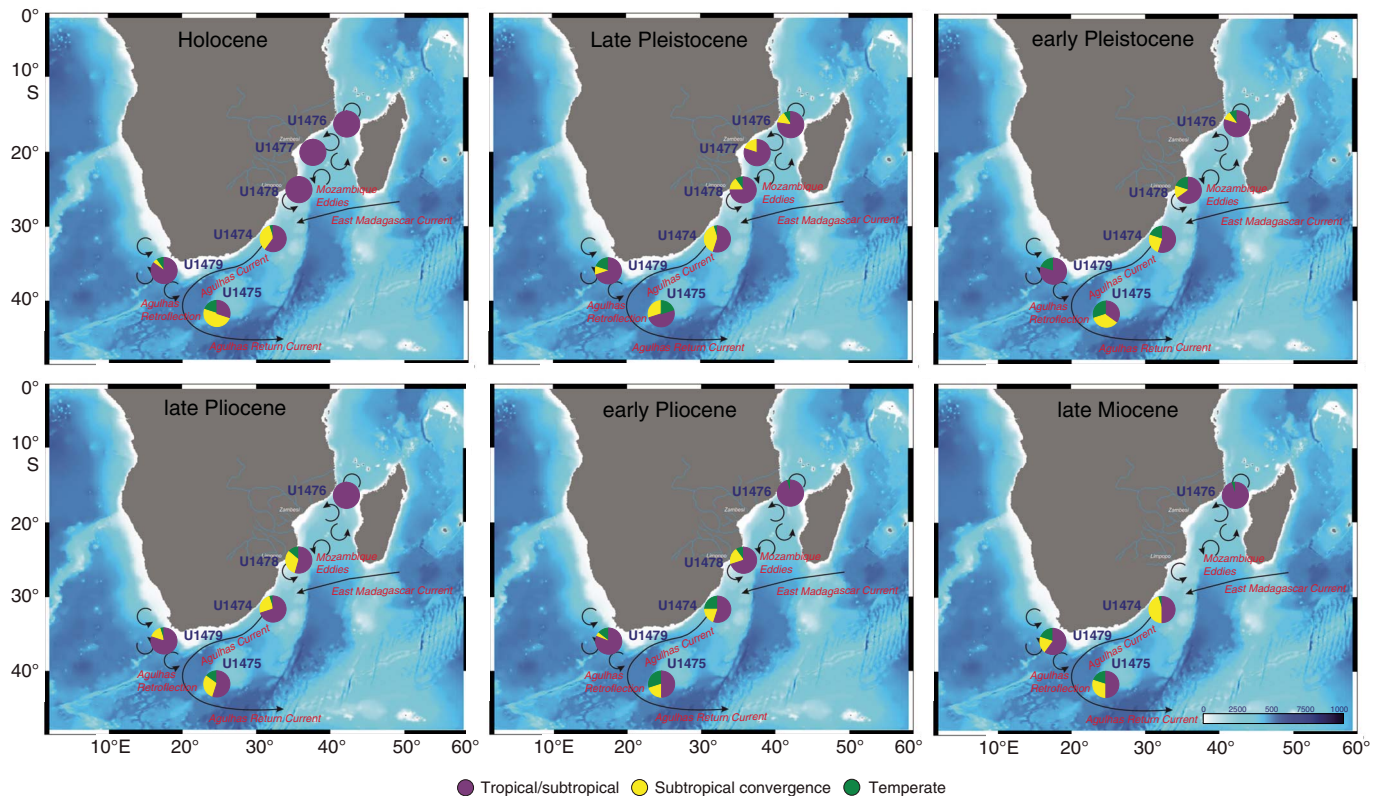


Figure F21. Summary of planktonic foraminifer abundance through time, Sites U1474–U1479.

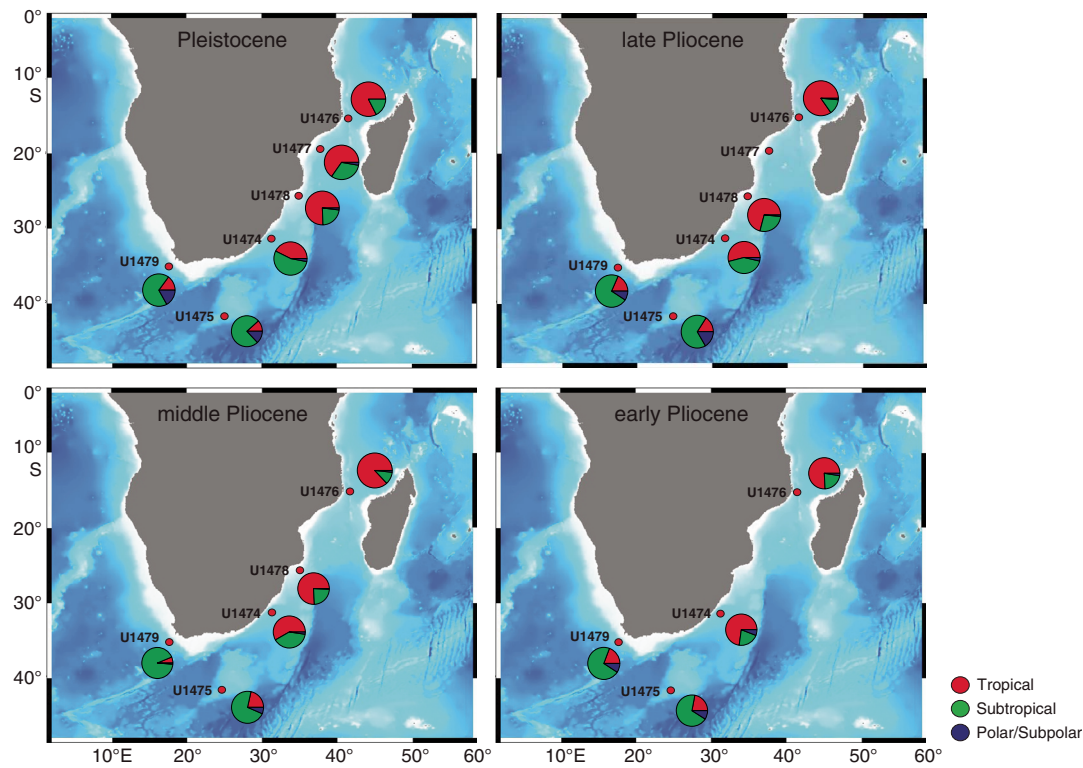


Figure F22. Total organic carbon (TOC) vs. Ba/Al ratio from bulk samples, Sites U1475–U1478.

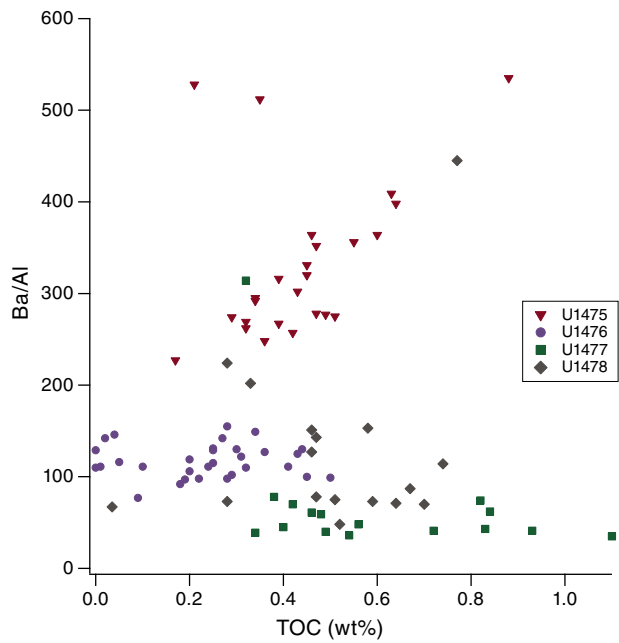




Figure F23. Summary of main shipboard paleomagnetic results (from best paleomagnetic age control [left] to uncertain age-control [right]). Accordingly, the chronologies of Site U1474, U1475, and U1478 are based on linking the normal and reversed paleomagnetic (sub)intervals to those of the paleomagnetic stratigraphy of Gradstein et al. (2012). Chronologies of Sites U1476 and U1478 that yield less straightforward paleomagnetic records were established by utilizing biostratigraphic age-depth tie-points as determined onboard.

