International Ocean Discovery Program Expedition 359 Scientific Prospectus Addendum

Sea Level, Currents, and Monsoon Evolution in the Indian Ocean

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Published by
International Ocean Discovery Program

Publisher's notes

This publication was prepared by the *JOIDES Resolution* Science Operator (JRSO) at Texas A&M University as an account of work performed under the International Ocean Discovery Program (IODP). Funding for the program is provided by the following agencies:

National Science Foundation (NSF), United States

Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan

European Consortium for Ocean Research Drilling (ECORD)

Ministry of Science and Technology (MOST), People's Republic of China

Korea Institute of Geoscience and Mineral Resources (KIGAM)

Australian Research Council (ARC) and GNS Science (New Zealand), Australian/New Zealand Consortium (ANZIC)

Ministry of Earth Sciences (MoES), India

Coordination for Improvement of Higher Education Personnel, Brazil (CAPES)

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Citation:
Betzler, C., Eberli, G.P., and Alvarez Zarikian, C.A., 2015. Sea level, currents, and monsoon evolution in the Indian Ocean. *International Ocean Discovery Program Scientific Prospectus Addendum,* 359. http://dx.doi.org/10.14379/iodp.sp.359add.2015

ISSN

World Wide Web: 2332-1385

April 2015

Introduction

This addendum to the Expedition 359 *Scientific Prospectus* (Betzler et al., 2014) addresses a modification to the scientific objectives and operations plan of the expedition. After consultation with and direction from the U.S. National Science Foundation (NSF), the Ancillary Proposal 849-APL will not be implemented as part of Expedition 359, and consequently the proposed sites (KK-03A and KK-03B) originally planned for scientific drilling in the Kerala-Konkan Basin have been dropped from the operations plan. Two new sites are proposed and described in this addendum, and a revised operations strategy and time estimates for seven primary sites in the Maldives archipelago are presented (Fig. **F1**). Also detailed in this addendum is an extension to the total penetration depth at primary proposed Site MAL-02A from 560 to 1010 meters below seafloor (mbsf). All other details contained within the original *Scientific Prospectus* published by the International Ocean Discovery Program in November 2014 (Betzler et al., 2014) remain the same. A summary of the primary sites targeted for Expedition 359 is shown in Table **T1.** The operations strategy and time estimates for the primary sites are presented in Table **T2.**

Scientific objectives

Proposed Site MAL-02A (primary site)

Proposed Site MAL-02A is located at 4.933156°N, 73.027983°E, approximately 1 nmi east of proposed Site MAL-01A in the western part of Kardiva Channel at a water depth of 516 m (Figs. **F1, F2**). The sediment is periplatform ooze. The seafloor is an overall flat surface covered by 400 m wide and 4 m high submarine mud waves. The site is selected just basinward of the first onlap of the oldest drift deposits (DS-01) onto the toe of slope of the drowned bank (top Platform Sequence 10) (Fig. **F3**). Here, DS-01 reaches its greatest thickness. Therefore, this site is expected to record a most complete predrowning–drowning–postdrowning succession, allowing reconstruction of environmental changes at this turnover.

The site is positioned to recover the sedimentary succession deposited during the late-stage evolution of the middle Miocene drowned carbonate bank and the onset of drift deposition. The specific objectives at this site are

1. To provide a detailed reconstruction of the predrowning, drowning, and postdrowning evolution of the carbonate bank by linking the seismic stratigraphic record to the sedimentary record;
2. To constrain the timing of this evolution, thus allowing age assignments of unconformities, sedimentary interruptions, sedimentary turnovers, and onset of drift deposition; and
3. To reconstruct and date the bank to drift turnover.

Deepening proposed Site MAL-02A will allow recovery of the Oligocene/Miocene boundary, which is calculated to be at 978 mbsf. The expected nature of the succession down to this boundary is chalk. An additional 30 m should be drilled for the logging rathole. The succession is characterized by a downhole increase in lithification from ooze at the top to chalk at the base (Fig. **F4**). A deeper penetration depth at proposed Site MAL-02A (to 1010 mbsf) would also help to ensure good logging results from the lower slope deposits of the drowned carbonate platform (PS-01 to PS-10). This is important, as the ooze, chalk, and limestone alternation at proposed Site MAL-01A could possibly create problems with regard to hole quality.

Proposed Site MAL-08A (new alternate site)

Proposed Site MAL-08A is located at 4.90693350°N, 73.00819003°E, in the westernmost part of the northern transect. It is located at the western margin of the Inner Sea in the western part of Kardiva Channel at a water depth of 432 m (Fig. **F2**). Inner Sea sediments are hemipelagic carbonate ooze consisting of an admixture of components exported from the atolls and pelagic components (periplatform ooze). The seafloor is an overall flat surface covered by 400 m wide and 4 m high submarine mud waves. The site is located at a key position to document and reconstruct the carbonate bank depositional system of the drowned Miocene bank and to link the seismic sequences to facies; here, a drowning unconformity does not mask underlying geometries, which is rare (Figs. **F5, F6**).

Proposed Site MAL-08A is positioned to recover the sedimentary succession deposited during the late-stage evolution of the drowned middle Miocene bank and to characterize the onset of drift sedimentation. The specific objectives are

1. To provide a detailed reconstruction of the predrowning, drowning, and postdrowning evolution of the carbonate bank by linking the seismic stratigraphic record to the sedimentary record (i.e., depositional facies);

2. To constrain the timing of this evolution, thus allowing age assignments of unconformities, sedimentary interruptions, sedimentary turnovers, and onset of drift deposition; and
3. To reconstruct and date the bank to drift turnover.

The target horizon at proposed Site MAL-08A is the Oligocene/Miocene boundary, which lies at the proposed depth of penetration of 1100 mbsf, including a rathole for logging. The upper part of the succession is characterized by carbonate ooze overlying the drowning unconformity. The nature of the unconformity is unclear. No strong lithification is expected, as impedance contrast is not very high and no acoustic blanking occurs below the unconformity (Fig. **F7**). The Platform Sequences 09 and 10, delimited by Sequence Boundaries (SB) 09 and 10, are expected to consist of chalk to limestone (proximal carbonate bank slope deposits). Downhole lithification is first expected to decrease because more distal slope deposits will be drilled. These deposits have lower aragonite contents because the source of neritic input was located further west. Therefore, the diagenetic potential of this sediment is reduced compared to the overlying, more proximal slope deposits. Degree of lithification toward the base of the succession is finally expected to increase, and limestone to chalk lithologies are expected in the lower interval of the site.

Results of existing nearby drilling sites

The sedimentary succession at nearby Ocean Drilling Program (ODP) Site 716 mostly consists of carbonate ooze composed of planktonic foraminifers, bioclasts, pteropods, and minor amounts of benthic foraminifers, changing downhole into ooze to chalk. It shows distinct changes of the amount of fine-grained (<63 µm) material (Fig. **F8**). Data for the fine fraction content of Site 716 is combined from different sources. To 65.05 mbsf, the core was newly sampled and the grain-size parameter measured at a 10 cm interval. Analysis of the interval between 32.29 and 27.63 mbsf has been done on data from Hole 716A. Between 264.4 and 147.4 mbsf, the fine fraction amount varies between 48% and 97% with an overall upcore decrease. In this interval, a trend of overall increase of grain size is superimposed on fluctuations of around 5% in the lower part and 40% in the upper part. Between 147.4 mbsf and the seafloor, several sediment packages occur, characterized by systematic trends of changes in the amount of fine fraction. The lower package is between 147.4 and 87.0 mbsf. At 28.73 mbsf, the amount of the fine fraction increases to 10.5 mbsf. The remaining interval is characterized by three coarsening-upward packages.

Proposed Site MAL-09A (new primary site)

Proposed Site MAL-09A lies east of the northern and southern transect. It is located to recover the entire drift succession (DS01–DS09). This site was selected to replace previous primary Site MAL-04B (Betzler et al., 2014), which is believed to have a mass flow intercalated into the succession at a depth of 720 ms between 63250 and 69000, based on analysis of a new parasound line recovered crossing the site. The specific objectives for the new primary site are

1. To analyze cyclostratigraphy of drift deposits, therefore providing reconstructions of changes in the current regime and monsoon cyclicity; and
2. To constrain the timing of unconformities and sedimentary interruptions.

Proposed Site MAL-09A is located at 4.85025773°N, 73.28367339°E, approximately 9.1 km south of Site 716/proposed Site MAL-04B in the Inner Sea part of Kardiva Channel (Figs. **F1, F9**) in a water depth of 488 m. Proposed penetration is 714 mbsf. The sediment is periplatform ooze. The seafloor is flat overall. The site is located to recover a complete distal succession of DS-01 to DS-09 (Figs. **F10, F11**). It is located near the deepest and oldest gateway of the Maldives, the northeastern Kardiva Channel. This will allow us to characterize the onset of the current-controlled depositional regime and to date the reorganizations of the system indicated by the occurrence of SBs DS-02–DS09.

The target horizon at proposed Site MAL-09A is the basal SB of PS-09, which was formed during the middle Miocene. The model for subsurface velocity variations is shown in Figure **F12** and shows that the proposed depth of PS-09 is 663 mbsf. An additional 50 m should be drilled for the logging rathole, resulting in a total depth of penetration of 713 mbsf. The succession is characterized by a downhole increase in lithification from ooze at the top to chalk at the base.

Results of existing nearby drilling sites

The carbonate ooze succession drilled at Site 716 is presented in Figure **F8.**

Operations plan/drilling strategy

The coring and drilling program for Expedition 359 targets seven primary and two alternate sites located in waters of the Republic of the Maldives. The planned sequence of drill sites, coring/downhole measurements, and time estimates is provided in Table

T2. The final operations plan and number of sites to be cored is contingent upon changes to the R/V *JOIDES Resolution* operations schedule, operational risks, and the outcome of a request for permission to occupy these sites. The current planned operations schedule also includes two half-day moorings for required ship clearance and immigration formalities, one at the arrival to and one at the exit from the Maldives.

For operational efficiency, the proposed sites will be occupied in the following sequence: MAL-07A, MAL-06B, MAL-05A, MAL-01A, MAL-02A, MAL-03A, and MAL-09A. The coring strategy will consist of triple advanced piston corer (APC) coring using nonmagnetic core barrels to ~200 mbsf or APC refusal at proposed Sites MAL-07A, MAL-06B, and MAL-03A. Coring using the extended core barrel (XCB) system will be used to advance the holes to total depths at proposed Sites MAL-07A (642 mbsf), MAL-06B (604 mbsf), MAL-03A (435 mbsf), MAL-02A (325 mbsf), and MAL-09A (554 mbsf). Coring with the rotary core barrel (RCB) system will be used to advance to total depth at proposed Sites MAL-05A (420 mbsf), MAL-01A (1060 mbsf), and MAL-02A (1010 mbsf). Multiple holes at selected sites will allow us to build a composite section at each site.

Coring operations at proposed Sites MAL-08A and MAL-09A and the extended penetration depth at proposed Site MAL-02A are pending EPSP approval.

All APC sections will be cored using nonmagnetic core barrels. Only cores in Hole A at each site will be oriented. The half-length (4.7 m) APC coring system will be employed to maximize APC penetration where desirable. For planning purposes, the APC refusal depth for most sites is estimated at 200 mbsf, although we anticipate that this may be exceeded at some of the more carbonate mud–rich sites, especially when using the half-length APC system.

All sites will be wireline logged using standard logging tool strings: triple combination (triple combo) and Formation MicroScanner (FMS)-sonic. Three proposed sites (MAL-07A, MAL-01A, and MAL-09A) also will be logged with the Versatile Seismic Imager (VSI).

References

Betzler, C., Eberli, G.P., Giosan, L., and Alvarez Zarikian, C.A., 2014. Sea level, currents, and monsoon evolution in the Indian Ocean. *International Ocean Discovery Program Scientific Prospectus,* 359. **http://dx.doi.org/10.14379/iodp.sp.359.2014**

Lüdmann, T., Kalvelage, C., Betzler, C., Fürstenau, J., and Hübscher, C., 2013. The Maldives, a giant isolated carbonate platform dominated by bottom currents. *Marine and Petroleum Geology*, 43:326–340. **http://dx.doi.org/10.1016/j.marpetgeo.2013.01.004**

Table T1. Proposed sites, Expedition 359.

Proposed sites	Location	Water depth (mbsf)	Penetration (mbsf)
MAL-01A	4°55.9865′N, 73°0.6792′E	512	1060
MAL-02A	4°55.9894′N, 73°.6790′E	483	1010*
MAL-03A	4°55.9838′N, 73°4.2783′E	520	532
MAL-04B	4°55.7664′N, 73°17.2066′E	536	590
MAL-05A	4°45.9833′N, 72°59.0333′E	380	420
MAL-06B	4°46.2658′N, 73°4.0109′E	379	604
MAL-07A	4°45.9833′N, 73°8.1366′E	419	710
MAL-08A*	4°54.4160′N, 73°0.4914′E	432	1100*
MAL-09A*	4°51.0155′N, 73°17.0204′E	488	714*

* = pending EPSP approval. MAL-08A and MAL-09A are new proposed sites that are not in the Expedition 359 *Scientific Prospectus* (Betzler et al., 2014). MAL-04B and MAL-08A are proposed alternate sites.

Table T2. Operations plan and time estimates for Expedition 359.

Site	Location (Latitude, longitude)	Seafloor depth (mbrf)	Operations description	Transit (days)	Drilling/ coring (days)	Wireline log (days)
Darwin, Australia			Begin Expedition 5.0	Port Call Days		
			Transit ~3568 nmi from Darwin to Male @ 10.5 knots	14.0		
Male, Maldives			Clear into Maldives 0.5	Port Call Days		
			Transit ~49 nmi from Male to Site MAL-07A @ 10.5 knots	0.2		
MAL-07A	4°45.9833'N	430	Hole A: APC to 200 mbsf		1.0	
EPSP-710 mbsf	73°8.1366'E		Hole B: APC to 200 mbsf		0.6	
(DRIFT SITE)			Hole C: APC to 200 mbsf; XCB to 642 mbsf & wireline log (WL)		2.8	1.4
			(WL with triple combo, FMS-sonic, & VSI)			
			(also includes 6 h of MDHDS/ERS testing)			
			Subtotal Days On-Site: 5.8			
			Transit ~4 nmi from Site MAL-07A to Site MAL-06B @ 10.5 knots	0.1		
MAL-06B	4°46.2658'N	390	Hole A: APC to 200 mbsf		0.7	
EPSP-604 mbsf	73°4.0109'E		Hole B: APC to 200 mbsf		0.4	
(DRIFT SITE)			Hole C: APC to 200 mbsf; XCB to 604 mbsf & wireline log		2.1	1.0
			(WL with triple combo & FMS-sonic)			
			Subtotal Days On-Site: 4.2			
			Transit ~5 nmi from Site MAL-06B to Site MAL-05A @ 10.5 knots	0.1		
MAL-05A	4°45.9833'N	391	Hole A: APC/XCB to 170 mbsf		0.7	
EPSP-420 mbsf	72°59.0333'E		Hole B: Drill; RCB to 420 mbsf & wireline log		1.9	0.9
			(WL with triple combo & FMS-sonic)			
			Subtotal Days On-Site: 3.5			
			Transit ~10 nmi from Site MAL-05A to Site MAL-01A @ 10.5 knots	0.1		
MAL-01A	4°55.9865'N	523	Hole A: APC to 80 mbsf		0.5	
EPSP-1060 mbsf	73°0.6792'E		Hole B: Drill down to 80 mbsf and RCB to 1060 mbsf & wireline log		6.7	1.9
			(WL with triple combo, FMS-sonic, & VSI)			
			Subtotal Days On-Site: 9.1			
			Transit ~1 nmi from Site MAL-01A to Site MAL-02A @ 0.5 knots	0.1		
MAL-02A	4°55.9894'N	494	Hole A: APC to 200 mbsf; XCB to 325 mbsf		**1.4**	
EPSP-560 mbsf	73°1.6790'E		Hole B: Drill to 320 mbsf; RCB to 1010 mbsf & wireline log			
			(WL with triple combo & FMS-sonic)		**5.6**	**1.3**
			Subtotal Days On-Site: 8.3			
			Transit ~3 nmi from Site MAL-02A to Site MAL-03A @ 10.5 knots	0.1		
MAL-03A	4°55.9838'N	531	Hole A: APC to 200 mbsf		0.8	
EPSP-532 mbsf	73°4.2783'E		Hole B: APC to 200 mbsf		0.5	
(DRIFT SITE)			Hole C: APC to 200 mbsf; XCB to 435 mbsf & wireline log		1.9	0.9
			(WL with triple combo & FMS-sonic)			
			(also includes MDHDS/ERS testing)			
			Subtotal Days On-Site: 4.1			
			Transit ~13 nmi from Site MAL-03A to Site MAL-04B @ 10.5 knots	0.2		
MAL-09A	4°51.0155'N	499	Hole A: Drill/wash to 170 mbsf (already cored at ODP Site 716)		3.1	1.1
EPSP Depth TBD	73°17.0204'E		APC/XCB to 714 mbsf & wireline log			
			(with triple combo, FMS-sonic, & VSI)			
			Subtotal Days On-Site: 4.2			
			Transit ~57 nmi from Site MAL-04B to Male @ 10.5 knots	0.2		
Male, Maldives			Clear out of Maldives 0.5	Port Call Days		
			Transit ~414 nmi from Male to Colombo @ 10.5 knots	1.6		
Colombo, Sri Lanka			End Expedition	**16.7**	**30.7**	**8.5**

Port Call:	**6.0**	**Total Operating Days:**	**55.9**
Subtotal On-Site:	**39.2**	**Total Expedition:**	**61.9**

Seafloor depth corrected to rig floor dual elevator stool or meters below rig floor (mbrf). MDHS/ERS = motion decoupled hydraulic delivery system/Electrical Release System.

Figure F1. Locations of Expedition 359 sites in the Maldives archipelago.

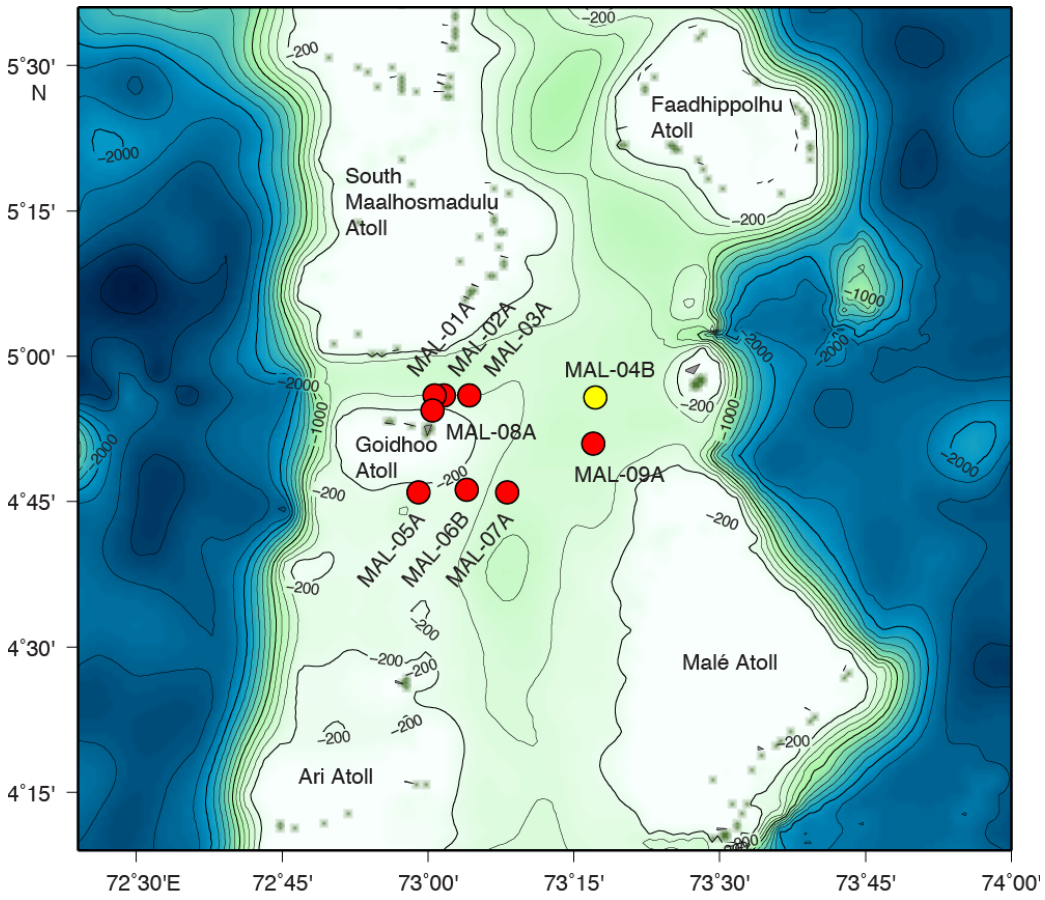


Figure F2. Locations of proposed Sites MAL-02A and MAL-08A.

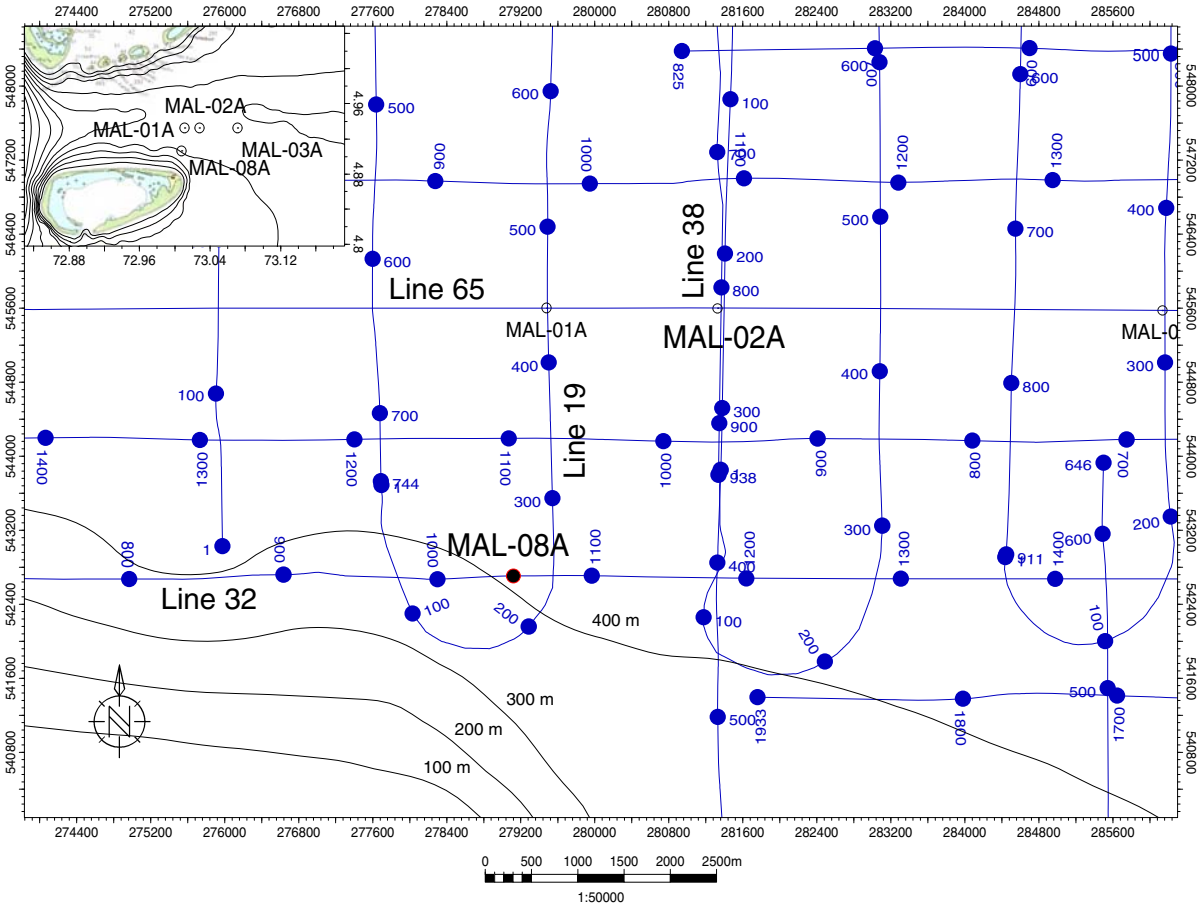


Figure F3. Interpreted Line 65 with proposed Site MAL-02A. PS = sequence boundaries defined in the carbonate bank, DS = drift sequence boundaries.

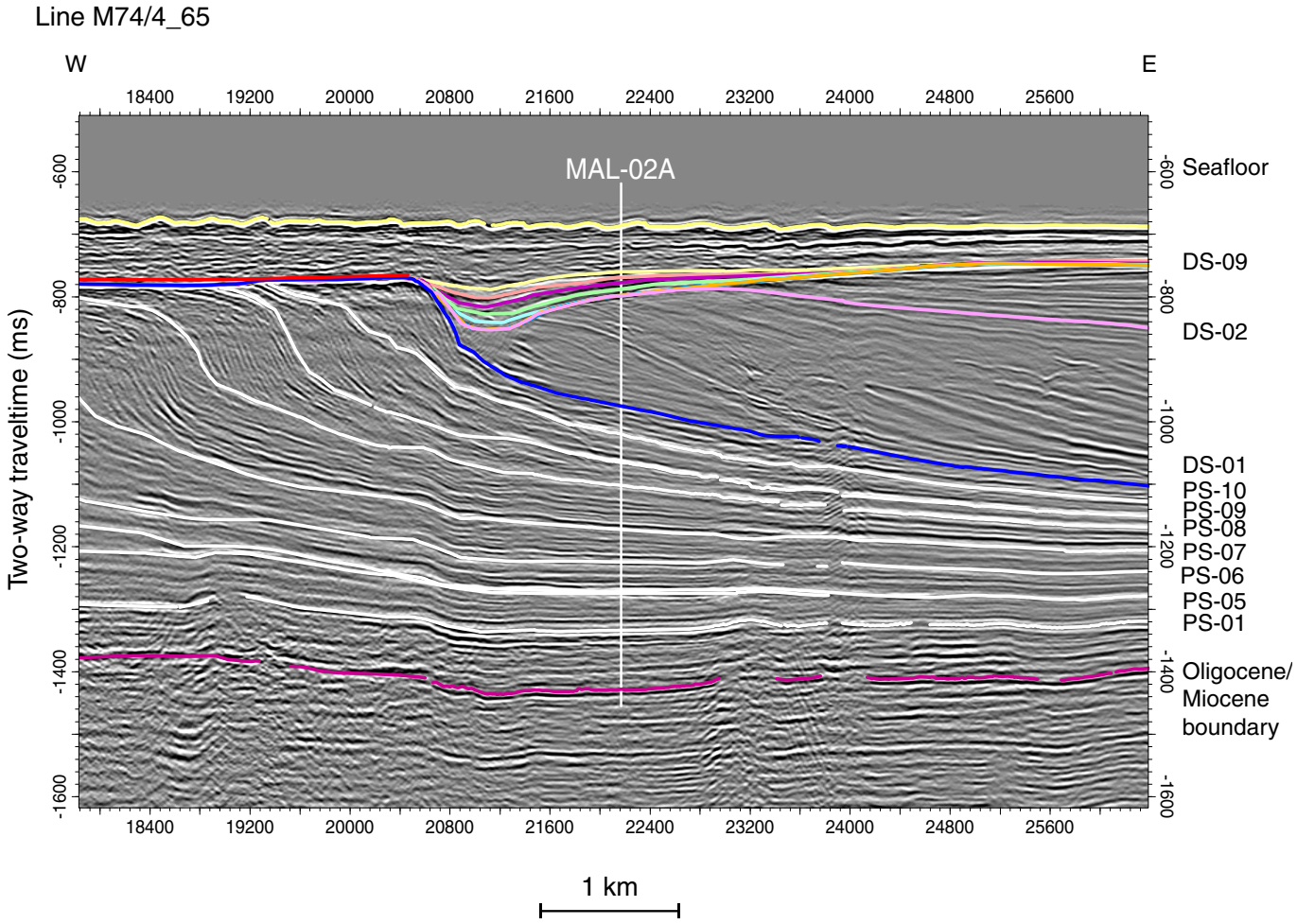


Figure F4. Estimated lithologic column at extended proposed Site MAL-02A with velocity model and corresponding seismic profile with seismic sequence boundaries. PS = sequence boundaries defined in the carbonate bank, DS = drift sequence boundaries.

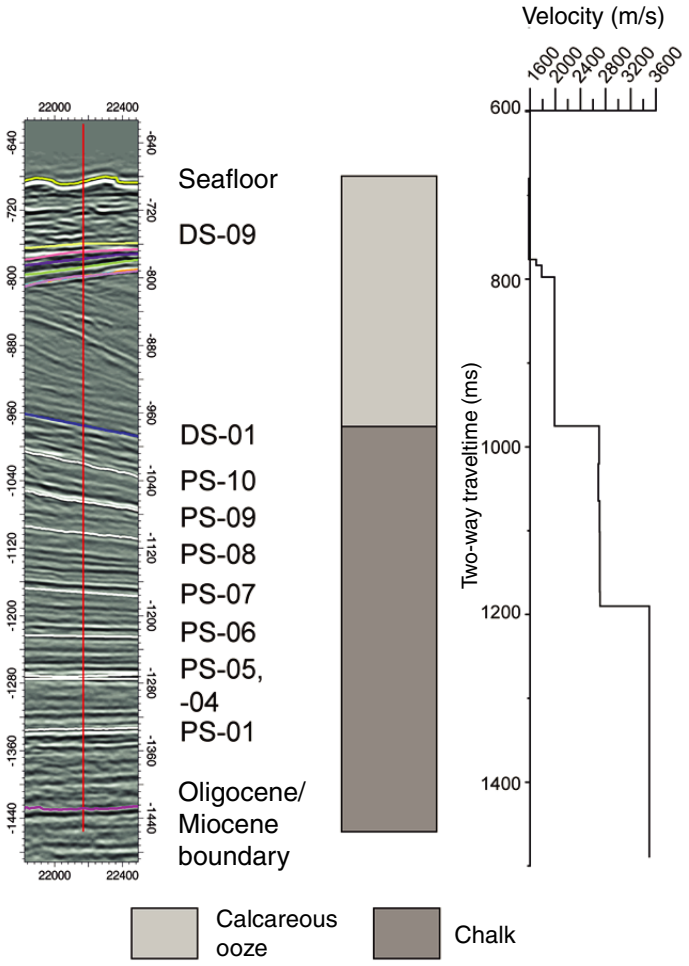


Figure F5. Seismic Line SO236_32 with position of proposed Site MAL-08A and interpretation of sequence boundaries. PS = sequence boundaries defined in the carbonate bank, DS = drift sequence boundaries. Arrow = position of crossing Line 19 (shown in Fig. **F6**).

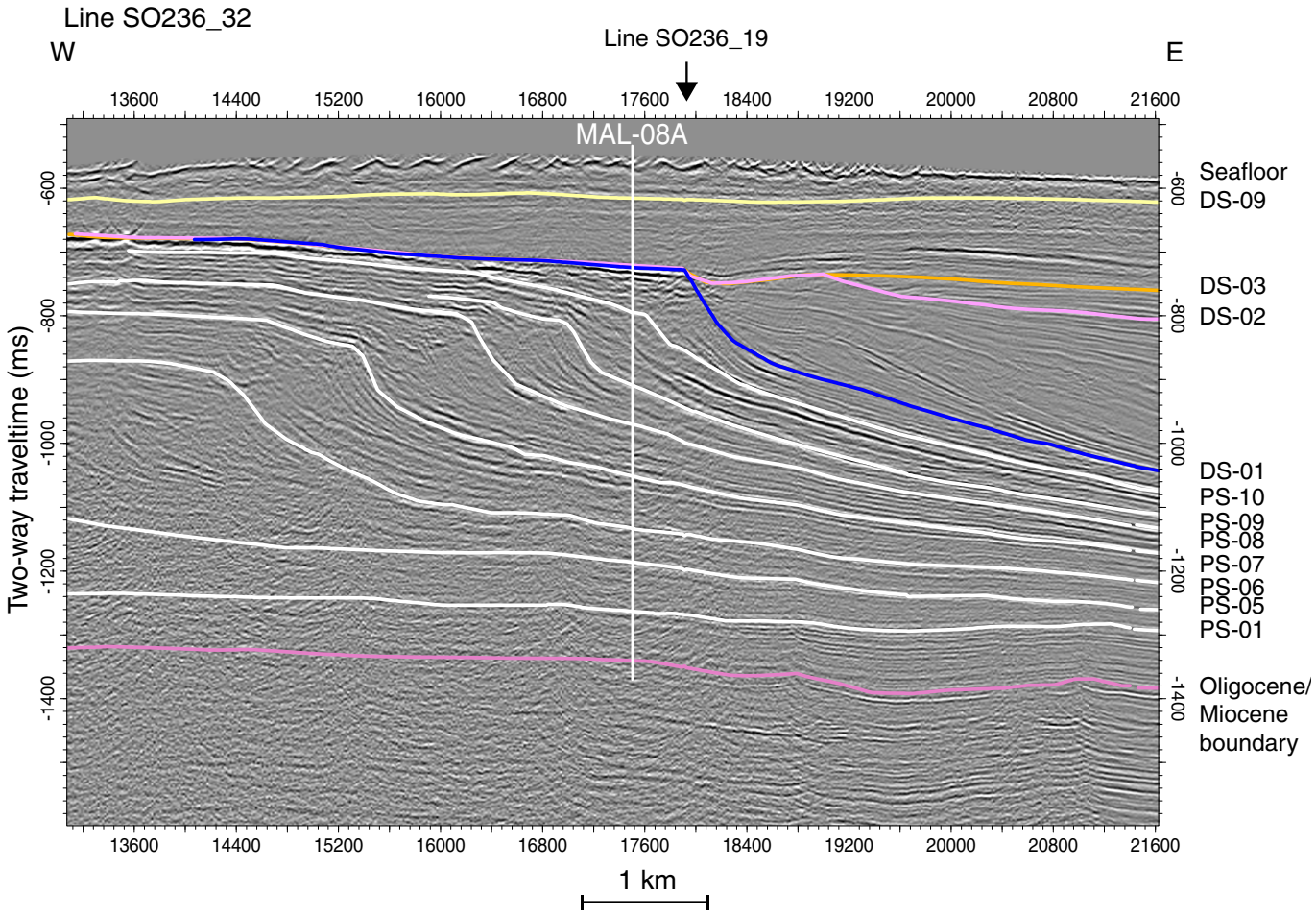


Figure F6. Seismic Line SO236_19 with position of proposed Site MAL-08A and interpretation of sequence boundaries. PS = names of sequence boundaries defined in the carbonate bank, DS = drift sequence boundaries.

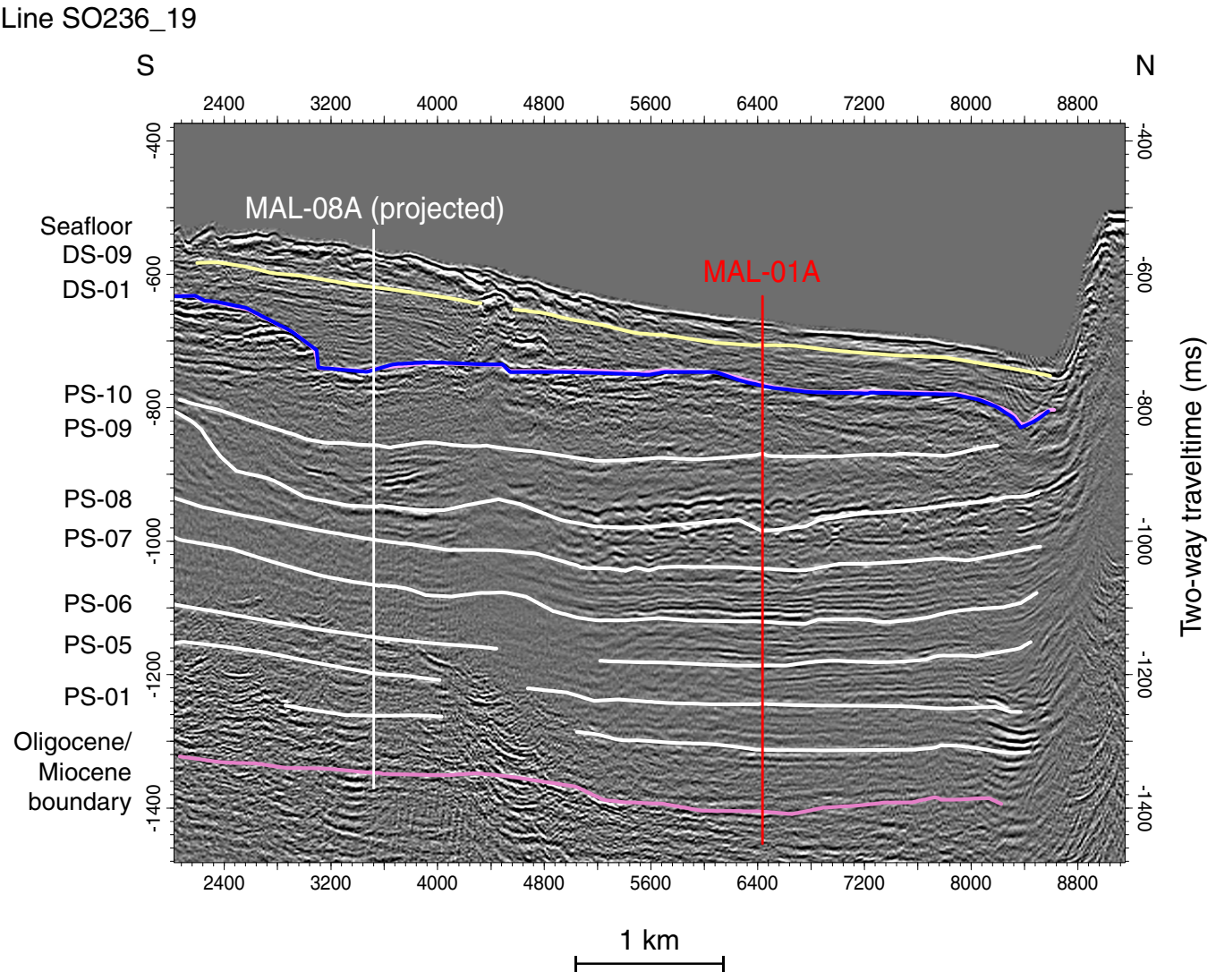


Figure F7. Estimated lithologic column at proposed Site MAL-09A with velocity model and corresponding seismic profile with seismic sequence boundaries. PS = sequence boundaries defined in the carbonate bank, DS = drift sequence boundaries.

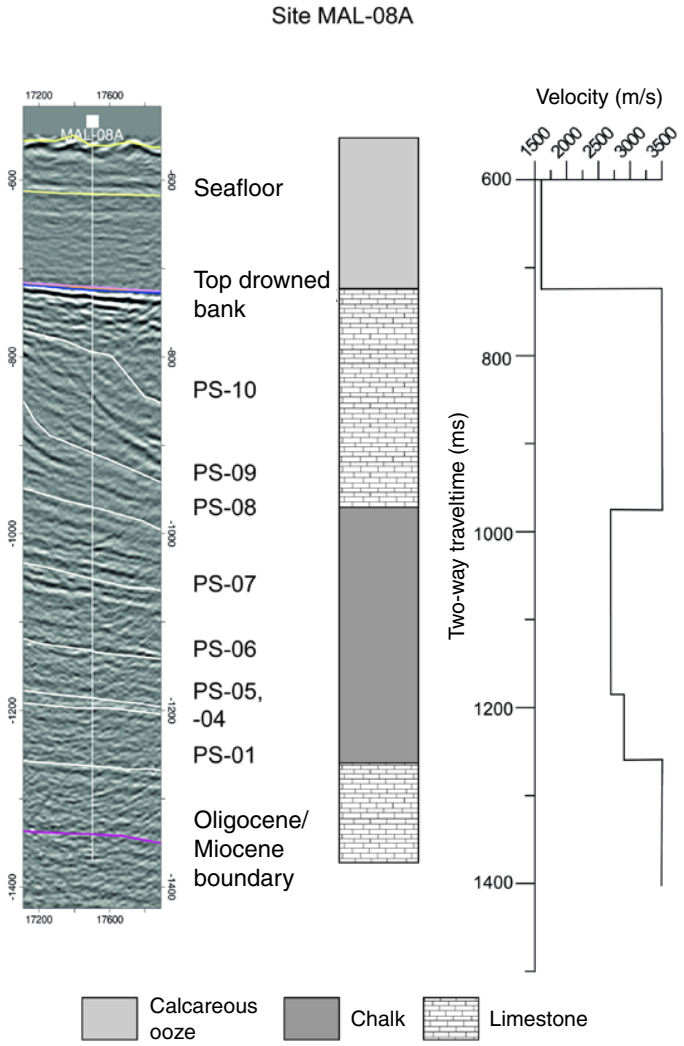


Figure F8. A. West–east running section through Inner Sea with ODP Site 716 and changes in the amount of the fine fraction < 63 µm. Color scheme for fine fraction contents: dark blue = 0%–10%, light blue = 10%–30%, green = 30%–50%, yellow = 50%–70%, orange = 70%–80%, red = 80%–100%. SP = shotpoint. **B.** Post–late middle Miocene mega Units 1 to 9 as proposed by Lüdmann et al. (2013).

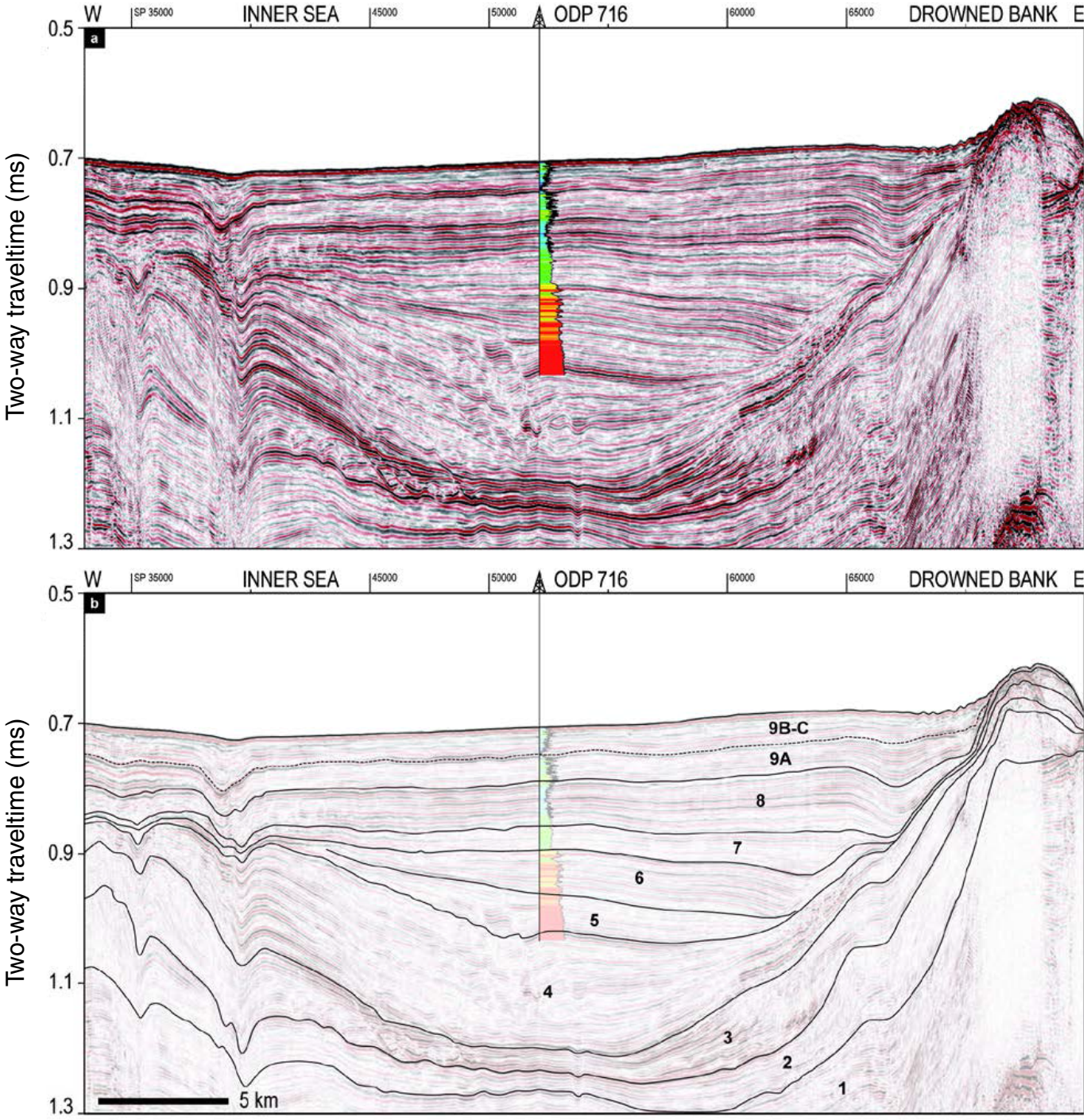


Figure F9. Locations of proposed primary Site MAL-09A and proposed alternate Site MAL-04B.

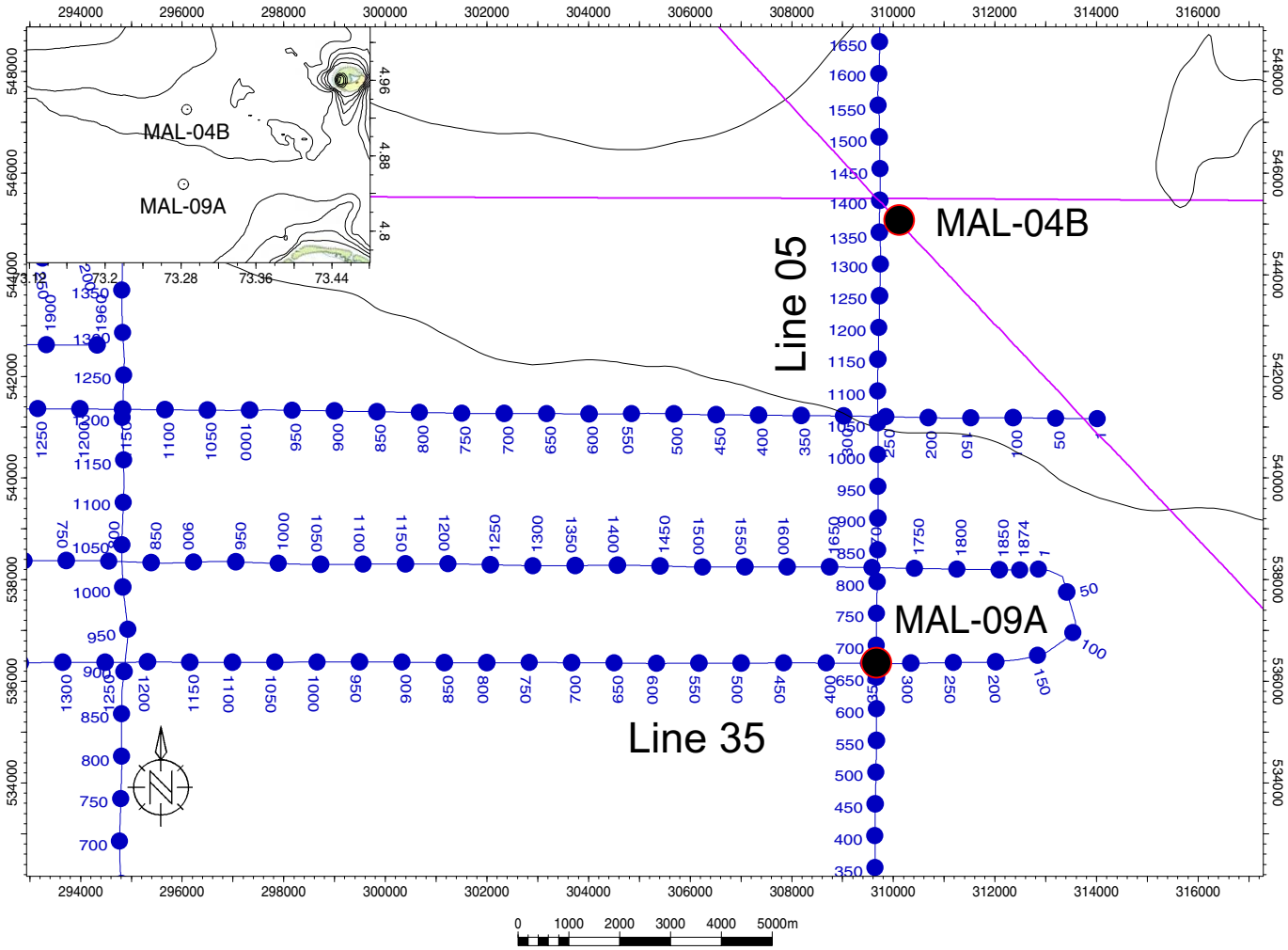


Figure F10. Seismic Line SO236_35 with location of proposed Site MAL-09A and drift sequence boundaries. PS = sequence boundaries defined in the carbonate bank, DS = drift sequence boundaries.

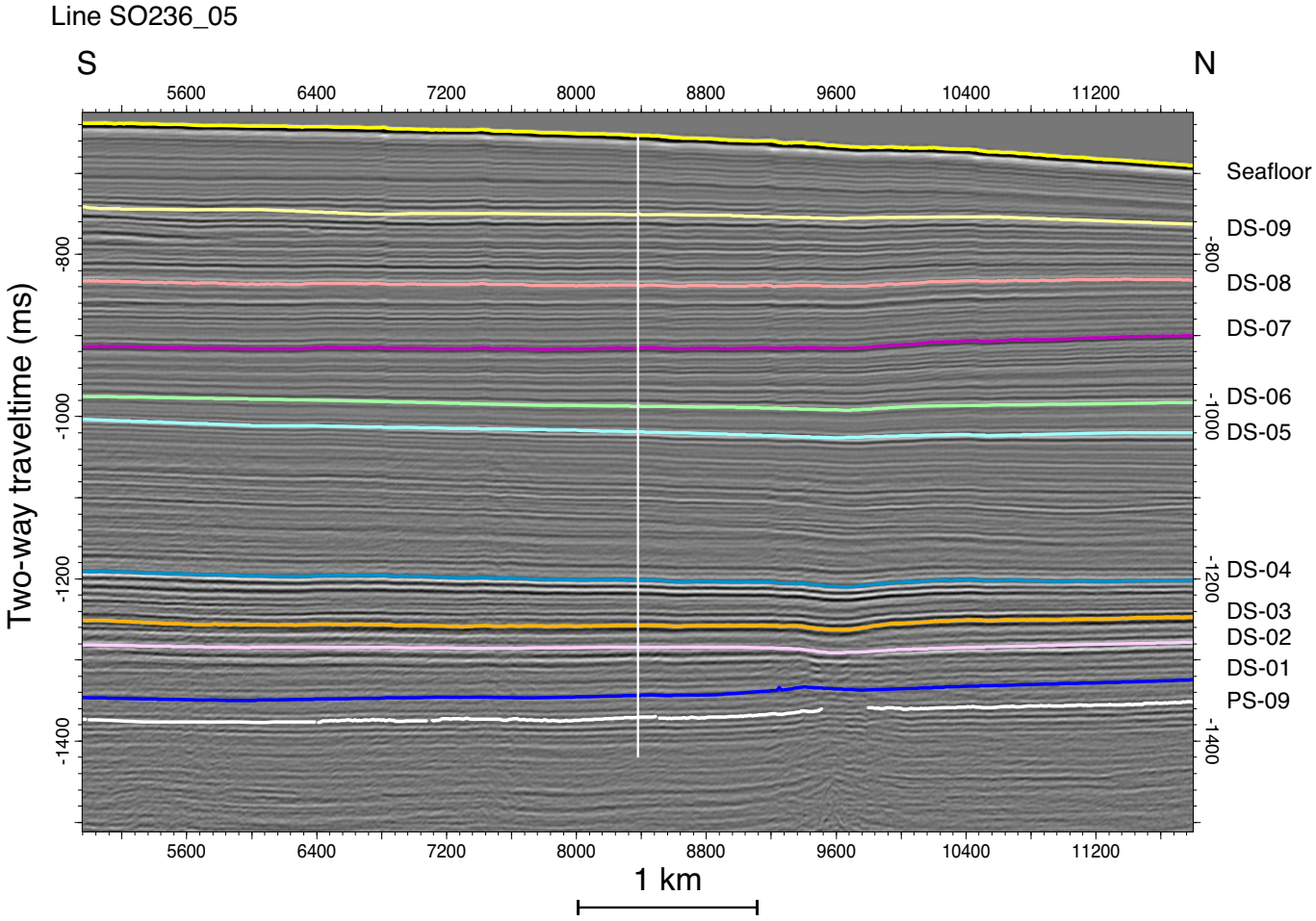


Figure F11. Seismic Line SO236_05 with location of proposed Site MAL-09A and drift sequence boundaries.PS = sequence boundaries defined in the carbonate bank, DS = drift sequence boundaries.

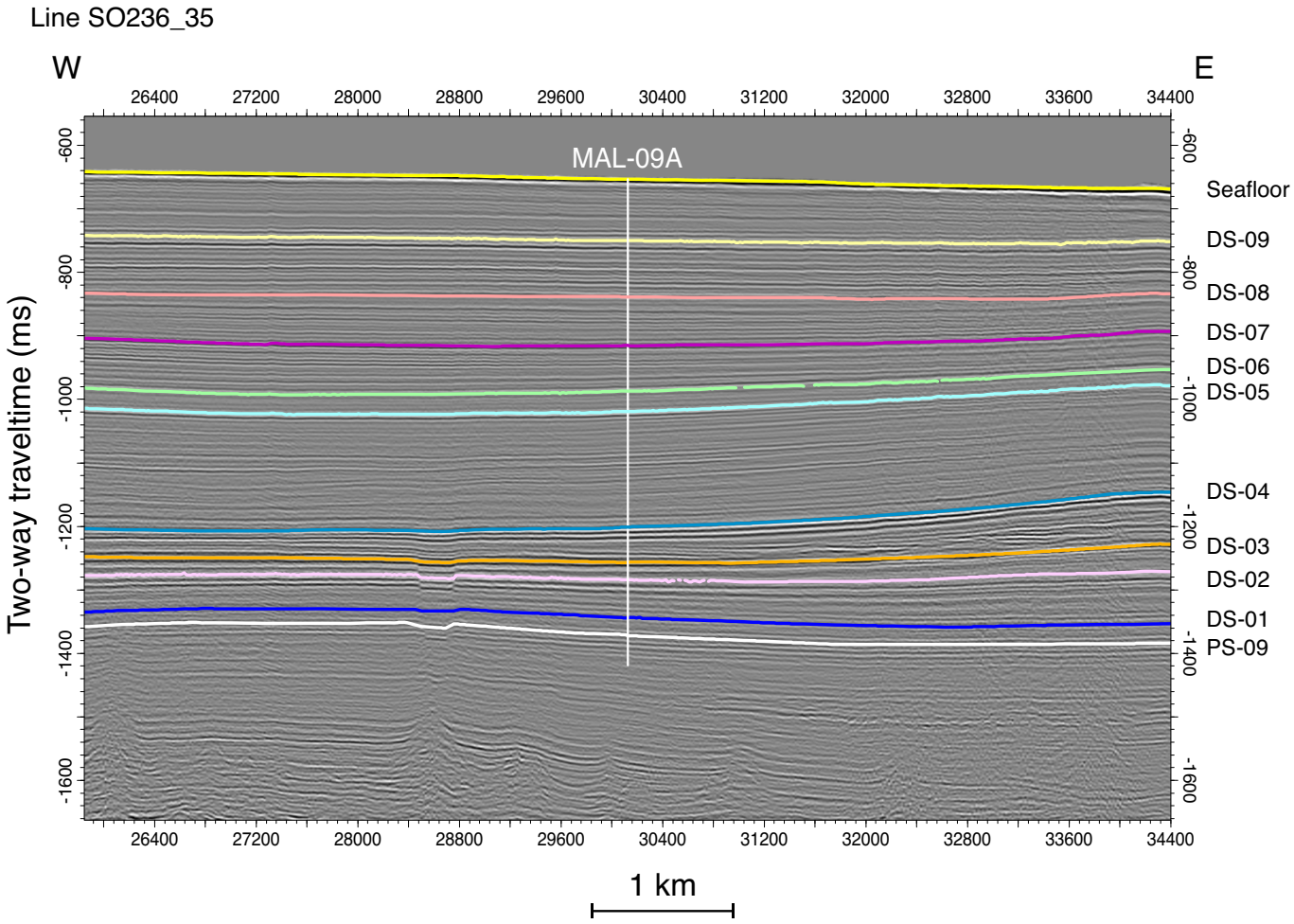
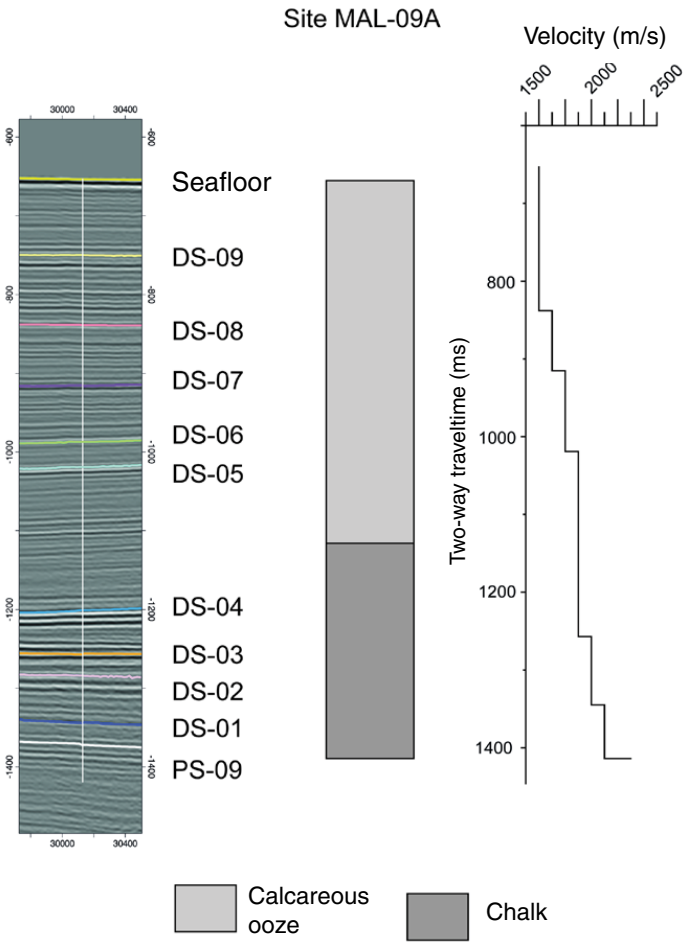


Figure F12. Estimated lithologic column at proposed Site MAL-09A with velocity model and corresponding seismic profile with seismic sequence boundaries. PS = sequence boundaries defined in the carbonate bank, DS = drift sequence boundaries.



Site summaries

Site MAL-02A

Priority:	Primary
Position:	4.933156°N, 73.027983°E
Jurisdiction:	Maldives
Water depth (m):	483
Target drilling depth (mbsf):	1010 pending EPSP approval
Approved maximum penetration (mbsf):	560
Survey coverage (track map; seismic profile):	• Location map (Fig. **F2;** see **F19** in Betzler et al., 2014) • Primary line(s): Line 65 (Fig. **F3;** see **F21** in Betzler et al., 2014)
Objective(s):	1. Provide detailed reconstruction of the predrowning, drowning, and postdrowning evolution of the carbonate bank by linking the seismic stratigraphic record to the sedimentary record 2. Constrain the timing of this evolution, allowing age assignments of unconformities, sedimentary interruptions, sedimentary turnovers, and onset of drift deposition 3. Reconstruct and date bank to drift turnover
Drilling program:	Single APC hole to 200 mbsf and then XCB to 325 mbsf Hole A: APCT-3 measurements and orientation Hole B: drill to ~320 mbsf, RCB to 560 mbsf
Logging and downhole measurement program:	Wireline log with triple combo and FMS-sonic
Nature of rock anticipated:	Calcareous ooze, chalk, possibly limestone

Site summaries (continued)

Site MAL-08A

Priority:	Alternate
Position:	4.90693350°N, 73.00819003°E
Jurisdiction:	Maldives
Water depth (m):	432
Target drilling depth (mbsf):	1100 pending EPSP approval
Approved maximum penetration (mbsf):	Pending EPSP approval
Survey coverage (track map; seismic profile):	• Location map (Fig. **F2**) • Primary lines: Line SO236-32 (Fig. **F5**), Line SO236-19 (Fig. **F6**)
Objective(s):	1. Provide a detailed reconstruction of the predrowning, drowning, and postdrowning evolution of the carbonate bank by linking the seismic stratigraphic record to the sedimentary record (i.e., depositional facies) 2. Constrain the timing of this evolution, thus allowing age assignments of unconformities, sedimentary interruptions, sedimentary turnovers, and onset of drift deposition 3. Reconstruct and date the bank to drift turnover
Drilling program:	Hole A: APC to 80 mbsf Hole B: drill/wash to 80 mbsf, RCB to 1100 mbsf
Logging and downhole measurement program:	Wireline log with triple combo and FMS-sonic
Nature of rock anticipated:	Hemipelagic carbonate ooze, limestone, chalk

Site MAL-09A

Priority:	Primary
Position:	4.85025773°N, 73.28367339°E
Jurisdiction:	Maldives
Water depth (m):	488
Target drilling depth (mbsf):	714 pending EPSP approval
Approved maximum penetration (mbsf):	Pending EPSP approval
Survey coverage (track map; seismic profile):	• Location map (Figs. **F1, F9**) • Primary lines: Line SO236-35 (Fig. **F10**), Line SO236-05 (Fig. **F11**).
Objective(s):	1. Analyze cyclostratigraphy of drift deposits, therefore providing reconstructions of changes in the current regime and monsoon cyclicity 2. Constrain the timing of unconformities and sedimentary interruptions
Drilling program:	Hole A: drill/wash to 170 mbsf, APC/XCB to 714 mbsf
Logging and downhole measurement program:	Wireline log with triple combo, FMS-sonic, and VSI
Nature of rock anticipated:	Hemipelagic carbonate ooze