A Plate Too Far: Lessons Learned and Insight Gained from scientific and operational achievements during IODP Expedition 358 in the Nankai Trough.

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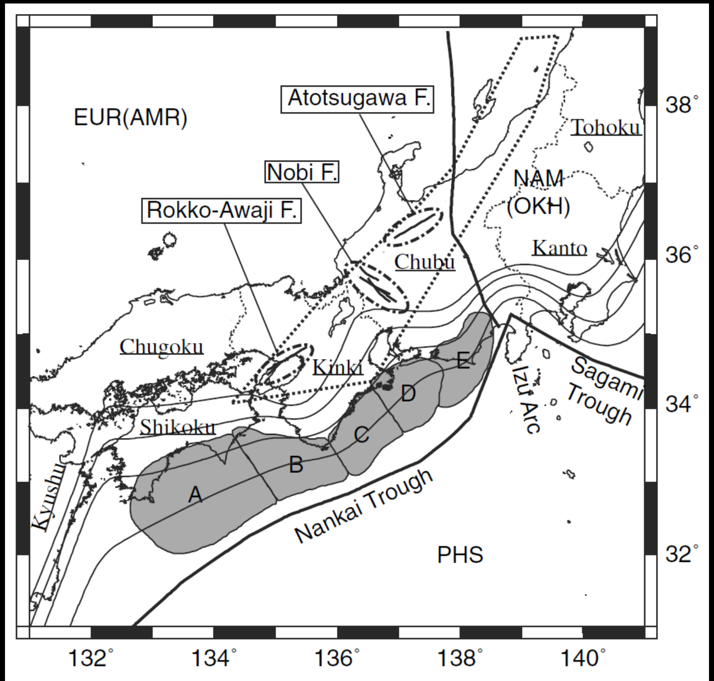
Why Nankai?

- The Nankai region is a major area of the megathrust earthquakes that shake Japan and especially the Nankaidō (Shikoku island) region of Japan, west of the Tōnankai region and Tōkai region (southern part of Honshu island),
- The quakes are caused by ruptures in the Nankai zone of the Nankai megathrust, specifically segments A and/or B,
- The earthquakes in the area occur roughly every 100 to 200 years and are highly destructive,
- The most recent earthquake that rattled the area was the 1946 Nankaidō earthquake,
- The Nankai Trough area was chosen as the focus of earthquake mechanism research under the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) project because of:
    - Extensive research in the area and the historical records of earthquakes and tsunamis dating back into the seventh century.
    - The seismogenic zone, where most earthquakes occur is at relatively shallow depth of about six kilometres below the seafloor and therefore accessible by D/V Chikyu.



Tectonic setting in central Japan. Thick solid lines represent plate boundaries after Bird [2003]. Abbreviations for plates: NAM, North American; OKH, Okhotsk; EUR, Eurasian; AMR, Amurian; PHS, Philippine Sea. Smooth thin solid lines are depth contours on the upper surface of the PHS plate [Hashimoto et al., 2004], contour interval 10 km. The thick dotted line represents the high strain rate zone called the Niigata-Kobe Tectonic Zone (NKTZ) [after Sagiya et al., 2000]. The thick lines enclosed by the chain lines in the NKTZ denote the representative inland faults discussed in the text (names are boxed). Thin broken lines showthe regional boundaries of Japan, and underlined words are region names. Gray areas are slip regions (A–E) of interplate earthquakes along the Nankai Trough [Earthquake Research Committee, 2001]. After Shikakura et al, 2014

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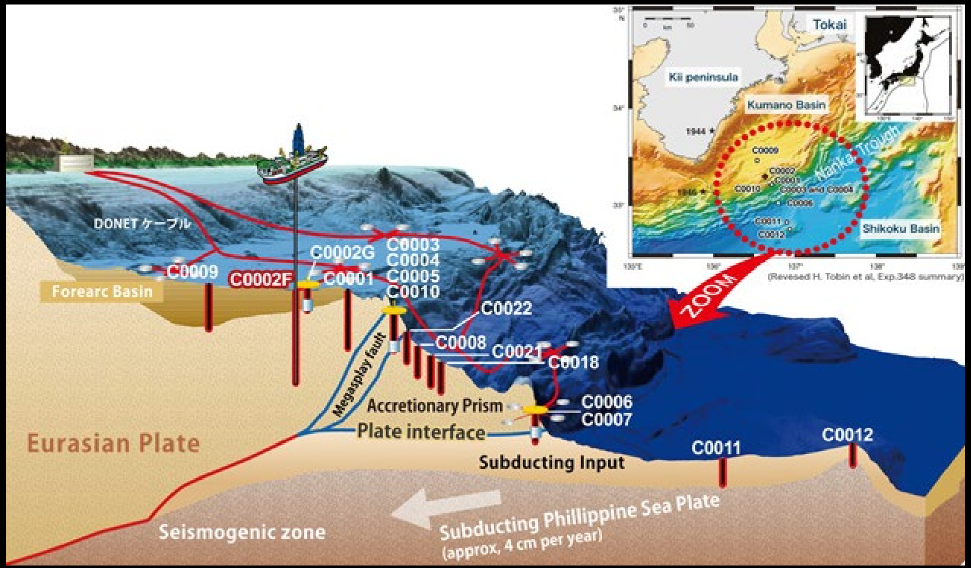
A brief history and timeline of the NanTroSEIZE project

NanTroSEIZE is a complex ocean drilling project that began drilling in 2007, with multiple expeditions and teams of scientists from all around the world. NanTroSEIZE attempted for the first time to drill, sample, and instrument the earthquake-causing, or seismogenic portion of Earth's crust, where violent, large-scale earthquakes have repeatedly occurred throughout history.

The Nankai Trough is located beneath the ocean off the southwest coast of Japan. It is one of the most active earthquake zones on the planet. The plan for NanTroSEIZE included drilling, below the ocean, very deep into the Earth to observe earthquake mechanisms. Samples were collected in order to study the frictional properties of the rock and sensors installed deep beneath the sea floor to record earthquakes up close and in real time.

The sensors and sample data have begun to yield insights into the processes responsible for earthquakes and tsunami. The data may shed light on how water and rock interact in subduction zones to influence earthquake occurrence in Nankai and at other subduction zones around the world.



IODP Site C0002 and other NanTroSEIZE drill sites in the Nankai Trough off the Kii Peninsula

2007 - 2008

- Exp. 314
  - LWD transect at all Stage 1 sites
- Exp. 315
  - Megasplay Riser Pilot
- Exp. 316
  - Shallow Megasplay and Frontal Thrusts

2009

- Exp. 319
  - Riser/Riserless Observatory 1
- Exp. 322
  - Subduction Inputs

2010

- Exp. 326
  - Plate Boundary Deep Riser 1
- Exp. 332
  - Riserless Observatory 2
- Exp. 333
  - Inputs Coring 2 and Heat Flow

2012

- Exp. 338
  - Plate Boundary Deep Riser 2

2013

- Exp. 348
  - Plate Boundary Deep Riser 3 (continued)

2016

- Exp. 365
  - Shallow Megasplay Long-Term Borehole Monitoring System

2018

- Exp. 380
  - Frontal Thrust Long-Term Borehole Monitoring System
- Exp. 358
  - NanTroSEIZE Plate Boundary Deep Riser 4

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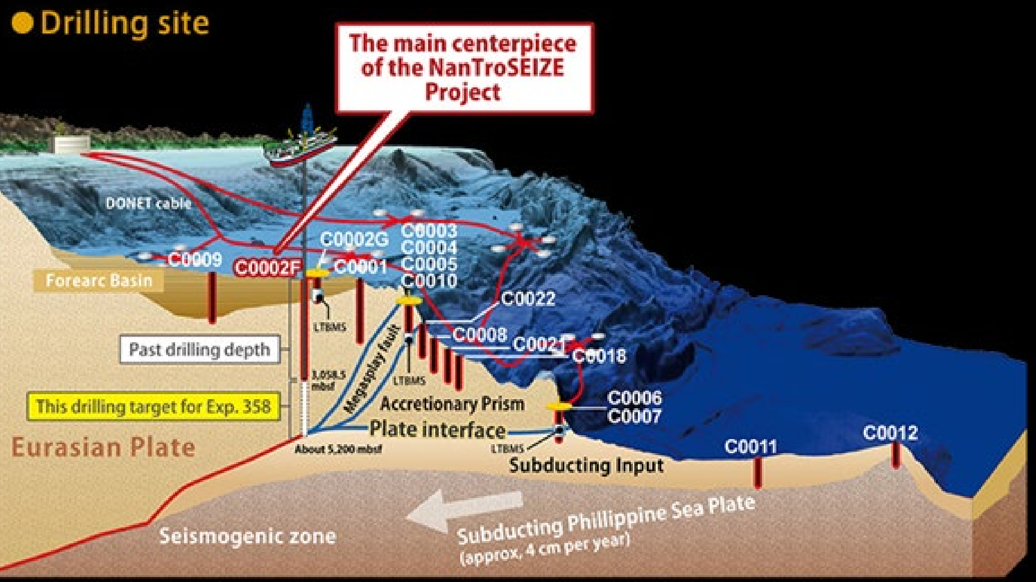
IODP Expedition 358 – Plate Boundary Deep Riser 4 - Overview

IODP Site C0002 is the deep centrepiece of the NanTroSEIZE Project, intended to access the plate interface fault system at a location where it is believed to be capable of seismogenic locking and slip, and to have slipped coseismically in the 1944 Tōnankai earthquake.

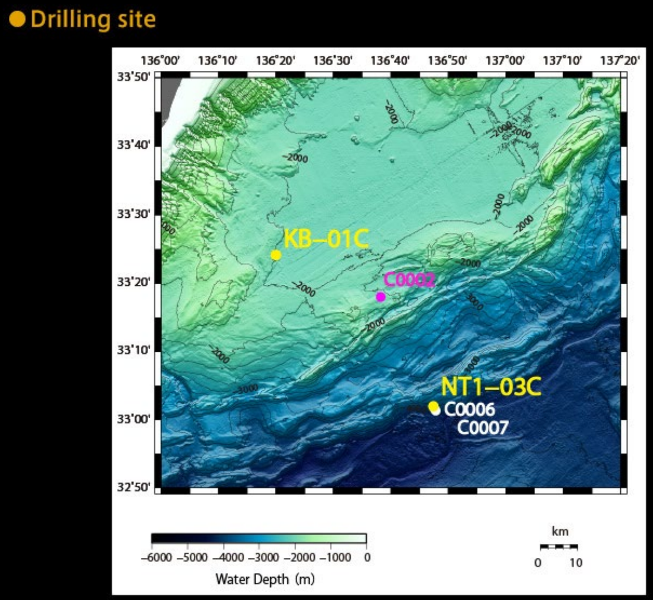
The Primary Goal

To deepen riser hole C0002F/N/P from 3000 mbsf to the primary megathrust fault target at ~5200 mbsf, using logging-while-drilling (LWD), downhole measurements, and drill cuttings analysis extensively, in addition to limited coring intervals.



The Contingency Plan

Implement riserless drilling at sites in the toe region of Nankai Trough and in Kumano Basin to complement and reinforce scientific findings of previous NanTroSEIZE expeditions.



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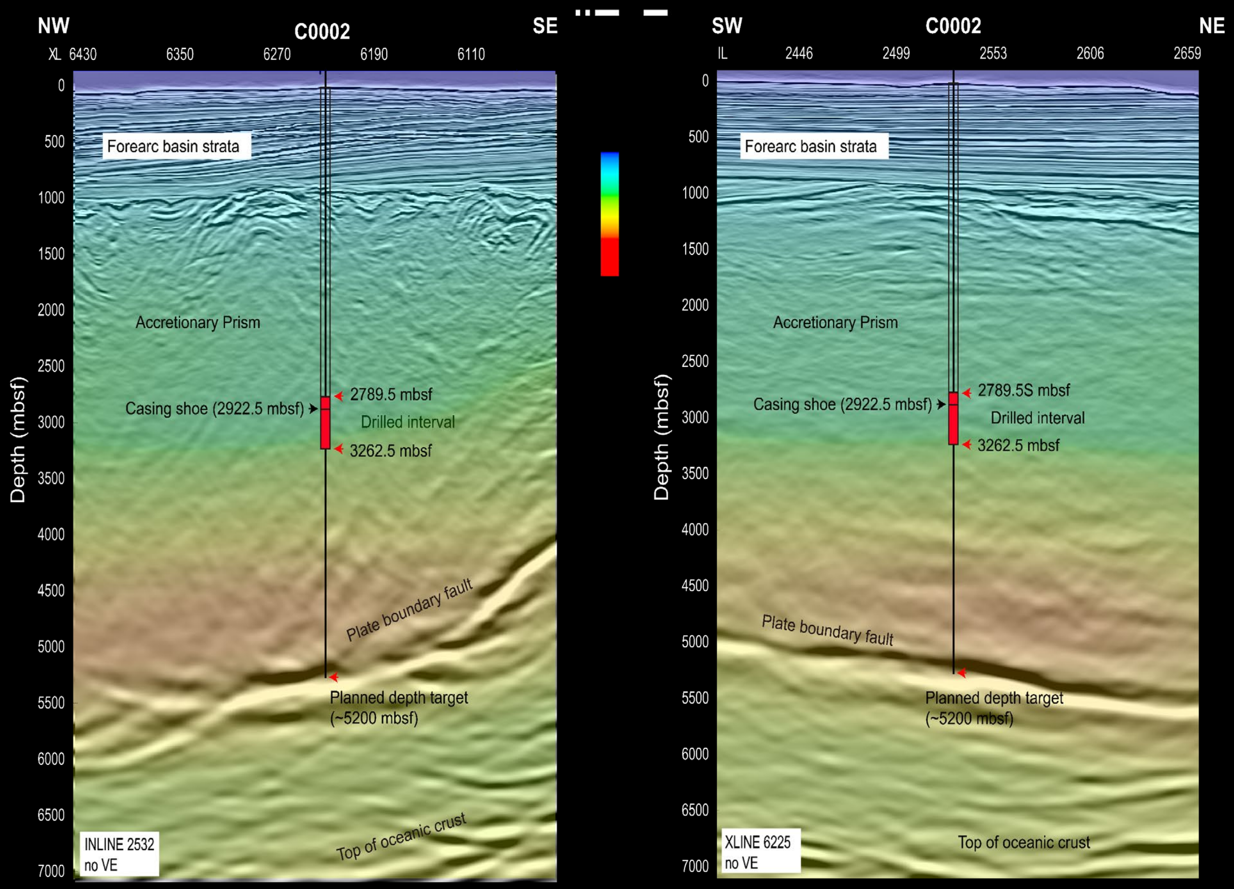
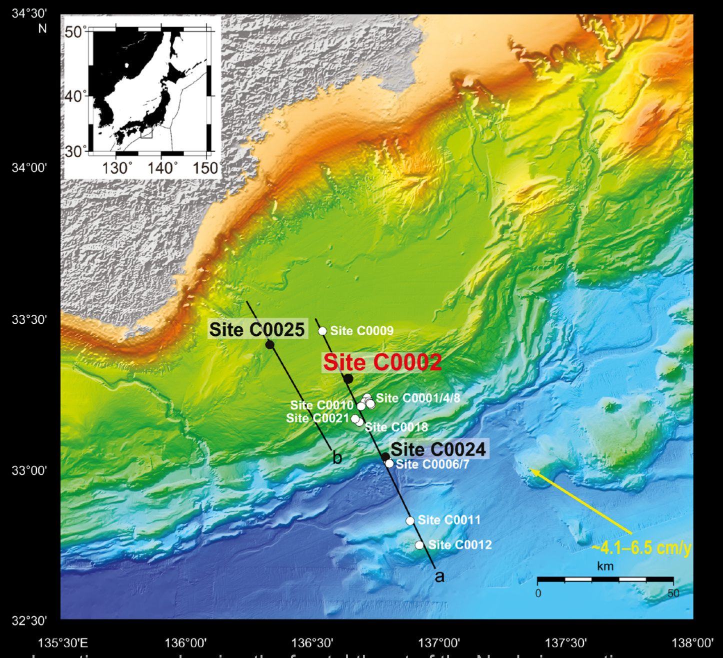
IODP Expedition 358 – Plate Boundary Deep Riser 4 – The drilling target

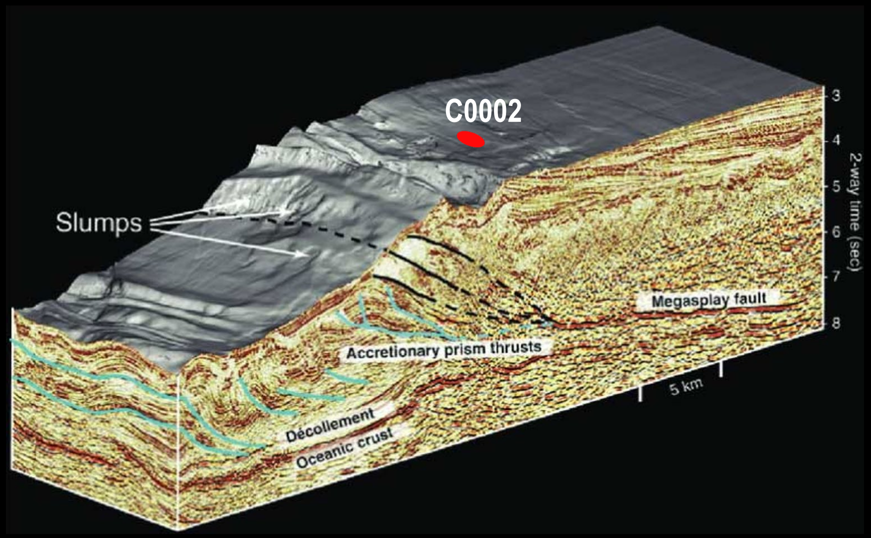
The goal of the expedition was to sample the reflector identified as the likely plate boundary fault at site C0002 by extending the riser hole C0002F/N/P.



A schematic of Site C0002 showing inline and crossline seismic images of the plate boundary target and actual interval drilled during Exp. 358 (red filled box).



Location map showing the frontal thrust of the Nankai accretionary prism and location of Site C0002 (red). IODP 358 Summary



3D Seismic volume depicting the location of Site C0002 in relation to megasplay fault, of plate boundary (After Moore, et al., 2007)

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IODP Expedition 358 – Plate Boundary Deep Riser 4 – The Plan

- **Science leadership**

  The expedition hosted a total of 47 scientists selected from 8 IODP member countries. The science team was led by the following 9 science leaders: Takehiro Hirose (JAMSTEC), Matt Ikari (MARUM), Kyuichi Kanagawa (Chiba University), Gaku Kimura (Tokyo University of Marine Science and Technology), Masataka Kinoshita (University of Tokyo), Hiroko Kitajima (Texas A&M University), Demian Saffer (Pennsylvania State University/The University of Texas at Austin, Jackson School of Geosciences), Harold Tobin (University of Washington), and Asuka Yamaguchi (University of Tokyo)

- **Drilling Well on Paper (DWOP) exercise x2**

  A standard oil & gas practice during preparatory stages of drilling a new well. Meeting where science and drilling teams get together. Extensive discussion, analysis of every operational steps related to oncoming expedition, presentation and introduction of new technology

  - ❖ **Geological model**
    Presentation and discussion of the geological plan – Discuss the structural and pressure uncertainties included in the model
  - ❖ **Drilling program**
    Presentation and discussion of the drilling program – Discuss and analyse all operational sequence required to drill the hole
  - ❖ **Real-Time Geomechanics concept**
    Introduction of the real-time geomechanics team that will be working alongside drilling and science teams on board the ship
  - ❖ **Non-Stop-Drilling (NSD) technique**
    Introduction of the NSD designed to reduce downhole pressure/flow fluctuations during connection operations
  - ❖ **New drilling fluid additives - FRACSEAL®**
    Introduction of the drilling additive – sealant – designed to plug any fractures and keep well stable
  - ❖ **Expandable casing**
    Introduction of novel casing technique with an expandable casing

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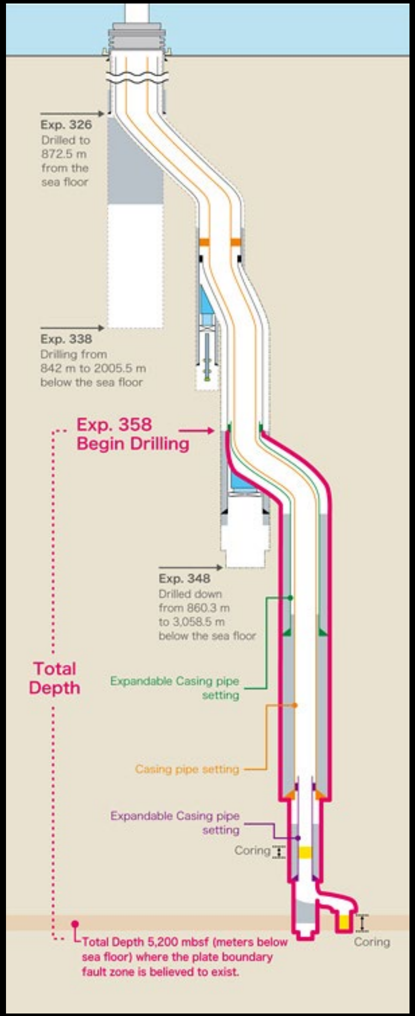
IODP Expedition 358 – Plate Boundary Deep Riser 4 – The Plan



The drilling program and the overall plan of the expedition expected the drilling operations to be completed in 4 sections:

- **Section 1 from 2922 to 3700mbsf**
  Extensive logging with LWD tools and extended leak off test (ELOT) for downhole pressure estimation
- **Section 2 from 3700 to 4500mbsf**
  Extensive logging with LWD, seismic tools and extended leak off test (ELOT)
- **Section 3 from 4500 to 5000mbsf**
  Extensive logging with LWD, seismic tools, extended leak off test and coring between 4700 to 4750mbsf
- **Section 4 from 5000 to 5200mbsf**
  Extensive logging with LWD tools and coring across the plate boundary

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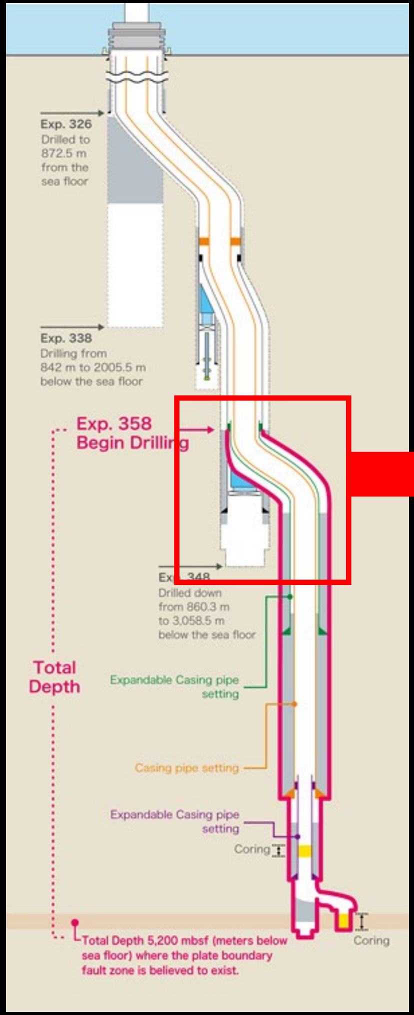
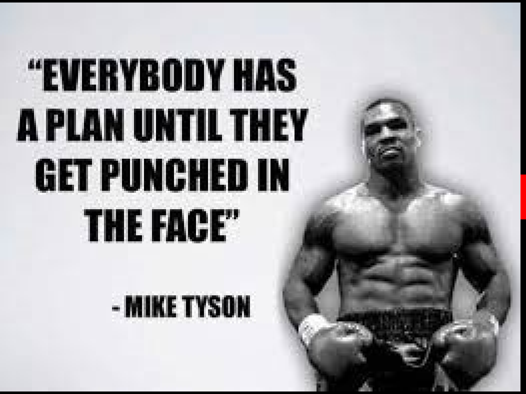
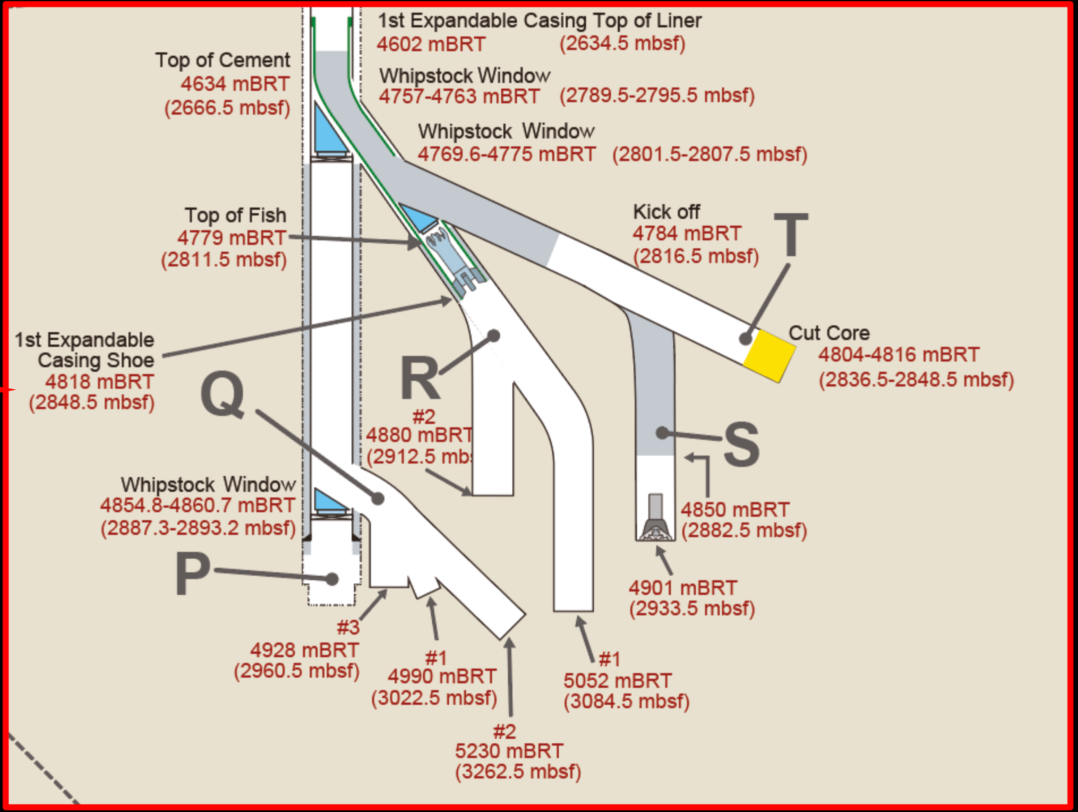
IODP Expedition 358 – Plate Boundary Deep Riser 4 – The Plan vs The Reality

THE PLAN





THE REALITY



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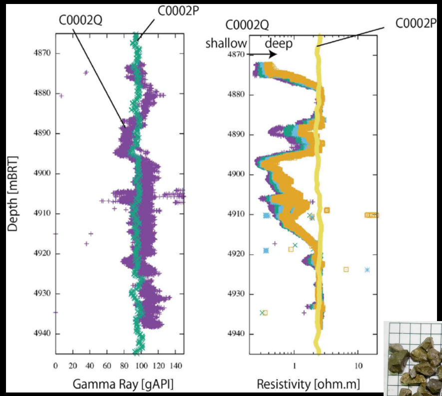
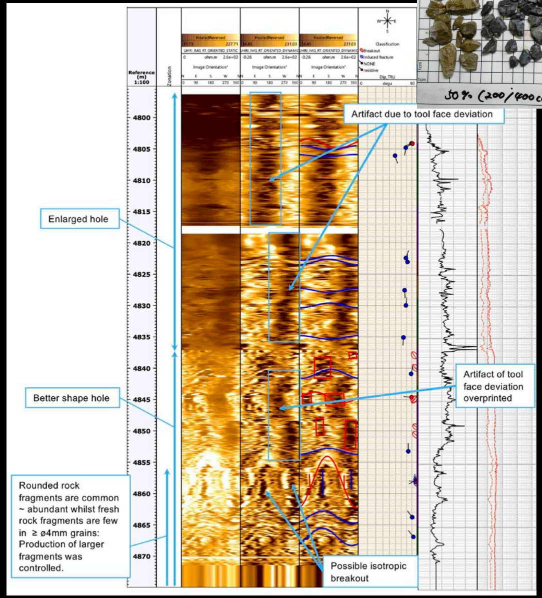
IODP Expedition 358 – Plate Boundary Deep Riser 4 – The Plan vs The Reality

However, due to the fragile nature of the geological formation comprising the accretionary prism drilling operations were extremely challenging and difficult. Some of the issues faced by both the drilling and science teams can be summarized as follows:

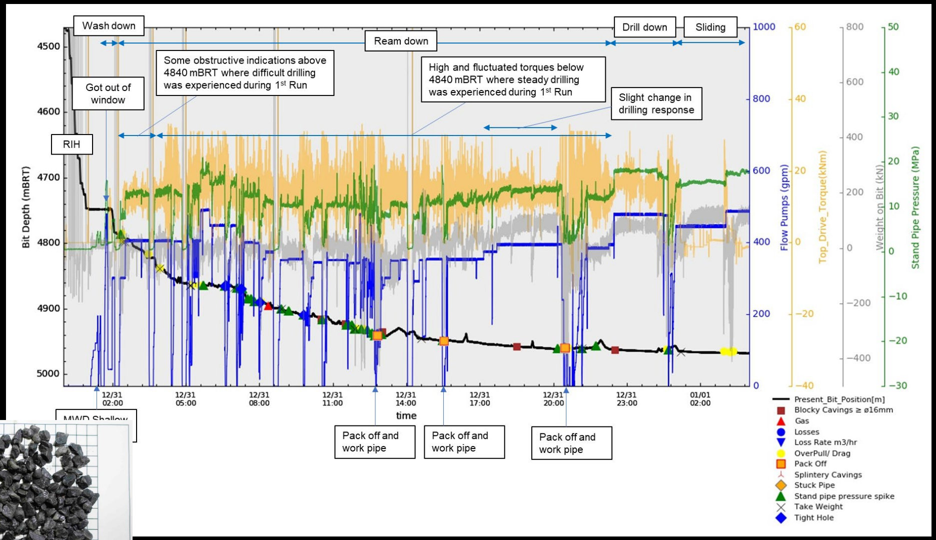
- Unable to re-enter previously drilled holes due to hole enlargement by borehole instability
- Vast amounts of cavings due to borehole instability
- Issues with cutting a window in the casing
- Low rate of penetration (ROP)
- Issues with Fracseal (mud additive) screening out
- Issues with cementing expandable casing
- Mechanical troubles at surface

Enlarged sections of newly drilled hole

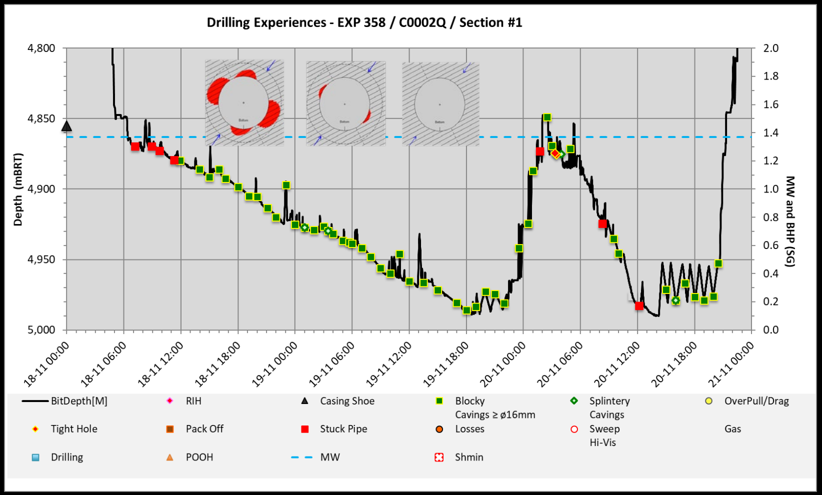




Difficulties in drilling due to fragile formation from the onset of operations



Vast amounts of large cavings and cement blocks plagued the drilling operations



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What lessons have we learnt and insights have we gained?

POSITIVE

- Minor success to deepen the original C0002P hole by 204 m. A new world record in scientific drilling.
- The application of industry standard stringent communication and protocols worked well and should be utilized in the future riser operations.
- Real-Time Geomechanics concept worked well and should also be utilized in the future riser operations.
- We proved that once farther away from the damage zone, the hole can be successfully drilled and maintained.
- An excellent experience for future training of both scientific and drilling teams with regards to operation design/planning, real-time execution and mitigation to rapidly changing environment.

NEGATIVE

- We underestimated the damage zone and the wellbore instability outside the 11 ¾”casing.
- Operational – failure to reach operational and geological targets.
- Management – lack of secondary and tertiary back-up options.

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The Future

The challenges born from side-tracking near the bottom of the previously drilled Hole C0002P (2014 IODP Exp. 348), proved greater than the multi-disciplinary teams expected and the overall objectives set for Exp. 358 were not achieved.

Nevertheless, despite the significant problems seen during several attempts, the hole was deepened 204 m. This was a minor success and it is believed, once away from the highly damaged area of the C0002P hole, drilling can produce a high-integrity hole following excellent communication and recommendations between drilling and scientific teams during complex drilling operations, especially in complex environments such as the Nankai Accretionary Prism.

Despite not achieving the ultimate goal of the expedition, the implemented industry drilling standards, real-time surveillance system, real time geomechanics, and strict communication protocols, and integrating both scientific and drilling teams have demonstrated their value and should become standard practice during future IODP/ICDP operations.

JAMSTEC has hired an impartial (3rd party), experienced drilling industry engineering contractor to review operations and provide recommendations for future drilling.

JAMSTEC is examining these and other recommendations while reviewing possibilities (including starting a new hole) to continue this exiting and extremely important project.

Appendix 1

Background information/research with regards to Nankai Trough and NanTroSEIZE project

JAMSTEC NanTroSEIZE website – an excellent source of information about all Nankai expeditions - https://www.jamstec.go.jp/chikyu/e/nantroseize/

IODP website – an irreplaceable source of information about international scientific drilling - http://www.iodp.org/

A selection of scientific papers on Nankai Through and IODP expeditions related to NanTroSEIZE project

Eiichiro Araki, Demian M. Saffer, Achim J. Kopf, Laura M. Wallace, Toshinori Kimura, Yuya Machida, Satoshi Ide, Earl Davis, IODP Expedition 365 shipboard scientists. Recurring and triggered slow-slip events near the trench at the Nankai Trough subduction megathrust. *Science* 16 Jun 2017: Vol. 356, Issue 6343, pp. 1157-1160 https://doi.org/10.1126/science.aan3120

Sakaguchi, A., Chester, F., Curewitz, D., Fabbri, O., Goldsby, D., Kimura, G., Li, C.-F., Masaki, Y., Screaton, E.J., Tsutsumi, A., Ujiie, K., and Yamaguchi, A., 2011. Seismic slip propagation to the updip end of plate boundary subduction interface faults: vitrinite reflectance geothermometry on Integrated Ocean Drilling Program NanTroSEIZE cores. *Geology,* 39(4):395–398. doi:10.1130/G31642.1

Strasser, M., Moore, G., Kimura, G. *et al.* Origin and evolution of a splay fault in the Nankai accretionary wedge. *Nature Geosci* **2,** 648–652 (2009). https://doi.org/10.1038/ngeo609

Tobin, H.J., and Kinoshita, M., 2006. NanTroSEIZE: the IODP Nankai Trough Seismogenic Zone Experiment. *Scientific Drilling*, 2:23–27. https://doi.org/10.2204/iodp.sd.2.06.2006

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Appendix 2

New technology used in scientific drilling during the IODP Exp. 358

Drilling Fluids and hydraulics
Fracseal – cellulose fibre sealant http://drilchem.com/products/fracseal/
NSD – non stop drilling http://www.adrilltech.com/

Drilling tools and bits
LWD/MWD https://www.slb.com/drilling/surface-and-downhole-logging/logging-while-drilling-services

Rotary Steerable RSS https://www.slb.com/drilling/bottomhole-assemblies/directional-drilling/powerdrive-xceed-rotary-steerable-system

Bits
- StingBlade https://www.slb.com/drilling/bottomhole-assemblies/drill-bits/blade-family-bits/stingblade-conical-diamond-element-bit
- AxeBlade https://www.slb.com/drilling/bottomhole-assemblies/drill-bits/blade-family-bits/axeblade-ridged-diamond-element-bit

Underreamer https://www.drillstar-industries.com/oil-and-gas/drilling/z-reamer/

Casing
Whipstocks https://www.youtube.com/watch?v=Xisf_S9cqww
Expandable casing https://www.enventuregt.com/en/products-solutions/technology/technology-overview/how-expandable-technology-works

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Appendix 3

Shipboard Scientists

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THE END

We would like to thank you for your time learning more about our experience during the IODP expedition 358