PROJECT MOHOLE INITIAL FEASIBILITY STUDY

FOR 2017 DRILLING

Prepared For
Integrated Ocean Drilling Program

Final Report

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1 Executive Summary

The purpose of this document is to provide a feasibility study of drilling and coring activities that would be conducted in an ultra-deepwater environment and in very high temperature igneous rocks to reach the upper mantle in the oceanic crust. The study is focused on what would be required for planning, drilling and coring in the Pacific Ocean and to point out some of the critical issues that the Integrated Ocean Drilling Program (IODP) should be aware of. Much of the information included is based on data provided by IODP, the Center for Deep Earth Exploration (CDEX), public domain and Blade's past experience with numerous frontier projects in the offshore deepwater oil and gas and geothermal industries. However, since to date, no wells have been drilled with the combined extreme conditions of such deepwater environments (≈ 4000 meters) and high temperature formations (≈ 200-250 °C), a significant effort has been put in order to look at different industries and the most recent technologies.

This feasibility study is divided in several sections covering the different technologies, tools and procedures needed to achieve 'Project Mohole' goal which is to core to the upper mantle.

The main challenges discussed in this study are threefold and as follows:

- Drilling with riser in ultra-deepwater environments with water depths around 4000 meters which will set a new world record.
- Drilling and coring in very high temperature igneous rocks with bottom-hole temperatures that are estimated to be as high as 250°C which will also set a new world record.
- Drilling and coring a very deep hole with a total drilled and/or cored interval around 6000 meters in the oceanic crust below the Pacific Ocean seafloor in order to reach the upper mantle which will be a major achievement for the worldwide scientific community.

The obvious constraints for such projects versus 'normal' offshore operations are the extreme water depths where drilling and coring operations need to be conducted, the extreme high temperatures present in very hard igneous rocks that push the limit of all the drilling and coring tools and special procedures that are routinely used in less demanding environments.

This report includes several discussions and analyses concerning environmental data, marine drilling riser options, deepwater subsea equipment, drill-pipe design, wellbore design, down-hole tools, drilling fluids, various advanced technologies and operational time and costs estimations.

The results of this work show that drilling to the mantle is certainly feasible and that there are existing industry solutions to many of the technological challenges associated with drilling this type of borehole.

2 Introduction

IODP (Integrated Ocean Drilling Program) has requested from Blade Energy Partners the preparation of a study to investigate the feasibility of the MoHole Drilling Project planned for 2017. The objective of the project is to drill in the Pacific Ocean in water depths greater than 3500 meters a very deep hole through oceanic crust to reach the upper mantle.

The first four sections cover the executive summary, introduction, candidate locations and literature search. Section 5 reviews and compares different marine drilling riser options and subsea equipments that are currently available in the ultra-deepwater industry and shows that the Chikyu drill-ship could conduct drilling and coring operations through the deep seawater column with some components upgrades or modifications. Section 6 lists the design assumption used for this preliminary feasibility study. Section 7 discussed the current state-of-the-art drilling and coring methods and instruments for high temperature igneous rocks, and current limitations and design efforts that are needed to reach the deepest formations where temperature are expected to be greater than 150°C. General discussion and conclusions are covered respectively in section 8 where a summary of Blade findings is given with the way forward into the near future implementation of the 'Mohole Project', drilling into the Mohorovicic.

2.1 Feasibility Study Objectives

This feasibility study will initially address the following:

- New technologies which need to be implemented on the IODP drillship Chikyu that are expected to be available now or with enough time before 2017 to prepare for their use.

- Investigate the sensitivity to success and cost relative to the primary operational variables at IODP's three candidate sites.

- Investigate the primary scientific coring methods (whole 'full' coring vs. spot coring vs. no coring).

- Provide a recommendation of the most efficient and most viable first order operational implementation plan for (various levels of scientific) success.

- Provide an estimate of the total cost of the complete project scoping and well design study following feedback from IODP on the results of this initial Feasibility Study.

2.2 Project Mohole Scientific Objectives

The primary scientific goals of the Mohole Drilling Project as defined in several IODP documents are as follows:

- Continuous core, including samples of all boundaries, across the region identified by seismic imaging as the Moho, and the lithologic transition from cumulate magmatic rocks to residual peridotites.

- Continuous coring of the lower 500m of the mafic and ultramafic cumulate rocks in the oceanic crust.

- Continuous coring of 500m of peridotites and associated lithologies in the uppermost mantle below the Moho

- Obtain sufficient cores from intervals of the lower oceanic crust to test models of crustal accretion and melt movement, to resolve the geometry and intensity of hydrothermal circulation, and to document the limits and activity of the deep microbial biosphere.
- A continuous, comprehensive suite of geophysical logs (wireline, Logging While Drilling/Coring) and borehole experiments to measure *in situ* physical properties, to acquire borehole images, and to identify key geophysical and lithologic regions and transitions (e.g., Layer 2-3 boundary, the Moho) throughout the ocean crust and into the upper mantle.

2.3 Required Geophysical Characteristics of the Project Area

The IODP has determined that the well-site location selected for this project should have the following characteristics. Items ‘a’ to ‘e’ are considered essential for success and items ‘f’ to ‘h’ are considered highly desirable, but not essential.

a) Crust formed at fast-spreading rate (>40 mm yr -1 half rate).

b) Simple tectonic setting with very low-relief seafloor and smooth basement relief; away from fracture zones, propagator pseudo-faults, relict overlapping spreading basins, seamounts, or other indicators of late-stage intraplate volcanism. Connection to the host plate active constructive and destructive boundaries would provide important scientific information.

c) Crustal seismic velocity structure should not be anomalous relative to current understanding of “normal” fast-spread Pacific crust, indicative of layered structure.

d) A sharp, strong, single-reflection Moho imaged with Multi-Channel Seismic (MCS) techniques.

e) A strong wide-angle Moho reflection (PmP), as observed in seismic refraction data, with distinct and clearly identifiable sub-Moho refractions (Pn).

f) A clear upper mantle seismic anisotropy.

g) A crust formed at an original latitude greater than 15°.

h) A location with relatively high upper crustal seismic velocities indicative of massive volcanic formations to enable the initiation of a deep drill hole.

The following technological constrains limit the range of potential sites:

- Technology for re-circulating drilling mud (riser or alternative) is currently untested at water depths greater than 3000m.

- Prior scientific ocean drilling experience is mostly limited to temperatures less than 200°C. Temperatures higher than ±250°C will may limit choices of drill bits and logging tools, may decrease core recovery, and may increase risk of hole failure, or require substantial re-design of drilling equipment. Based on plate cooling models, crust older than ±15–20 Ma should meet this requirement at Moho depths.

- Thickness of the crustal section above the Mohorovicic must be at least a few hundred meters less than the maximum penetration/logging/recovery depth of the drilling system to allow significant penetration in mantle peridotites.

- Target area should be in a region with good weather conditions at least eight months out of the year, with calm seas and gentle ocean bottom currents.

- Sediment thickness should be greater than 50m to support possible riser hardware and other seafloor infrastructure (re-entry cones/uppermost casing strings).

Targeted area should be close (less than ±1000 km) to major port facilities for logistical practicalities.

3 Candidate Location Summary

Three potential well-site locations are being considered as shown in the following map in Figure 1.

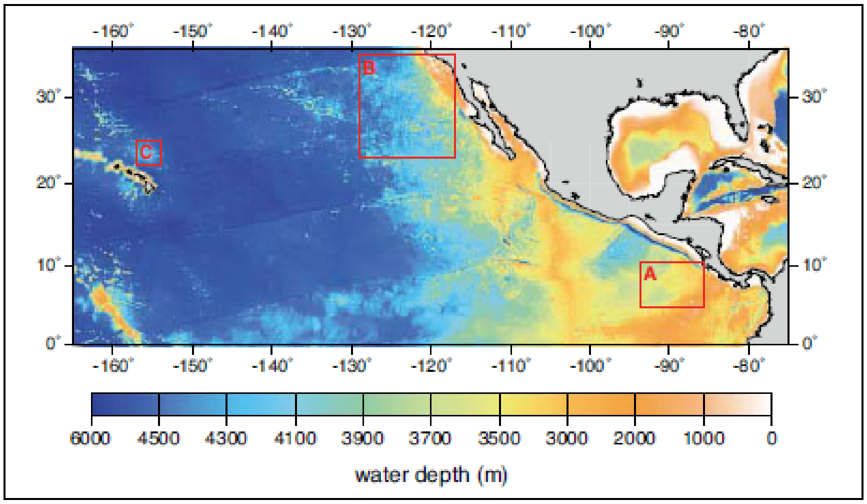

Figure 1—Bathymetric Map of Candidate Well Site Locations

- **Location A: Cocos Plate**

  This area encompasses a region of the Cocos Plate off Central America from Guatemala to northern Costa Rica.

Water Depth :	3,650 m .... 11,975 ft
Penetration (bsf) :	6,250 m .... 20,505 ft
Total Depth (brf) :	9,900 m .... 32,480 ft
Crustal Age :	15 - 19 Ma
Est. Moho Temperature :	≥ 250°C .... 482°F
Sediment Thickness :	250 - 300 m .... 820 - 984 ft
Latitude :	6.7 - 8.7°N
Longitude :	89.5 - 91.9°W
Analog Holes :	1256D,
Nearest Port :	Puerto de Caldera, Costa Rica, Port of Corinto, Nicaragua ±644km…..400 miles

- **Location B: Baja California**

  This area encompasses a region of the eastern Pacific plate located off Baja / Southern California.

Water Depth :	4,300 m .... 14,108 ft
Penetration (bsf) :	6,100 m .... 20,013 ft
Total Depth (brf) :	10,400 m .... 34,121 ft
Crustal Age :	20 - 30 Ma

Est. Moho Temperature : 200 - 250°C .... 392 - 482°F
Sediment Thickness : 80 - 130 m .... 262 - 427 ft
Latitude : 25 - 33°N
Longitude : 120 - 127°W
Analog Holes : None
Nearest Port : Long Beach, San Diego, Puerto de Ensenada Mexico
±800-1000km… 500-620 miles

- **<u>Location C: Hawaii</u>**

  This area is located off the northeastern cost of Oahu.

Water Depth : 4,050 m .... 13,287 ft
Penetration (bsf) : 6,700 m .... 21,982 ft
Total Depth (brf) : 10,750 m .... 35,269 ft
Crustal Age : 78 - 81 Ma
Est. Moho Temperature : ±150°C .... 302°F
Sediment Thickness : ±200 m .... 392 ft
Latitude : 22.9 - 23.9°N
Longitude : 154.5 - 155.8°W
Analog Holes : None
Nearest Port : Honolulu Harbor, Oahu
±400km……250mi

Each location has advantages and drawbacks as shown in Table 1.

Table 1—Pros and Cons for Well Sites

Location	Advantages	Disadvantages
Cocos Plate	Shallowest Water Depth	Highest Moho Temperature
	Well-known Tectonics	
	Previous Expedition Experience	
Baja	Large Water Depth Range	Few Data Available
	Modest Moho Temperature	Off-Ridge Volcanism
		Deepest Water Depth
Hawaii	Lowest Moho Temperature	Deepest Total Depth
	Nearby Port Facilities	Near large Hotspot
		Arch-Volcanism

4 Literature Search

Drilling and coring very high temperature igneous rocks in an ultra-deepwater environment to reach to upper mantle presents a number of additional challenges to 'normal' offshore well planning and operations. Some of the expected challenges, problems and possible solutions required are discussed in this section. Blade conducted an extensive literature survey in order to:

1. Develop an understanding of the 'Mohole Project' objectives.
2. Understand IODP experience and issues with previous scientific drilling expeditions.
3. Study and assess previous experience and latest technological trends in the geothermal and oilfield industries that could provide solutions to the 'Mohole' well.

4.1 IODP Workshops

The Integrated Ocean Drilling Program (IODP) has organized several workshops over the past five years dedicated specifically to the upcoming 'Mohole Project'. In this section, we are giving a brief overview from four of these workshops.

- On September 7-9, 2006 in Portland, Oregon, USA was organized a workshop called 'Mission Moho' that helped redefining the scientific goals for the near future in understanding the mechanisms related to the formation and evolution of the oceanic lithosphere.
- On July 27-29, 2009 in Southampton, UK was organized a workshop called 'Melting, Magma, Fluids, Life' that focused on the igneous basement of the ocean lithosphere and its role in the dynamics of Earth.
- On June 3-5, 2010 in Kanazawa, Japan was organized a workshop called 'The Mohole A Crustal Journey and Mantle Quest' that brought together geoscientists, marine geophysicists and offshore engineers to put together a plan for investigating technologies and procedures necessary to reach the upper mantle in the oceanic lithosphere and also identify the best site candidates to conduct drilling and coring operations.
- On September 9-11, 2010 in Washington DC, USA was organized a workshop called 'Reaching the Mantle Frontier Moho and Beyond' which was co-sponsored by the Deep Carbon Observatory (DCO). The workshop brought together key scientists and engineers from academia and industry to identify the key scientific objectives associated with innovative technology specifications and their associated implementation timelines and costs in order to develop a realistic roadmap for penetrating the Moho.

4.2 Previous DSDP, ODP and IODP Expeditions

The Deep Sea Drilling Project (DSDP) that ran between 1968 and 1983 and the Ocean Drilling Program (ODP) that ran between 1985 and 2004 were former international organizations which were replaced by today Integrated Ocean Drilling Program (IODP). Between 1968 and the early 2000s, the main focus of DSDP and ODP expeditions were the study of ocean basins of the world (oceanic seafloor, spreading rates, etc…) and to confirm the theory of plate tectonics enounced in the first half of the 20th century.

A great deal of literature is available concerning all scientific expeditions that have conducted for DSDP, ODP and IODP. The bulk of the documents contain summary reports, scientific findings, results, and oceanic crust lithology and seafloor maps for all expeditions that took place since 1968. Figure 2 below shows a snapshot from the Google Earth scientific borehole map that has been created and made publically available by IODP.

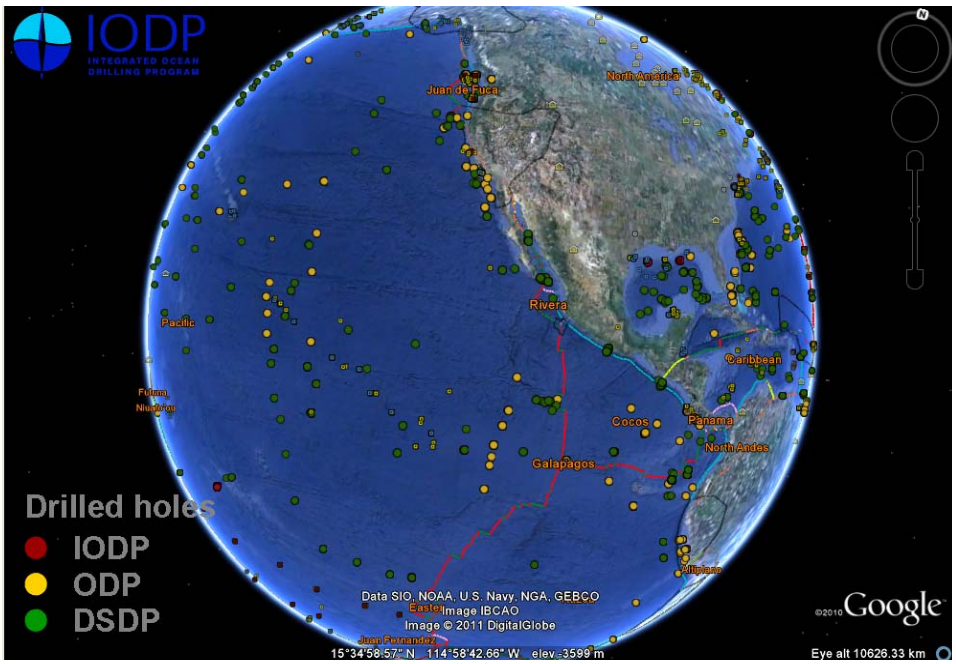

Figure 2—Google Earth Snapshot at Previous DSDP, ODP and IODP Expeditions in the Pacific North-East Quadrant (IODP, 2011)

The selection of documents that were reviewed was based on the three different locations considered to drill to the upper mantle. Therefore, all expeditions that have been conducted in the Cocos Plate, Baja California and Hawaii regions were first reviewed and then, relevant data were extracted and used for this feasibility study.

For instance, sites 504B and site 1256D in the Cocos Plate region provided a great amount of data to be used for design assumptions (see section 6) and drilling and coring techniques in high temperature igneous rocks of the oceanic crust (see section 7). At the site 1256D, several expeditions 206 and 309-312 recovered a complete section of upper oceanic crust from extrusive lava through the dikes and into the uppermost gabbros and reached a total depth of 1507 meters below the oceanic seafloor. Also, the site 504B is the second borehole where ODP has penetrated sheeted dikes to a total depth of 1800 meters below the seafloor.

4.3 Deep Continental Drilling

The KTB borehole in Germany was started in 1987 to provide the scientific community with a very deep borehole drilled in the continental crust. To date, the total depth reached was about 9100 meters (ICDP, 2000) and used a new drilling and coring technology similar in principle to the actual rotary core barrel currently used by IODP.

The Kola Superdeep Borehole in Russia was a previous attempt made between 1970 and 1989 to drill as deep as technically possible in the continental crust and to reach the upper mantle. After reaching a depth of 12262 meters, drilling was stopped mainly due to the higher than expected bottom-hole temperatures (BHT). Indeed, scientists expected rock temperatures of 100°C where they encountered temperatures greater than 180°C. These very high temperatures resulted in rocks behaving more like a plastic material than an anisotropic solid. Therefore, borehole conditions that became unstable when pulling out of the hole made impossible further progress to reach the upper mantle.

4.4 Geothermal Drilling

In the Iceland Deep Drilling Project (IDDP), drilling and coring in the continental crust at a depth interval ranging between 2400 meters and 4500 meters and at temperature as high as 500°C were planned. A conventional core barrel system capable of collecting 101.6 millimeters diameter core (4 inches) with a 184.15 millimeters outside diameter (7-1/4 inches) has been designed to operate in these high temperatures with a cooling system that should keep temperatures below 200°C (Skinner et al., 2010).

In the Kakkonda, Japan geothermal area, a static bottom-hole temperature greater than 500°C was achieved at a total depth of 3729 meters. Issues with this very high temperature environment were overcome using both a top-drive system to cool the bottom-hole assembly (BHA) when running each drill-pipe stand and employing a mud cooling system to cool the drilling fluid returns (Saito and Sakuma, 2000).

4.5 Ultra-Deepwater Drilling for Oil and Gas Resources

Deepwater riser drilling and deep borehole drilling are routinely achieved in several regions of the world (Gulf of Mexico, Brazil, West Africa, South India, and North-west Australia). Technologies and techniques are constantly advancing as operators and governments push towards drilling in deeper waters, deeper wells and higher pressure and temperature formations. Moreover, technology will continue to evolve and the gap between what IODP's 'Mohole Project' requirements and current techniques, tools and procedures used by the deepwater oil and gas industry is very narrow.

4.6 Other Industries Ongoing Research Effort

The National Aeronautics and Space Administration (NASA) is currently funding researching programs for ultra-high temperature tools. Because of the necessity to explore and take rock samples from our solar system planets, several technologies and systems need to be designed. For instance, Venus surface temperature around 450°C have encouraged the NASA to engineer concepts and tools for ultra-high temperature environments where motors, sensors, lubrication of mechanical parts are required to equip probes, vehicles and robots (Landis et al., 2004).

5 Marine Drilling Riser Analysis for Ultra-deepwater Drilling

IODP is planning to drill an exploratory ultra-deepwater well offshore in the Pacific Ocean. The ultra-deepwater drilling rig selected for these analyses is the Chikyu ship-shaped vessel. The planned water depth ranges between 3650 and 4300 meters depending on the location.

Several marine drilling riser analyses have been performed to assess the current limitations of the steel marine drilling riser which is onboard the Chikyu drilling vessel. For this preliminary analysis, the marine drilling riser design has mainly been focused on determining the required tension set by the drilling rig tensioning system and the loads seen by the marine drilling riser over the full column of seawater (between 3650 and 4300 meters) while the drilling riser is in a 'connected' mode (marine drilling riser is connected to the BOP with the LMRP).

Riser analyses in a 'disconnected' mode where the marine drilling riser is disconnected from the subsea equipment and free standing in the seawater is not investigated in this preliminary study.

5.1 Chikyu Drilling Rig and Equipment Description

The Chikyu drill-ship main equipment data provided by IODP and CDEX are summarized below:

General	
Rig Type	Science drill-ship
Commissioned	2005
Length	210m
Breadth	38m
Height	130m
Operating Draft	9.2m
Max Water Depth	2,500m
Cruising Speed	11.5 knots
Variable Deck Load	23,500 tons
Propulsion	Side and azimuth thrusters and DPS system
Complement	200 people

Drilling Equipment	
Derrick Rating	1250 tons
Block Rating	1250 tons
Top-Drive System	907 ton
Compensator	CMC, 518 ton capacity, 7.62m stroke.
Mud Pumps	3 National Oilwell 14-P-220, 7500 psi WP
Blow Out Preventers	18-3/4" 15,000 psi WP stack, (2) 10K WP Annulars

Mud Processing

Active Mud	510 m^3 (3,208 bbl)
Reserve Mud	1700 m^3 (10,693 bbl)
Bulk Mud	758 m^3 (4,768 bbl)
Bulk Cement	525 m^3 (3,302 bbl)

Riser Tensioners 6 sets by 363 ton capacity, 15.85m stroke

Table 2—Riser System Data (data provided by CDEX)

Equipment	Type	Principal Particulars	Weight
RISER SYSTEM Manufacturer: Cameron Model: LoadKing 4.0	Flanged Type Load Sharing Riser Marking Color : Green Blue Orange Red	19.5"ID x 90 ft/joint Rated for 1,814 ton (4,000 kips) (Load Share System) API X80 (Strength equivalent to X75 - NACE), Seam Welded Choke/Kill: 2 - ASTM A-519 Gr.4130, 6.25"OD/4.25"ID, 103.4 MPa (15,000 psi) Booster: 1 - ASTM A-519 Gr.4130, 5"OD/4"ID, 51.7 MPa (7,500 psi) Hydraulic: 1 - UNS S31803, 3.625"OD/3"ID, 34.5 MPa (5,000 psi) 19 - High Strength Riser Joint with 610 m (2,000 ft) W.D. Buoyancy 11 - High Strength Riser Joint with 914 m (3,000 ft) W.D. Buoyancy 22 - Low Strength Riser Joint with 1,524 m (5,000 ft) W.D. Buoyancy 22 - Low Strength Riser Joint with 2,134 m (7,000 ft) W.D. Buoyancy (Total 74 Joints with Buoyancy) 12 - Low Strength Riser Joint without Buoyancy 1 - High Strength Riser Joint without Buoyancy 1 - Centralizer Joint (Total 14 Joints without Buoyancy)	 19 x 28 ton 11 x 27.6 ton 22 x 26.8 ton 22 x 28.3 ton (Total 2,048 ton) 12 x 18.9 ton 20.3 ton 27.5 ton (Total 275 ton)
		Each 1 - Riser Pup Joint 60 ft (Riser Landing Joint), 35 ft, 30 ft, 25 ft, 20 ft, 15 ft, 10 ft	12.7 ton, 8.5 ton, 7.5 ton, 6.7 ton, 5.7 ton, 4.7 ton, 3.8 ton Total 49.6 ton
		1 - Telescopic Joint, 65 ft (19.8 m) stroke, 500 psi, 4,000 kips (1,814 ton), 25.019 mL 1 - Bumper Joint for Telescopic Joint, 4,000 kips, 25 ft 1 - Intermediate Flex Joint, Oilstates (for Telescopic Joint), 500 psi, +/- 20°, 4,000 kips (1,814 ton), 3.658 mL 1 - Safety Joint, 10 ft, 3,500 kips 1 - Termination Joint, 45 ftL 1 - Instrumented Joint, 35 ftL (10.668 mL) 2 - Riser Handling Tool with Test Plug, Hyd., 2,750 kips (1,247 ton), Cameron Hydraulic LoadKing (LK) 1 set - Tensioner Support Ring	38 ton 8.4 ton 11.1 ton 2.9 ton 14.1 ton 10.8 ton 4.4 ton & 3.2 ton 23.5 ton Total 117 ton

5.2 Marine Drilling Riser Analysis

5.2.1 Definition

A complete marine drilling riser analysis is a compilation of a number of analyses, which investigates the overall static and dynamic responses of a marine drilling riser for various environmental loads (1 Year Return Period, 10 Year Return Periods, Extreme or Storm Event), vessel loads (from -10% to +10 % of water depth vessel offset ≈ - 400 meters downstream to + 400 meters upstream) and drilling loads (seawater with 1.03 specific gravity to mud weights up to 1.7 specific gravity based on pore pressure assumptions described in section 6.3). Each analysis is investigated in detail with the pertinent drilling riser response characteristics plotted.

5.2.2 Hydrodynamics

A marine drilling riser is a tube that can be made of steel, aluminum, titanium or composite materials that is used to conduct drilling, running and setting casing, cementing and coring operations through the seawater column.

Wave and currents moving past the marine drilling riser will place forces upon the riser causing it to displace, rotate and stress. These forces are transmitted up the drilling riser to the drilling vessel and down the riser to the BOP stack and the conductor casing.

The force loadings are calculated using the industry standard Morrison's equation. This equation calculates the force per unit length along a cylindrical member. The equation is referenced below:

$$F = \frac{1}{2} C_D \frac{\rho}{g} D v^2 + C_M \frac{\rho}{g} \frac{\pi D^2}{4} a \qquad \text{(Eq. 1)}$$

where:

F = force per unit length
C_D = drag coefficient (values range between 1.1 to 1.3)
ρ = density of water
g = acceleration of gravity
D = riser pipe diameter
v = water particle velocity
C_M = mass coefficient (usually taken as 2.0)
a = water particle acceleration

Since Morrison's Equation is non-linear (note the velocity squared term and the diameter squared term), the wave water particle velocities are added to the current water particle velocities before they are squared. However, this is a conservative method because one could square the current velocities and wave velocities and then add them together in the equation and thereby gives lower hydrodynamic forces.

Moreover, because the marine drilling riser is a drag-dominated structure where the riser diameter is very small as compared to the wave length, the first half of Morrison's equation will dominate the load calculation. Thus, the velocity variable is the dominant term because the force is proportional to velocity squared. For instance, if the water particle velocity is doubled, the force on the marine drilling riser will increase by 4 times.

5.2.3 Beam Elements Model and Effective Tension Concept

A marine drilling riser can be modeled as a series of discrete tensioned beam elements and therefore the responses are not difficult to quantify. Moreover, rotations, displacements, and stresses are calculated from engineering mechanics.

In addition, one very important characteristic of a marine drilling riser is the fact that the riser can buckle even when the vessel is pulling on the riser with the tensioning system with a total force greater than the weight of the riser. Because of internal pressure, it is effective tension not actual or real tension that controls buckling of a marine drilling riser.

Effective tension is a mathematical derived expression, contained in the equation of motion for a marine drilling riser. Effective tension must always be a positive value to keep the riser from buckling. As shown in the following equation below, the effective tension is a function of real tension (as calculated from the law of statics), riser internal diameter (ID) and external diameter (OD), and, internal pressure and external pressure. Also, it is important to note how the internal pressure multiplied by the internal riser ID area decreases the effective tension value while external pressure multiplied by the external riser OD area increases the effective tension value. The problem is that the external pressure on a marine drilling riser is fixed (seawater) while the internal pressure is variable based on drilling, pore-pressure, fracture and wellbore stability conditions (mud weight used).

$$T_{effective} = T_{real} - p_i A_i + p_e A_e \qquad \text{(Eq. 2)}$$

where:

$T_{real} =$ Tension as calculated from free body diagrams

$p_i =$ Internal pressure

$A_i =$ Inside area of the riser $= \frac{\pi}{4} \cdot ID^2$

$p_e =$ External pressure

$A_e =$ External area of the riser $= \frac{\pi}{4} \cdot OD^2$

In order to satisfy the effective tension requirements, one must remember that the vessel tension must support not only the marine drilling riser weight but must also support the weight of the riser contents (drilling fluids).

Historically, oil and gas operators prefer to keep the well-head in compression during drilling in order to keep well-head fatigue at a minimum. Thus, the riser tension set by the tensioning system cannot over-pull the wet weight of the Lower Marine Riser Package (LMRP) / Blow-out Preventer (BOP) stack. If, for shallow water depths and heavy stacks, the compression load on the well-head keeps the fatigue damage at a minimum, when the water depth and mud weight increases the internal pressure becomes much larger at the bottom of the drilling riser (due to high mud weight) which results in the effective tension going negative unless more surface tension is pulled. When doing so, one could eventually over-pull the weight of the LMRP and possibly the BOP stack to keep the effective tension positive. This now places the well-head in tension and may result in fatigue damage to the wellhead system.

5.3 Metocean Data

As seen in Morrison's equation, environmental loading is important. Since operational limits are necessary to determine when the drilling vessel can run riser, set casing strings, drill and core, a full matrix of environmental loadings has to be investigated to set the operational boundaries.

5.3.1 Wave Data

The wave criteria are derived from National Maritime Research Institute data (NMRI, Tokyo, Japan). Since an exact well site has yet to be determined the highest wave heights were selected from area w19, w20 and w29 corresponding respectively to Baja, Hawaii and Cocos locations shown in Figure 3 below.

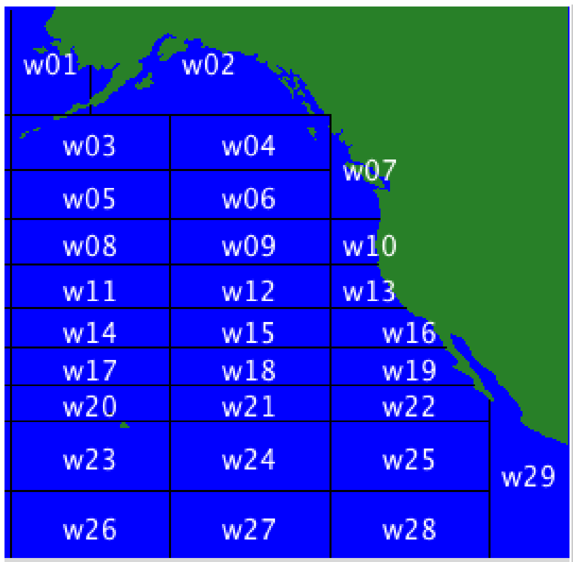

Figure 3—Pacific Ocean Wave Height Data Area Division, NMRI, Japan

The significant wave height and period used in the analyses and tied to the return period are summarized in Table 3 below. Significant wave height given in meters is the average of the highest one-third of the waves and is an industry used value. Also, significant wave period given in seconds is the average period of the highest one-third of waves in a given set of waves.

Table 3—Wave Data in the Pacific Ocean, Modified from NMRI, Japan

WAVE DATA (NMRI : 1974-1988)			
LOCATION	Significant Wave Height (m)	Maximum Wave Height (m)	Peak Period (s)
Cocos Plate	1	1.7	9
Hawaii	4	6.8	9
Baja California	3	5.1	9

5.3.2 Current Data

The ocean currents criteria are derived from two different sources: the National Oceanic and Atmospheric Administration (NOAA, USA) which measured near ocean surface currents at the three different locations from satellite altimeter and scatterometer instruments over a 18-year period (1993-2010). Also, the Japanese Oceanographic Data Center (JODC) has measured and generated statistical analyses in a one degree mesh in latitude and longitude for surface ocean currents using geomagnetic, electro kinetograph and acoustic Doppler instruments over a 41 year period (1953-1994) in the three region considered for drilling the oceanic crust to the upper mantle.

However, at this stage of the study, data for ocean current at mid water depth and deep ocean current were assumed based on Blade experience with other oceanic waters. Table 4 details the ocean current values used in the analyses.

Table 4—Surface Ocean Current Data in the Pacific Ocean, JODC, Japan and NOAA, USA

		LOCATION											
		Cocos Plate				Hawaii				Baja California			
	Return Period (Year)	Depth (meters)											
		1	500	1,000	4,000	1	500	1,000	4,000	1	500	1,000	4,000
Mean Ocean Surface Currents (JODC : 1953-1994) in knots	41	0.4	0.30	0.30	0.20	0.15	0.10	0.10	0.05	0.1	0.05	0.05	0.05
Mean Ocean Surface Currents (NOAA : 1993-2010) in knots	18	0.35	0.25	0.25	0.15	0.1	0.10	0.10	0.05	0.1	0.05	0.05	0.05

5.4 Marine Drilling Riser Configuration

To conduct, ultra-deepwater drilling operations, the drilling riser system is a complex multi-component system that forms a conduit between the Chikyu drilling vessel and the BOP at the seafloor. The major components from top to bottom are briefly described below:

- Riser tensioners are components enabling top tension to be applied to the marine drilling riser.
- The diverter enables the drilling fluid returns to be conveyed to the mud pits.

- The telescopic joint inner barrel is attached to the diverter with a flex/ball joint allowing an angular rotation at the top of the riser.
- The telescopic or slip joint is the link between the last upper riser joint and the drilling vessel. The slip joint stroke compensates vessel heave and offset.
- Riser joints are 20 to 30 meter long equipped with choke, kill and booster lines and also buoyancy modules to reduce the weight in water.
- Pup joints are short riser joints and generally without any buoyancy modules.
- The lower flex/ball joint enables angular rotation at the bottom of the riser to offset lateral movements of the drilling vessel and also displacement of the drilling riser due to environmental loading.
- The Lower Marine Riser Package (LMRP) placed on top of the Blow-out Preventer (BOP) provides a hydraulic way for disconnecting the drilling riser from the BOP when necessary. In the case of a disconnection, the BOP stays on top of the well-head to guaranty the safety of the wellbore drilled.

Figure 4 and Figure 5 illustrate the drilling vessel and marine drilling riser configurations.

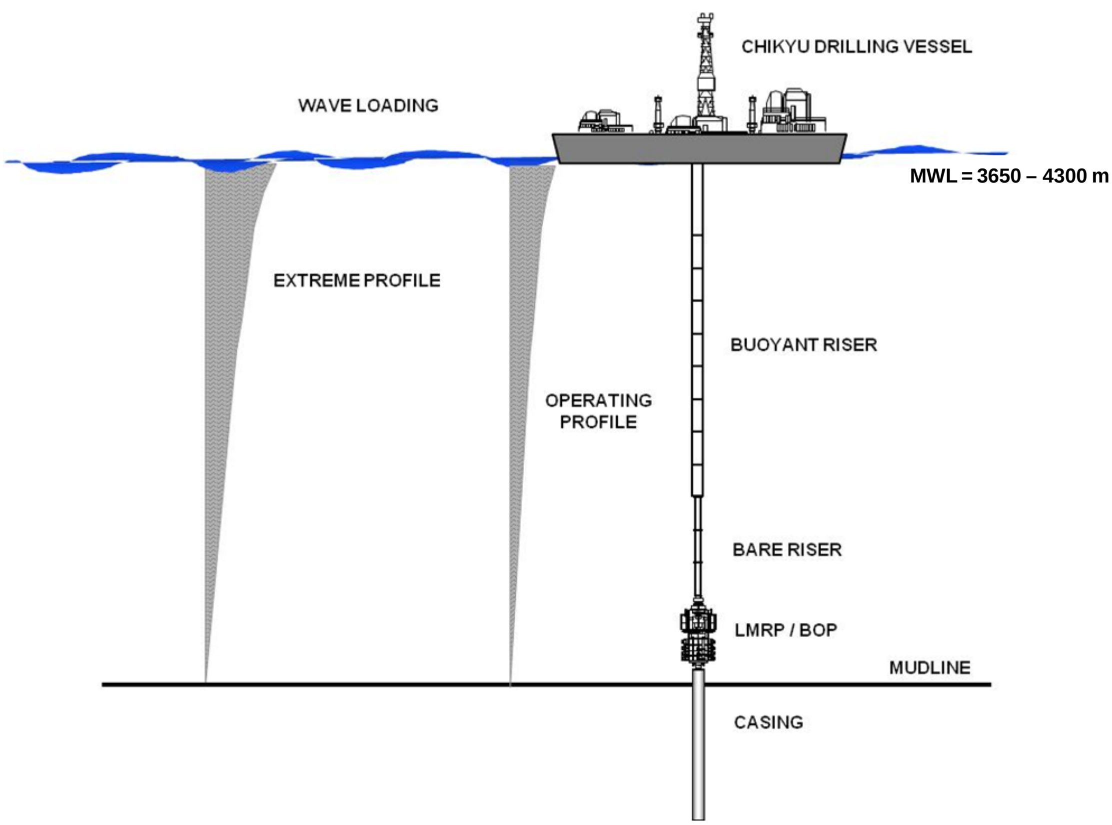

Figure 4—Chikyu Drilling Rig and Drilling Riser Connected Analysis Model

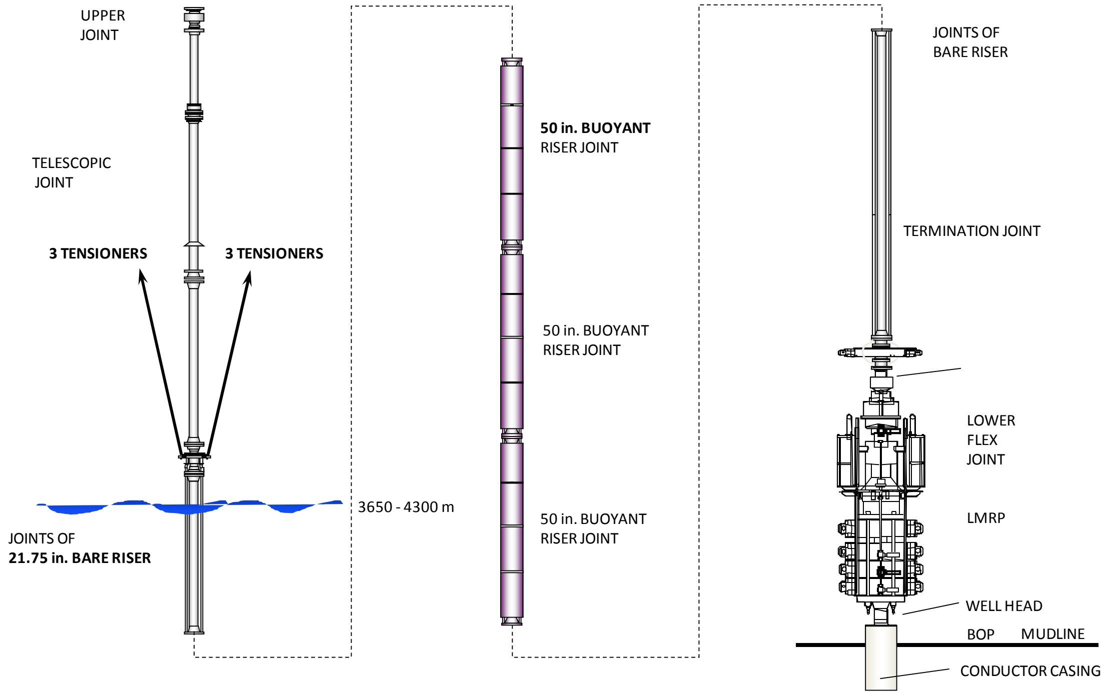

Figure 5—Detailed Drilling Riser and Subsea Components

5.5 Drilling Riser Options for Cocos Plate, Baja and Hawaii

Drilling with riser in water depths ranging between 3650 and 4300 meters demands to break the current 'riser drilling' world record set around 3000 meters water depths. Therefore, different marine drilling riser options need to be analyzed to emphasize on the current limitations and therefore new design, configuration and material needed for drilling risers to enable drilling in such ultra-deepwater. The different options for Mohole are as follows:

- Current Chikyu marine drilling riser
- Current Chikyu marine drilling riser bare joints with lighter buoyancy modules
- Titanium marine drilling riser
- Slim marine drilling riser
- Hybrid marine drilling riser
- Current Chikyu marine drilling riser with 2 more tensioners

To prevent the drilling riser from buckling, top tension is required during floating drilling operations. Top tensioners are used to ensure that a constant tension is set at the top of the marine drilling riser. From Chikyu specifications provided by CDEX, the drilling rig tensioner system has a maximum tension capacity at mid-stroke of 1512 ton (14821 kN). In addition, API 16Q (Marine Drilling Risers) and ISO 13624 – Part 1 (Design and Operation of Marine Drilling Riser Equipment) specifications require that the recommended tensioner system efficiency to be set at 90% of the maximum tension usage. Thus, bringing the allowable tension to 1360 ton (13340 kN). In addition, one needs to account for the case where one tensioner could fail and thereby the remaining available tension would be 1134 ton (11116 kN).

In the following sections 5.5.1 to 5.5.6, figures, curves and results are presented for the Hawaii location only for which water depths are estimated to be 4050 meters. The buckling limit curve represents the value of the real tension T_{real} that yields an effective tension $T_{effective}$ equal to zero as shown in equation 2. The minimum tension required curve represents the summation of the real tension T_{real}, the weight of the BOP and a safety margin of about 20 ton (200 kN). Slight variations and changes in values for required top tension and buckling limits were seen for the two other potential locations since Cocos water depths are expected to be 3650 meters and Baja water depths are evaluated to be around 4300 meters. However, a summary Table 5 gives a comparison for the six different options in section 5.5.7.

5.5.1 Current Chikyu Marine Drilling Riser

The following Figure 6 and Figure 7 present the buckling limits and minimum tension required when drilling to the upper mantle using the current marine drilling riser currently onboard the Chikyu drill-ship and using the same riser joint properties to enable the Chikyu to drill in water depths up to 4300 meters.

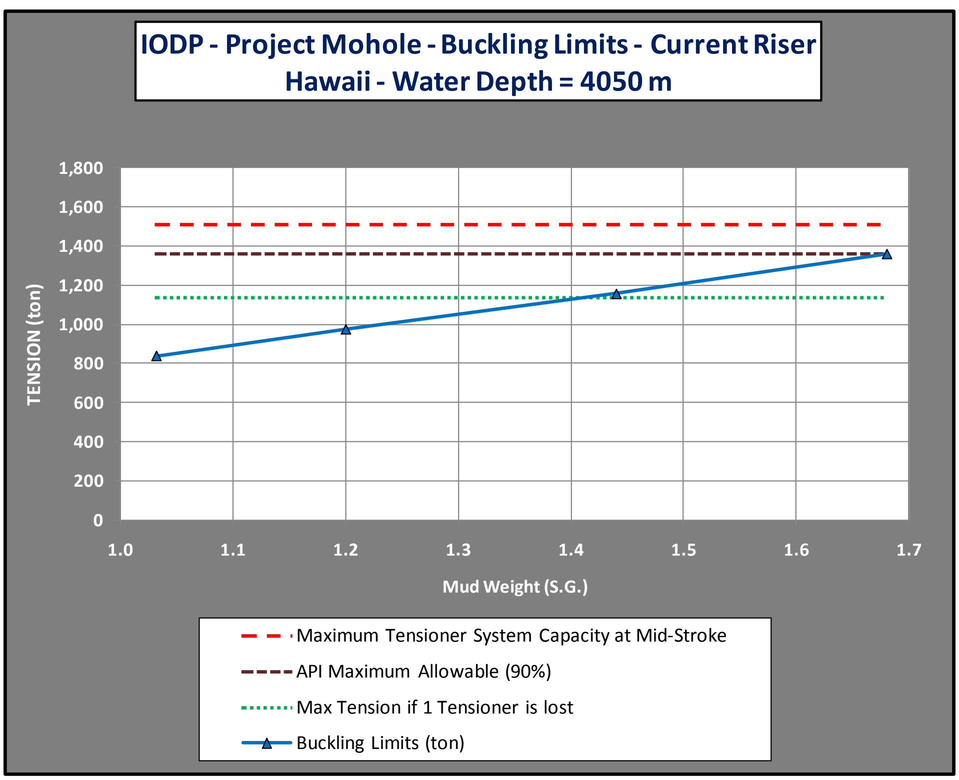

Figure 6—Buckling Limits for the Current Drilling Riser in 4050 meters of water

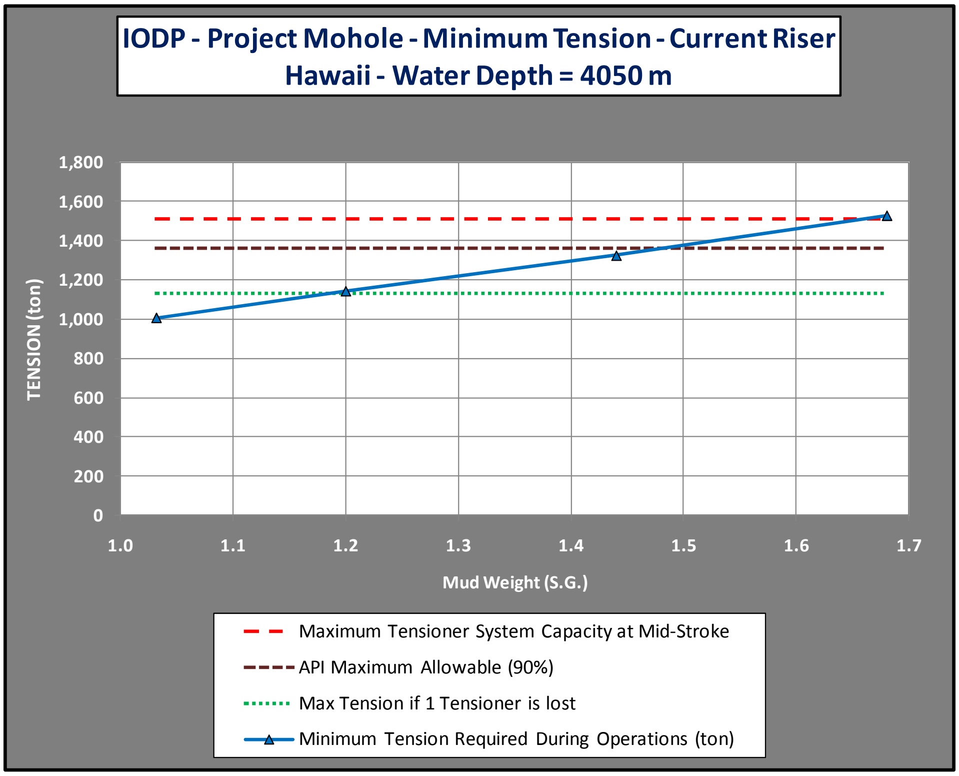

Figure 7—Minimum Tension for the Current Drilling Riser in 4050 meters of water

Based on the Hawaii location where the average water depth is estimated to be 4050 meters, and the current Chikyu marine drilling riser configuration, the riser will buckle when drilling with a mud weight greater than 1.47 S.G. Furthermore, if one tensioner is lost, the maximum mud weight is only 1.2 S.G.

5.5.2 Current Chikyu Marine Drilling Riser with Lighter Buoyancy Modules

The following Figure 8 and Figure 9 present the buckling limits and minimum tension required when drilling to the upper mantle using the current marine drilling riser currently onboard the Chikyu drill-ship and using improved buoyancy modules to help offset the increase in dry weight of the drilling riser.

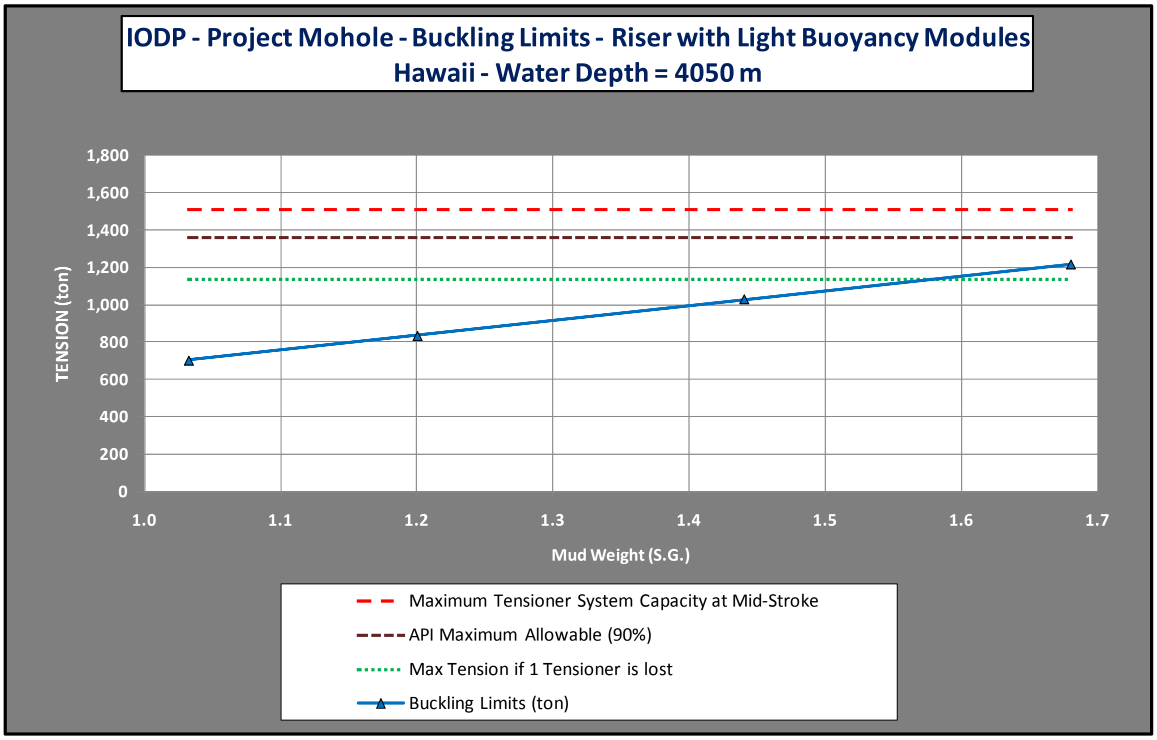

Figure 8—Buckling Limits for the Current Drilling Riser with Lighter Buoyancy Modules in 4050 meters of water

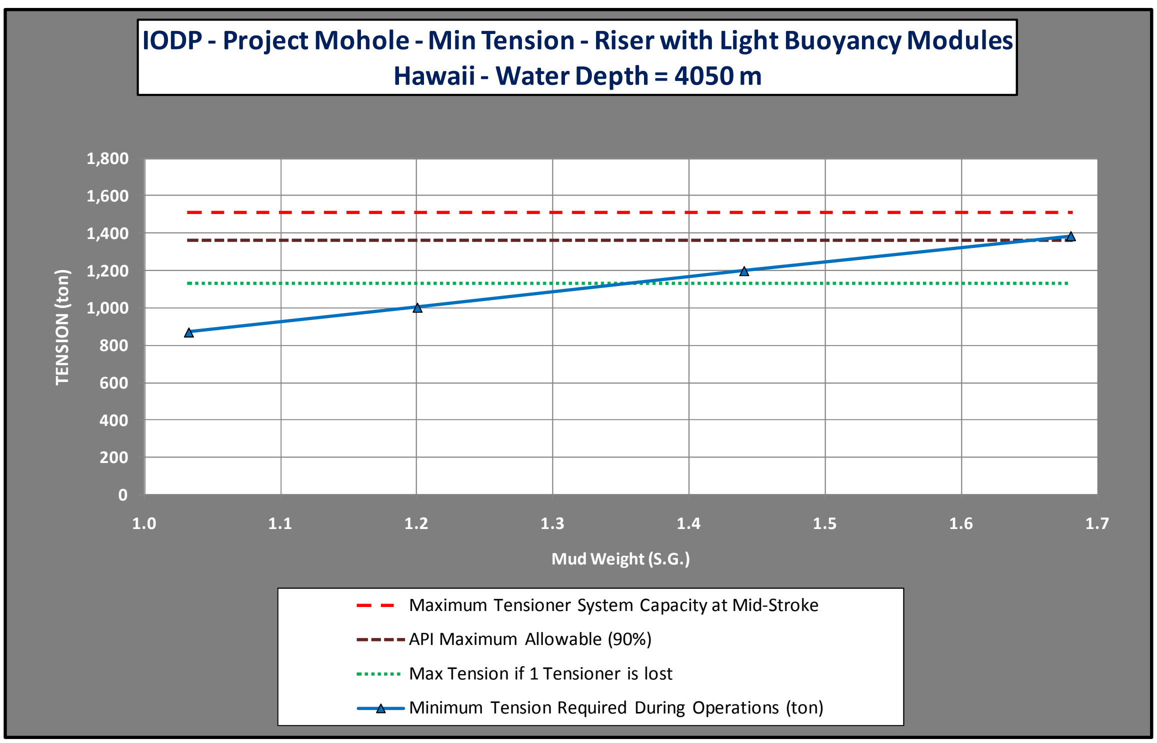

Figure 9—Minimum Tension for the Current Drilling Riser with Lighter Buoyancy Modules in 4050 meters of water

Based on the Hawaii location where the average water depth is estimated to be 4050 meters, and the current Chikyu marine drilling riser configuration associated with lighter buoyancy modules, the riser will buckle when drilling with a mud weight greater than 1.6 S.G. Furthermore, if one tensioner is lost, the maximum mud weight is only 1.35 S.G.

5.5.3 Titanium Marine Drilling Riser

Titanium physical and mechanical properties make it attractive when component weight is a limiting factor. ASTM, Grade 23 titanium alloy is the most widely used in the offshore industry for riser joints and connectors. With a density of 4430 kg/m^3, titanium is about 40% lighter than steel. Also, a few manufacturers have already designed and produced similar drilling 21-inch riser joints to the ones needed for the Mohole project.

The following Figure 10 and Figure 11 present the buckling limits and minimum tension required when drilling to the upper mantle using a titanium marine drilling riser.

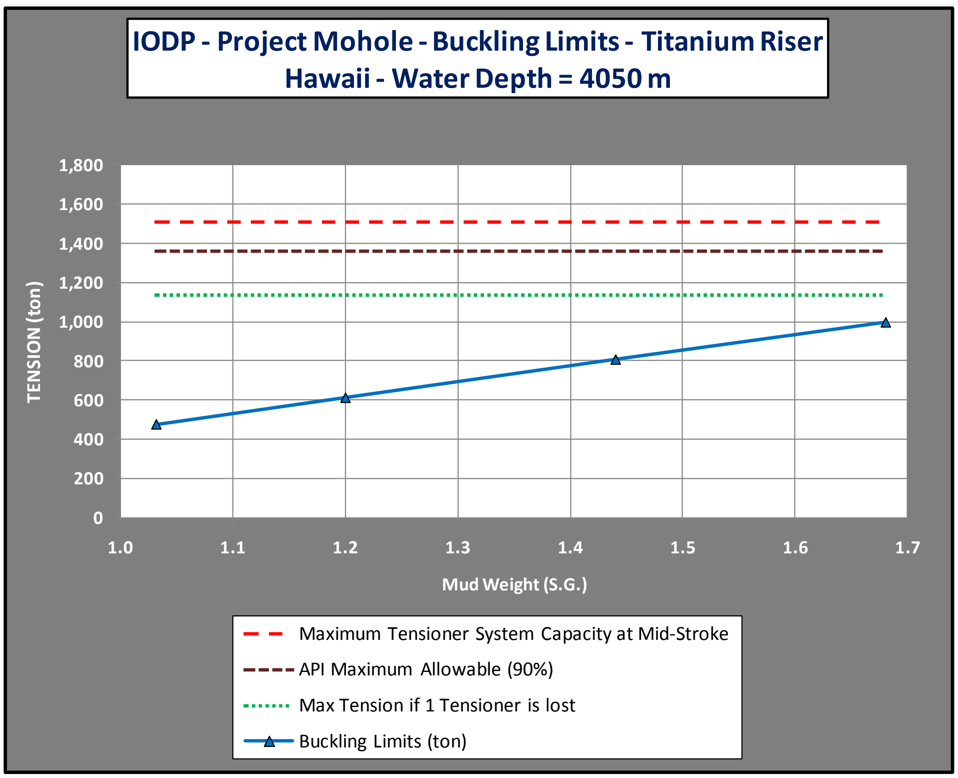

Figure 10—Buckling Limits for the Titanium Drilling Riser in 4050 meters of water

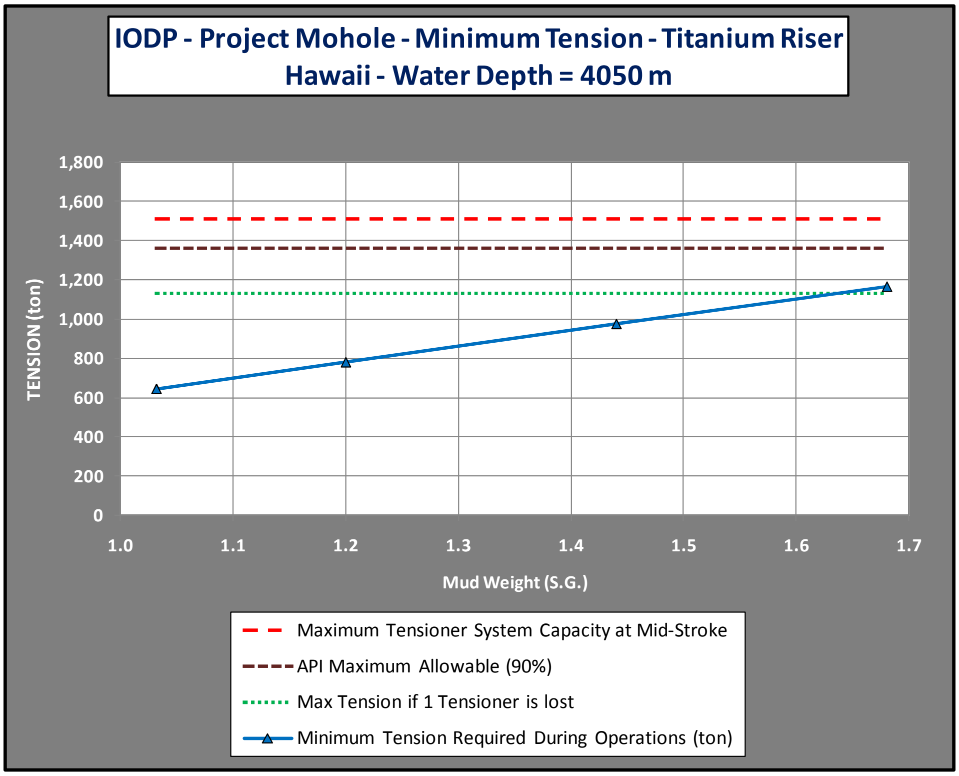

Figure 11—Minimum Tension for the Titanium Drilling Riser in 4050 meters of water

Based on the Hawaii location where the average water depth is estimated to be 4050 meters, and a titanium marine drilling riser, the riser will not buckle even when drilling with a mud weight greater than 1.7 S.G. In addition, if one tensioner is lost, the maximum mud weight could be as high as 1.65 S.G.

5.5.4 Slim Marine Drilling Riser

Slim riser using 16-inch diameter bare joints instead of 21-inch diameter standard joints has numerous advantages. First of all, weight saving for bare joints and joints with buoyancy modules ranges between 20% and 40% as compared with 21-inch riser joints. Riser cleaning and mud particles transport is more efficient. Also, the deck space and mud pit volume limitations make a smaller diameter drilling riser a better choice. In addition, there is no need for a smaller BOP stack because the slim riser connects with the same LMRP and 18-3/4 inch BOP stack used with the 21-inch riser. Finally, one or two manufacturers have already pre-designed and studied 16-inch riser joints to be used for ultra-deepwater applications. The slim riser configuration is illustrated in Figure 12 below.

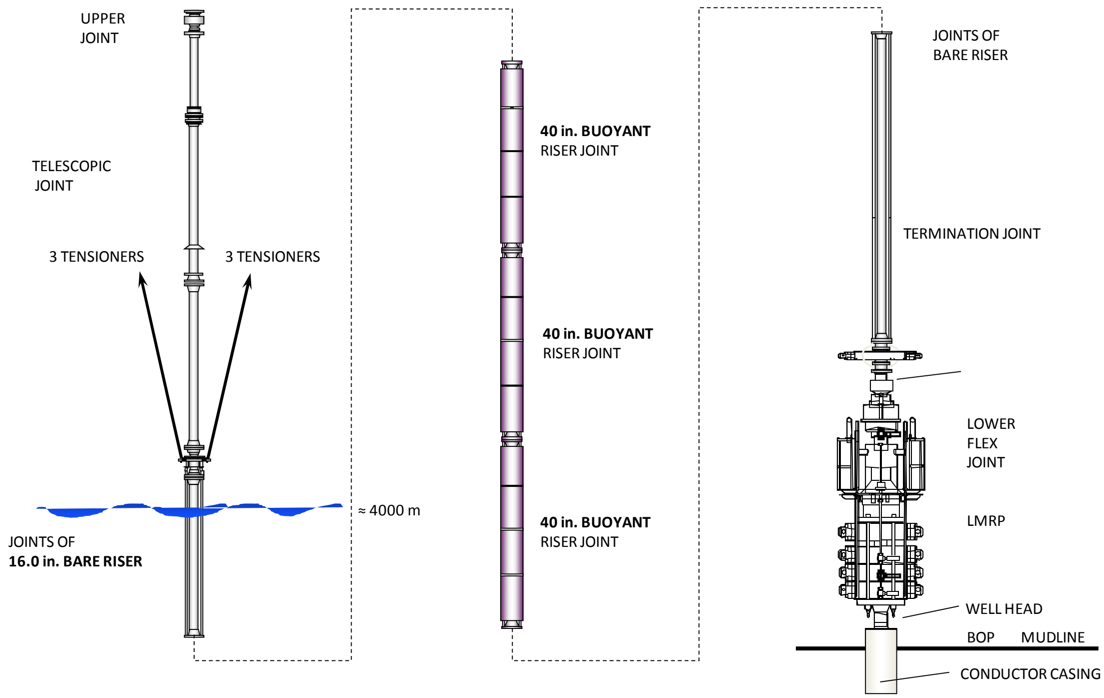

Figure 12—Detailed 16-inch Slim Drilling Riser and Subsea Components Configuration

The following Figure 13 and Figure 14 present the buckling limits and minimum tension required when drilling to the upper mantle using a 16-inch slim marine drilling riser.

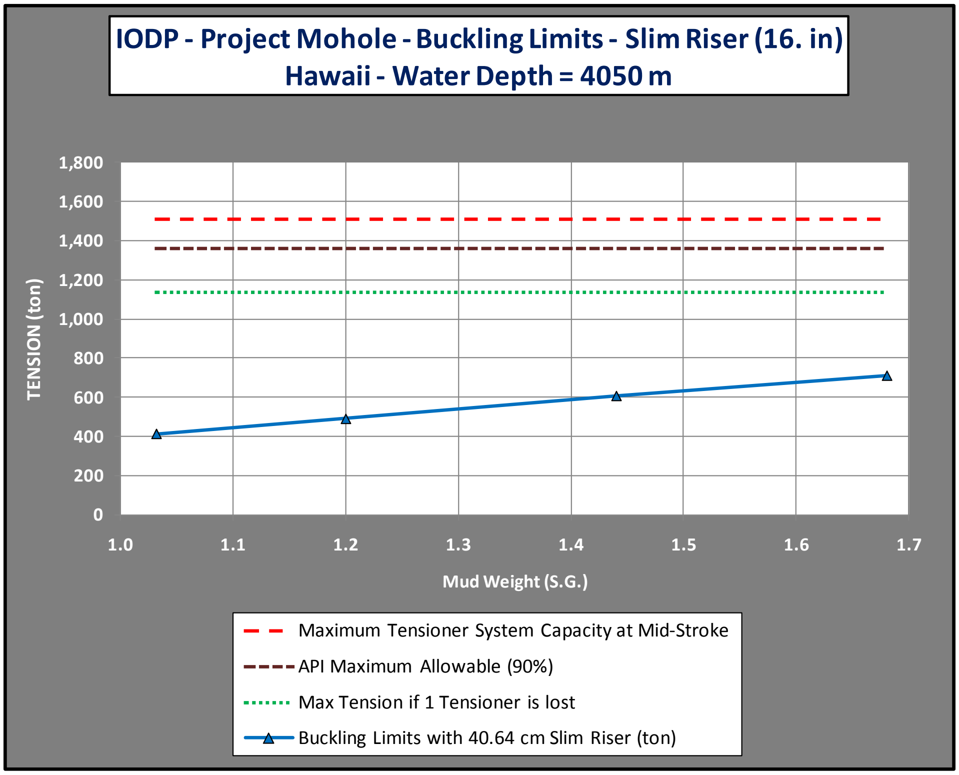

Figure 13—Buckling Limits for the 16-inch Slim Drilling Riser in 4050 meters of water

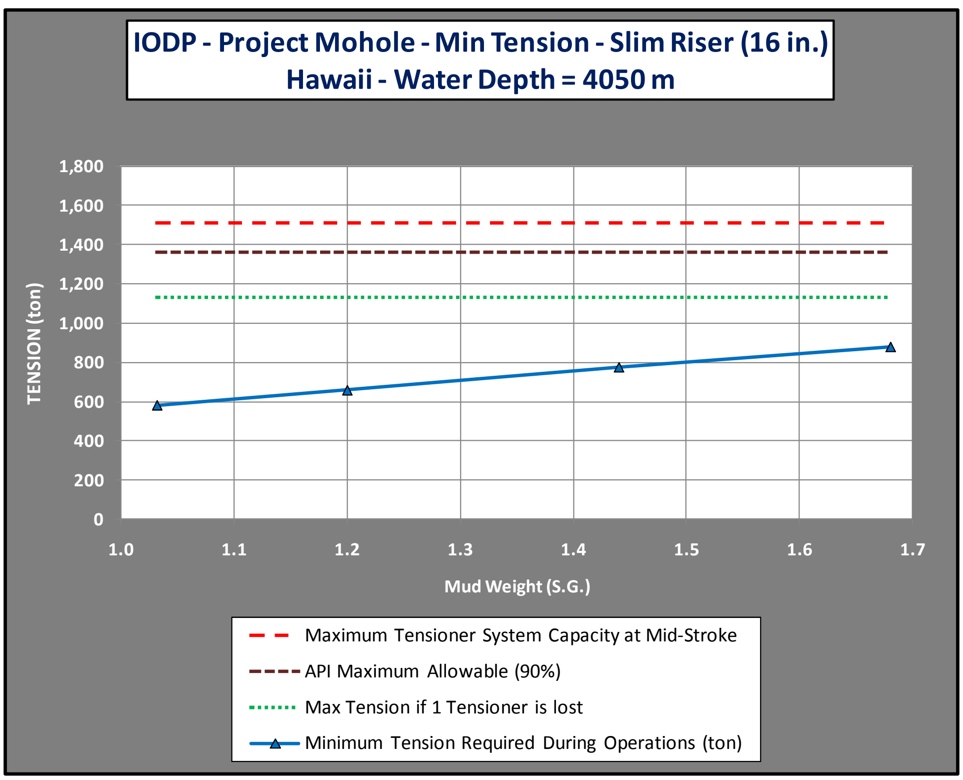

Figure 14—Minimum Tension for the 16-inch Slim Drilling Riser in 4050 meters of water

Based on the Hawaii location where the average water depth is estimated to be 4050 meters, and a 16-inch slim marine drilling riser, the riser will not buckle even when drilling with a mud weight greater than 1.7 S.G. In addition, if one tensioner is lost, the maximum mud weight could be greater than 1.7 S.G.

5.5.5 Hybrid Marine Drilling Riser

To save weight and to offset the cost increase associated with the full drilling riser made of titanium alloys, an hybrid configuration made of about 50% of steel joint (≈ 2000 meters of joints) from the current drilling riser available on the Chikyu vessel and about 50% of riser joints made of titanium (≈ 2000 meters) is investigated in the following and which present the buckling limits and minimum tension required when drilling to the upper mantle using an hybrid marine drilling riser configuration.

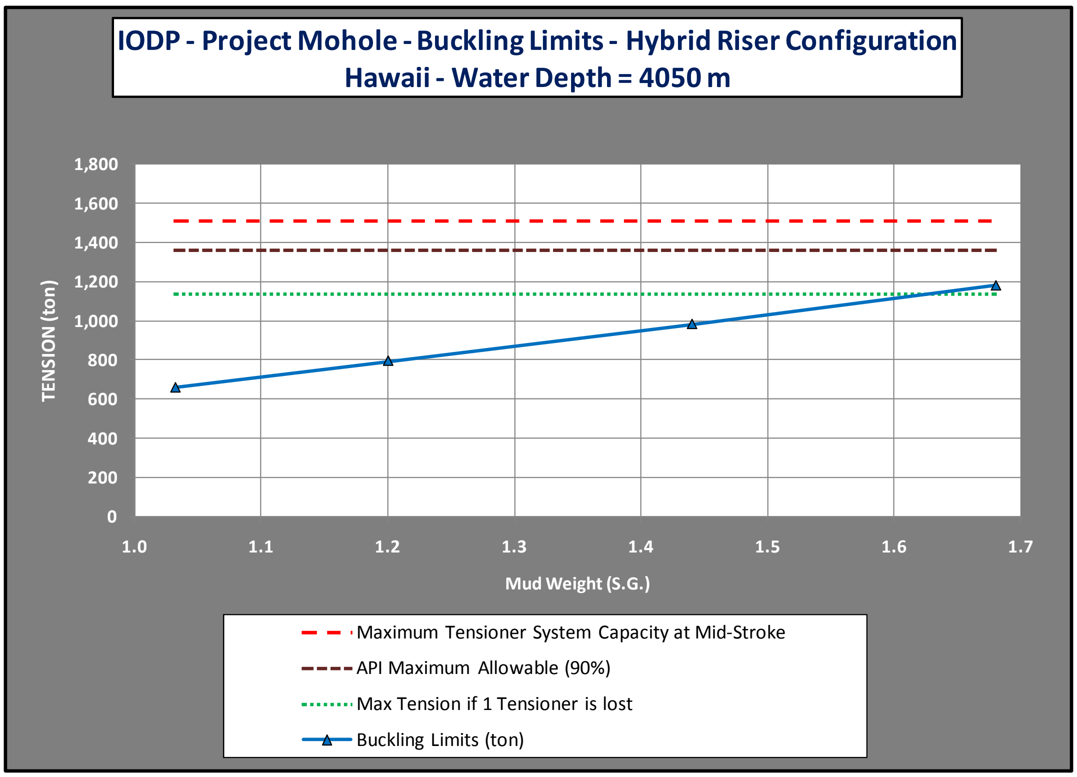

Figure 15—Buckling Limits for the Hybrid Drilling Riser Configuration in 4050 meters of water

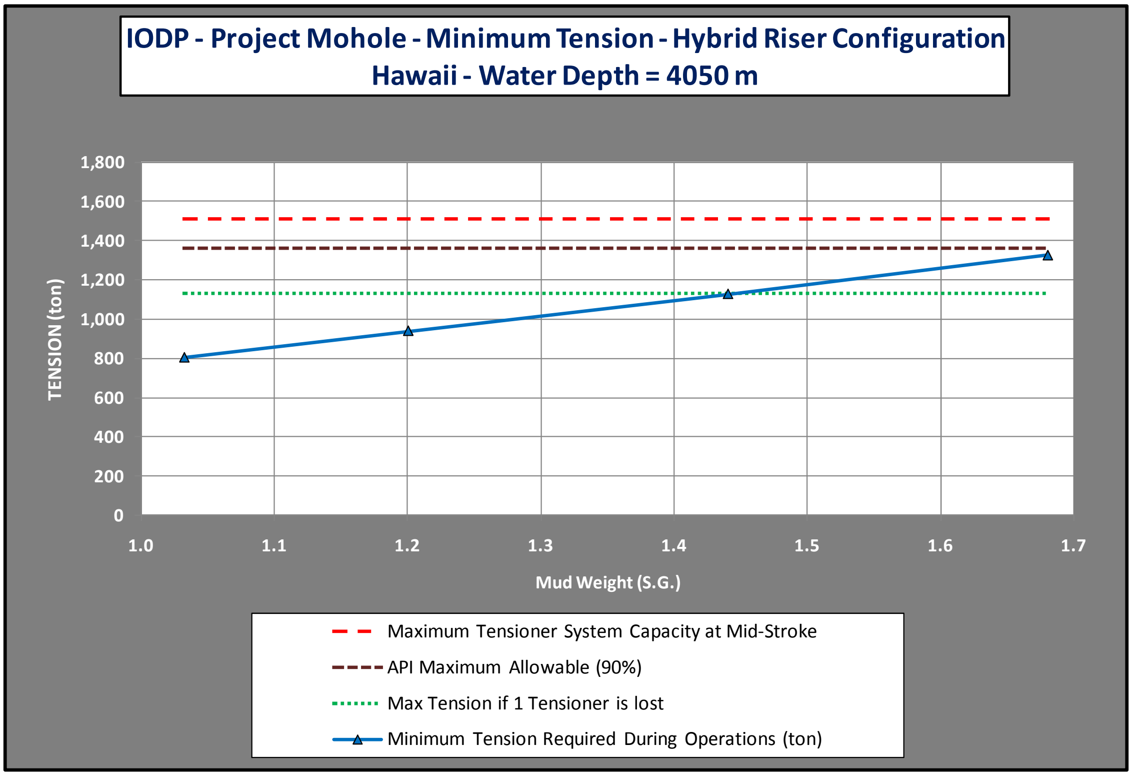

Figure 16—Minimum Tension for the Hybrid Drilling Riser Configuration in 4050 meters of water

Based on the Hawaii location where the average water depth is estimated to be 4050 meters, and the current Chikyu marine drilling riser configuration associated with lighter buoyancy modules, the hybrid riser configuration will buckle when drilling with a mud weight greater than 1.6 S.G. Furthermore, if one tensioner is lost, the maximum mud weight is only 1.35 S.G.

5.5.6 Current Chikyu Marine Drilling Riser with 2 More Tensioners

As mentioned previously, in order to prevent the drilling riser from buckling, top tension is required during floating drilling operations. If the drilling rig maximum tension capacity at mid-stroke of could be increased by adding two more tensioners (from six tensioners to eight tensioners), it would set the maximum tensioning capacity to 2015 ton (19762 kN) and 90% of the maximum tension usage to 1814 ton (17786 kN). In addition, even when one tensioner fails, the remaining available tension would be 1587 ton (15563 kN).

The following Figure 17 and Figure 18 present the buckling limits and minimum tension required when drilling to the upper mantle using the current marine drilling riser available on the Chikyu and adding two tensioners to the already six tensioners present onboard the drill-ship.

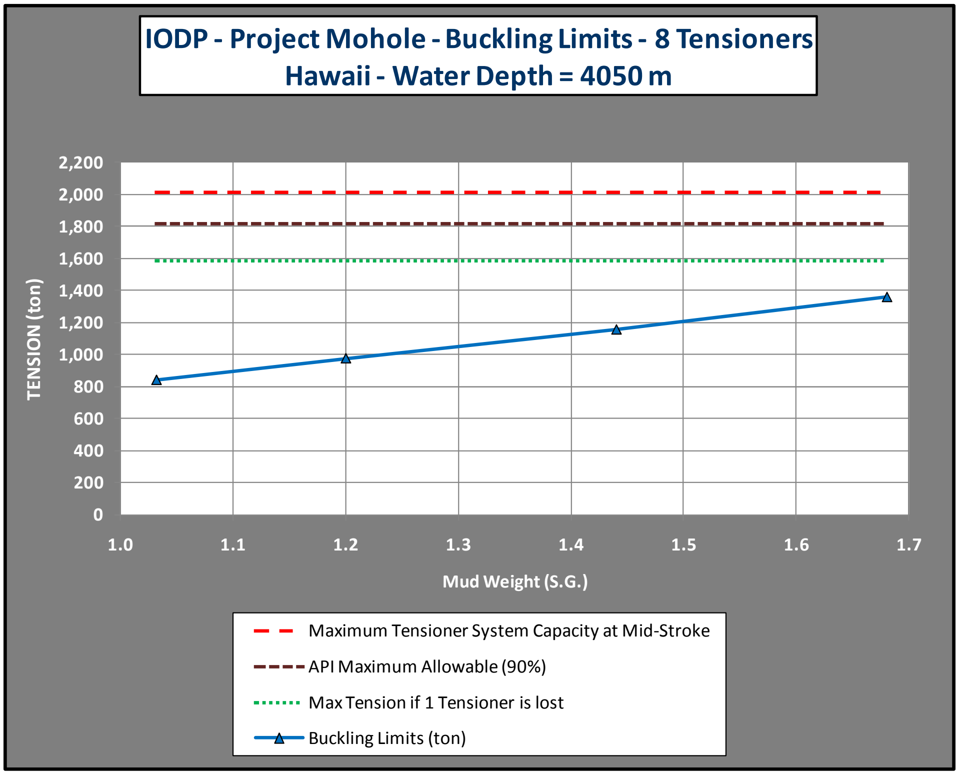

Figure 17—Buckling Limits for the Drilling Riser with 2 More Tensioners in 4050 meters of water

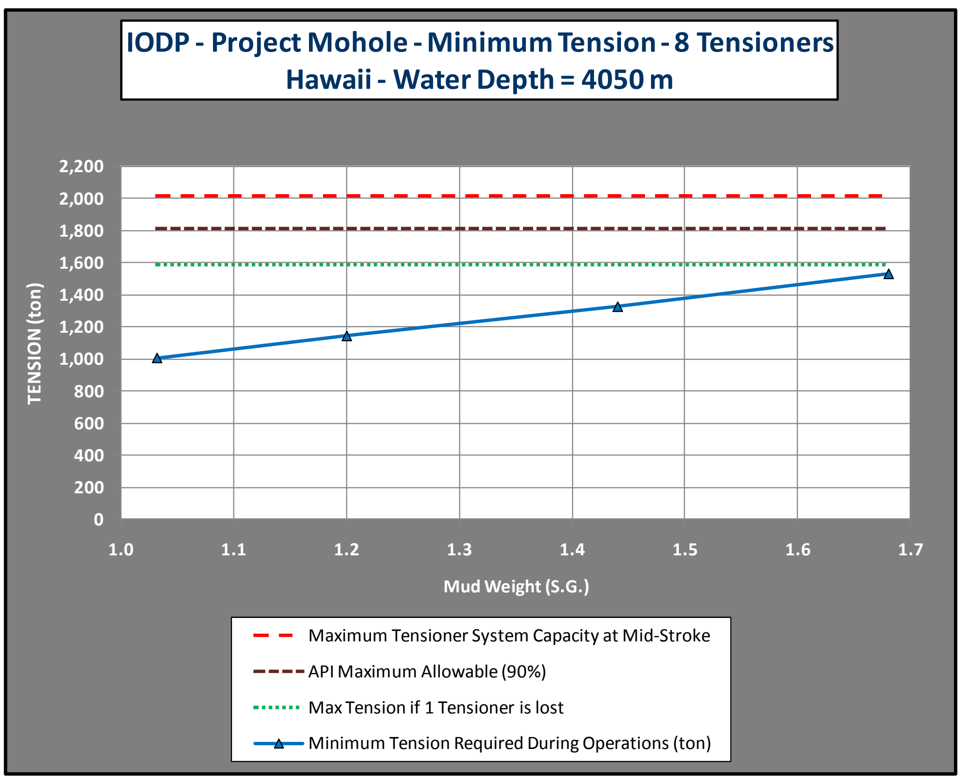

Figure 18—Minimum Tension for the Drilling Riser with 2 More Tensioners in 4050 meters of water

Based on the Hawaii location where the average water depth is estimated to be 4050 meters, and with two more tensioners on the Chikyu drill-ship and keeping the same steel marine drilling riser, the riser will not buckle even when drilling with a mud weight greater than 1.7 S.G. In addition, if one tensioner is lost, the maximum mud weight could be greater than 1.7 S.G.

5.5.7 Summary and Discussion

Table 5 below lists the limitations and benefits for each of the six drilling riser configurations that have been analyzed. Mud weight value limits in specific gravity (S.G.) are given; 'OK' must be read as mud weight greater than 1.7 S.G. can be used with this drilling riser configuration at this location.

Table 5—Summary Table for the 6 Different Drilling Riser Options Analyzed for the 3 Locations

WATER DEPTH		Current Chikyu Drilling Riser	Steel Riser with Lighter Buoyancy Modules	Titanium Riser	Slim Riser (16" OD)	Hybrid Riser (Steel + Titanium)	Current Chikyu Drilling Riser with 8 Tensioners
WATER DEPTH (3650 m) - COCOS PLATE	Maximum Drilling Fluid (S.G.) in Riser if 1 Tensioner is lost =	OK up to 1.3 SG	OK up to 1.45 SG	OK	OK	OK up to 1.55	OK
	Maximum Drilling Fluid (S.G.) in Riser if API Maximum Allowable (90%) =	OK up to 1.55 SG	OK	OK	OK	OK	OK
WATER DEPTH (4050 m) - HAWAII	Maximum Drilling Fluid (S.G.) in Riser if 1 Tensioner is lost =	OK up to 1.2 SG	OK up to 1.35 SG	OK up to 1.65 SG	OK	OK up to 1.43	OK
	Maximum Drilling Fluid (S.G.) in Riser if API Maximum Allowable (90%) =	OK up to 1.45 SG	OK up to 1.65 SG	OK	OK	OK	OK
WATER DEPTH (4300 m) - BAJA CALIFORNIA	Maximum Drilling Fluid (S.G.) in Riser if 1 Tensioner is lost =	NOT OK	OK up to 1.2 SG	OK up to 1.55 SG	OK	OK up to 1.35	OK up to 1.55 SG
	Maximum Drilling Fluid (S.G.) in Riser if API Maximum Allowable (90%) =	NOT OK	OK up to 1.45 SG	OK	OK	OK	OK

Existing technologies, components and materials available in the ultra-deepwater industry should enable the Chikyu drilling vessel to conduct offshore operations in water depths ranging between 3650 and 4300 meters off Baja, Cocos and Hawaii.

It is important to note that some drilling riser options such as aluminum drilling riser and composite materials drilling riser have not been analyzed because the technology maturity and relative low interest for specific drilling riser applications. Therefore, reliable data could not be found to run detailed analyses and also results from these analyses could not have been compared to the other six configurations.

5.5.8 Technologies Ranking (Boston Square Matrix)

To help comparing and ranking the different drilling riser options, three independent criteria have been identified. They are listed as follows:

- Technology maturity ranging from 'emerging' to 'very mature'

- Capital cost ranging from ‘low’ to ‘high’
- Easiness to design, construct and maintain the riser system option ranging from ‘easy/flexible’ to ‘difficult’

In order to rank the marine drilling riser options, a Boston Square Matrix (BSM) which allows consistent ranking with the several criteria can be used. For our application, it includes capital cost on the x axis, easiness to design, construct, and maintain on the y axis, and technology maturity using four different circle sizes ranging from small for ‘emerging’ to large for ‘very mature’. Figure 19 shown below ranks the different marine drilling riser options as of mid 2011. Current research and development programs and oil and gas operations field trials may change the Boston Square Matrix presented in Figure 19.

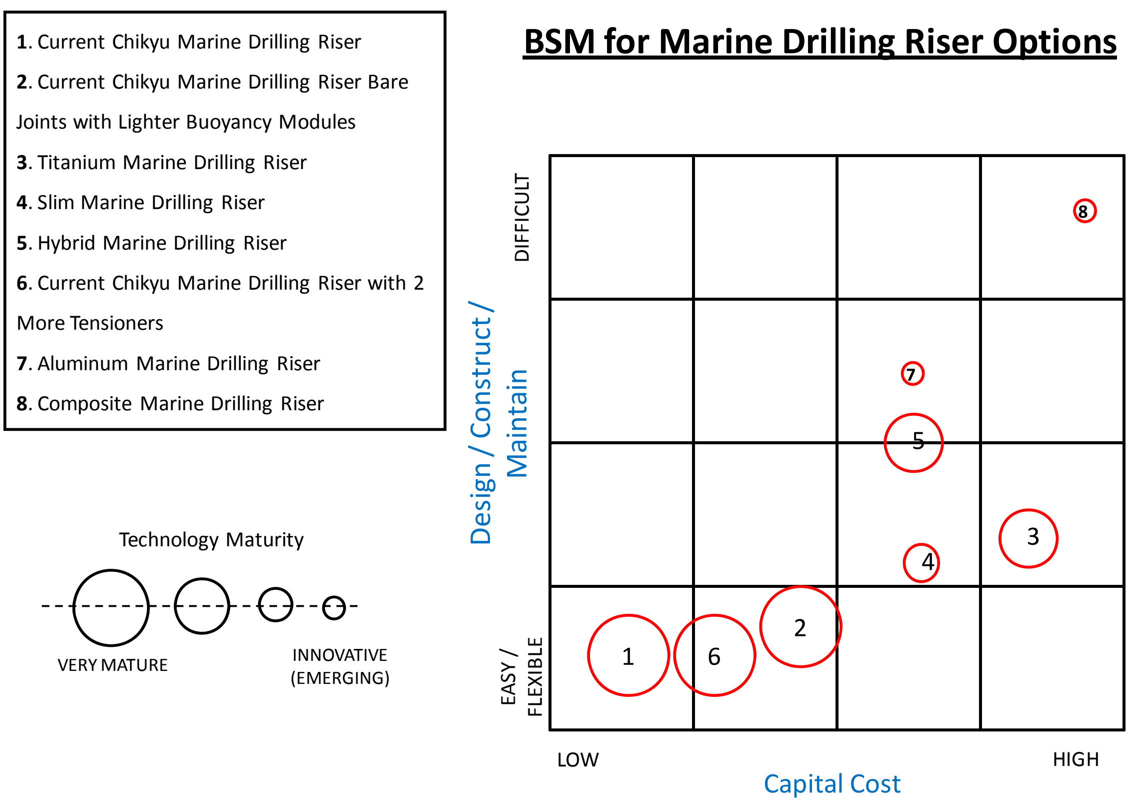

Figure 19—Boston Square Matrix for Marine Drilling Riser Options

5.6 Drilling Riser Dynamic Analyses

Dynamic analyses cover the scenario when the marine drilling riser is installed and the Chikyu drilling rig is drilling ahead through the riser and LMRP/BOP system. The Chikyu drilling vessel and marine drilling riser are exposed from minimal to extreme environmental loadings. The tension on the riser is held constant but the vessel is moving back and forth on the ocean surface in order to maintain position over the well site.

5.6.1 Definition

In the dynamic analyses, multiple variables are changed to understand the dynamic response of the marine drilling riser. The most critical variables are waves, current, tension, mud weight and vessel offset. Waves and ocean current are expressed in term of 1 year return period, 10 year return or extreme return period (storm, hurricane, etc…). Tension as seen in the previous section 5 is set at the top of the riser and is expressed in tons or kilo Newton. Mud weight necessary to drill through the sediments and igneous rocks to reach the upper mantle is expected to range between 1.03 S.G. to 1.7 S.G. Vessel offset is expressed as a percentage of water depth and if the vessel is upstream or downstream of the well. A value of –10% offset in 4000 meters of water signifies the vessel is upstream 400 meters from the well. A value of + 10% signifies the vessel is downstream 400 meters. In addition, the Chikyu drill-ship dynamic behavior is given by a unique set of data called Response Amplitude Operator (RAO) which has been provided by IODP and CDEX. Notably, the six RAOs correspond to the vessel's six degrees of freedom (surge, sway, heave and roll, pitch, yaw) which give a specific response for a given floating unit for a certain wave height and wave period.

For the Hawaii location with water depths averaging 4050 meters, the tension is varied from 900 ton to 1350 ton, mud weight from 1.03 S.G. to 1.68 S.G., vessel offset from –10% to +10%, and one environmental loading (10 Year Return Period). Table 6 summarizes the dynamic connected analyses performed.

Table 6—Summary of Dynamic Connected Analyses Performed

Dynamic Connected Riser Analysis - Hawaii - Water Depth = 4050 meters												
Tension (ton)	900			1050			1250			1350		
Tension (kN)	8826			10297			12258			13239		
Mud Weight (S.G.)	1.03			1.2			1.44			1.68		
Vessel Offset	-10%	0%	10%	-10%	0%	10%	-10%	0%	10%	-10%	0%	10%
10 Year Return	√	√	√	√	√	√	√	√	√	√	√	√

From a dynamic analysis, several loads are analyzed and checked to ensure the marine drilling riser integrity:

- Shear force at the top of the drilling riser
- Shear force at the top of the LMRP/BOP
- Rotation at the top of the drilling riser
- Maximum slip-joint stroke
- Maximum VME stress in the drilling riser

API 16Q Recommended Practice for Design, Selection, Operation and Maintenance of Marine Drilling Riser Systems details the operating limits for marine drilling risers. Table

7 summarizes these limits. The critical parameters are the amount of flex/ball joint rotation, maximum stress and vessel tension.

Table 7—Operating Limits for Steel Marine Drilling Riser as per API 16Q

DESIGN PARAMETER	RISER DYNAMIC CONNECTED		RISER DISCONNECTED
	DRILLING	NON-DRILLING	
Mean Flex / Ball Joint Angle	Mean 2.0 degrees	N/A	N/A
Maximum Flex / Ball Joint Angle	Max **4.0 degrees**	90% available (**9.0 degrees**)	90% available (**9.0 degrees**)
Maximum Dynamic VME Stress	0.4*minimum yield point (**32 ksi for X-80 Riser Material**)	0.67*minimum yield point (**53.6 ksi for X-80 Riser Material**)	0.67*minimum yield point (**53.6 ksi for X-80 Riser Material**)
Maximum tension Setting	90% of capacity (**1360 ton**)	90% of capacity (**1360 ton**)	N/A

From data provided by CDEX, maximum riser angle must not exceed 6 degrees.

5.6.2 Shear Force at the Top of the Riser (on the Chikyu Vessel)

This is the lateral load which is transferred from the marine drilling riser onto the vessel. It is important because the dynamically positioned system must not only work against the wind, waves, and currents which are acting on the vessel but the vessel must also be able to withstand with all its loads and the load from the marine drilling riser. Figure 20 plots the shear forces on the vessel as a function of vessel offset, tension, mud weight and environment.

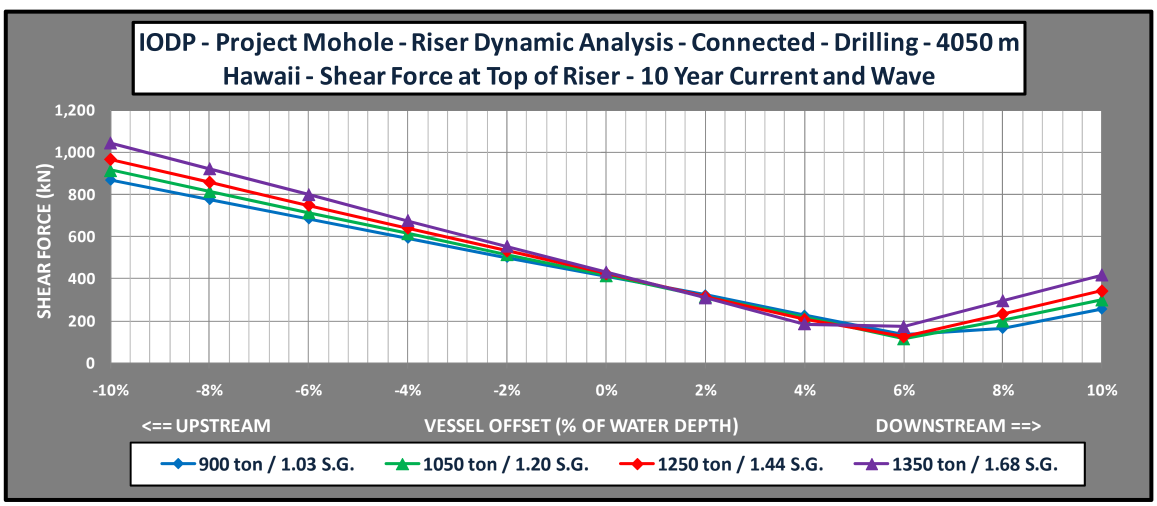

Figure 20—Shear Force at Top of the Riser

The maximum shear force at the top of the marine drilling riser for the 10 year return period is at -10% offset which is over 1000 kN for 1350 ton of tension and 1.68 S.G. mud weight.

5.6.3 Shear Force at the Top of the LMRP/BOP

This is the lateral load, which is transferred from the marine drilling riser into the top of the BOP. This load does not cause any problems for the BOP stack (except potentially at the LMRP-BOP connector) because the stack and frame is extremely stiff, but this load is transferred into the wellhead and conductor as a shear force and a bending moment (BOP stack acts as a lever arm). The shear force and moment load control the design of the conductor and connectors. Figure 21 plots the shear forces on the BOP for the 10 year criteria as a function of vessel offset, tension, mud weight and environment.

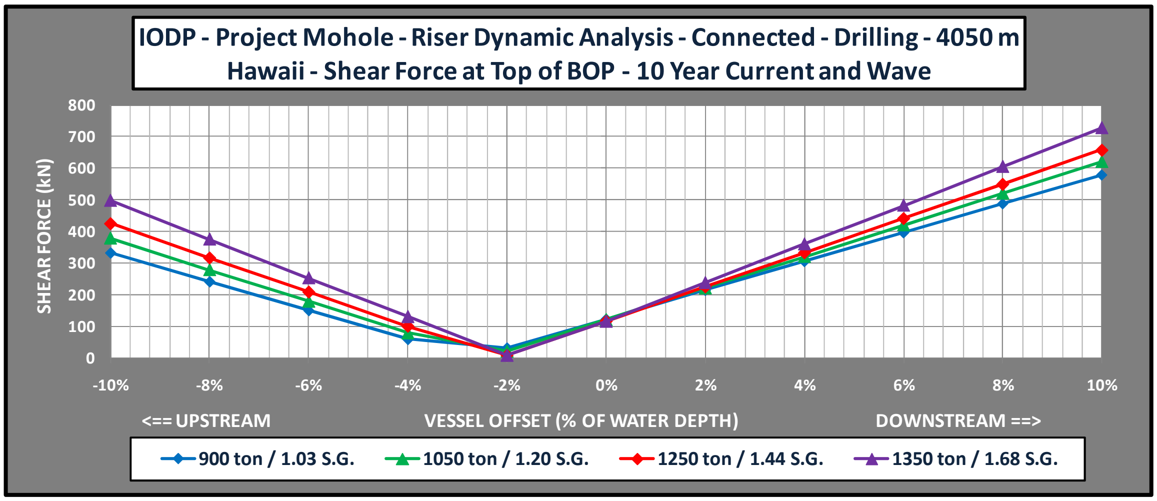

Figure 21—Shear Force at Top of the BOP

The maximum shear force at the top of the BOP for the 10 year return period is at +10% offset which is over 700 kN for 1350 ton of tension and 1.68 S.G. mud weight.

5.6.4 Rotation at the Top of the Drilling Riser

This is the rotation which occurs at the top of the marine drilling riser. During the non-drilling period of 10 year return the riser angle should not exceed 9 degrees to prevent the flex / ball joint from severe damage as per API 16Q. Figure 22 plots the rotation at the top of the marine drilling riser for the 10 year criteria as a function of vessel offset, tension, mud weight and environment.

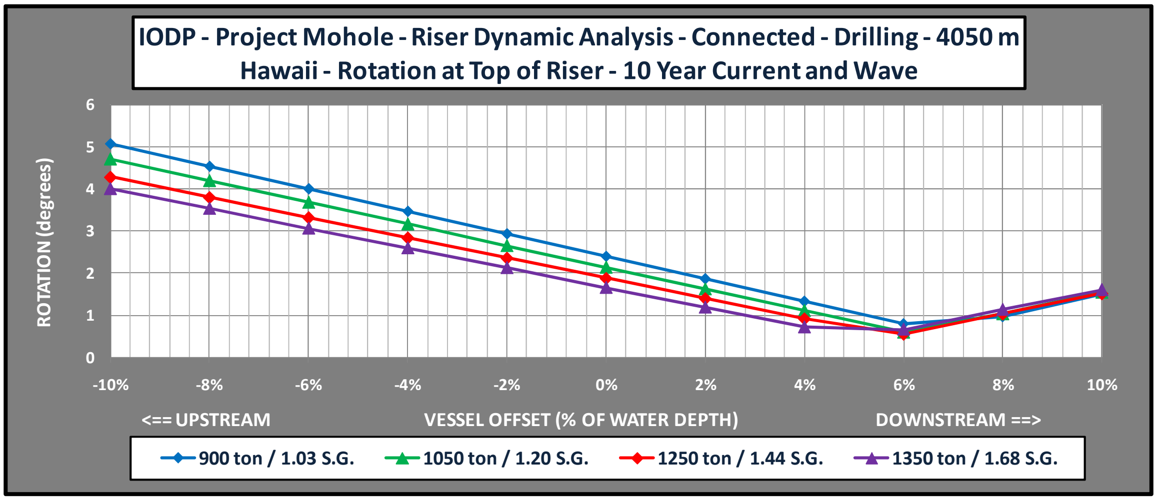

Figure 22—Rotation at the Top of the Drilling Riser

As one can see the operating window at the top of the riser due to rotation is quite large and ranges between -6% of vessel offset for the worst case with 900 ton of tension and 1.03 S.G. of mud weight (rotation must be kept at a maximum of 4 degrees) and +10% of vessel offset.

5.6.5 Maximum Slip-Joint Stroke

As the vessel heaves and moves off location the slip joint (telescopic joint) strokes in and out to maintain a connection with the marine drilling riser and the vessel while keeping the tension constant at the top of the riser. From the Chikyu data provided by CDEX, the slip joint has a limitation of about 7.45 meters stroke. Figure 23 plots the slip joint stokes for the three environments.

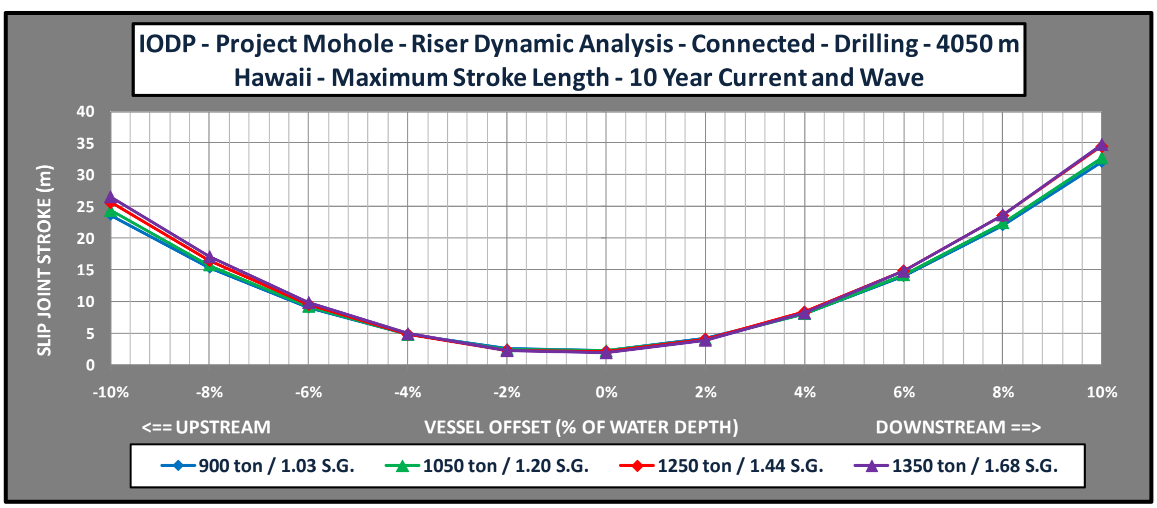

Figure 23—Maximum Slip-Joint Stroke Length

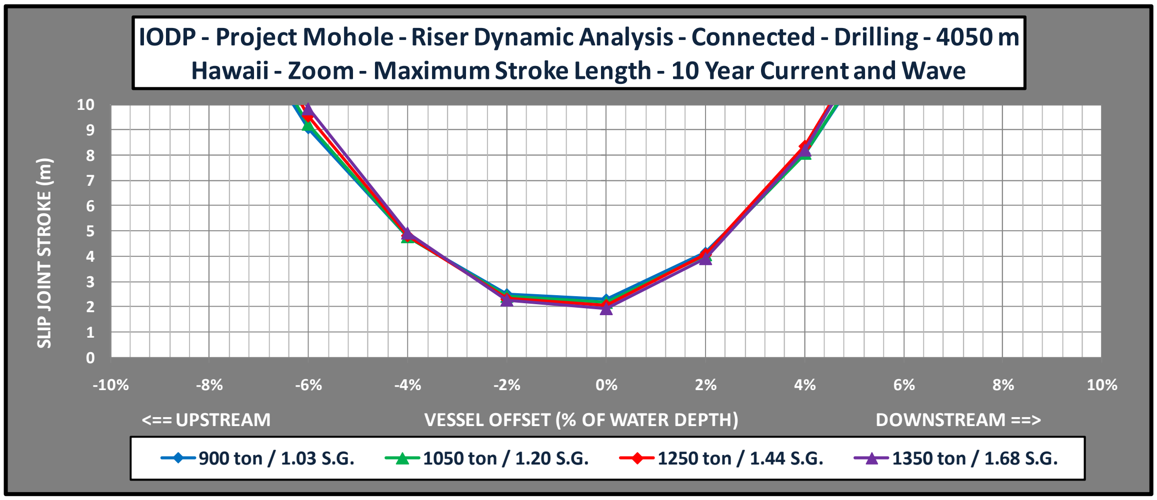

Figure 24—Maximum Slip-Joint Stroke Length Zoom

Figure 24 above shows that the maximum slip-joint stroke for the 10 year return period stays below the maximum values of 7.45 meters for vessel offset between -5% and +4%.

5.6.6 Maximum VME in the Marine Drilling Riser

As with most marine structures the maximum Von Mises (VME) stress must be controlled. The marine drilling riser currently onboard the Chikyu has a minimum yield point of 550 MPa (API X-80 material = 80 ksi). Keep in mind that per API 16Q, the maximum allowable for drilling is 220 MPa (32 ksi) and 370 MPa (53.6 ksi) when non-drilling. Figure 25 plots the VME stress as a function of vessel offset.

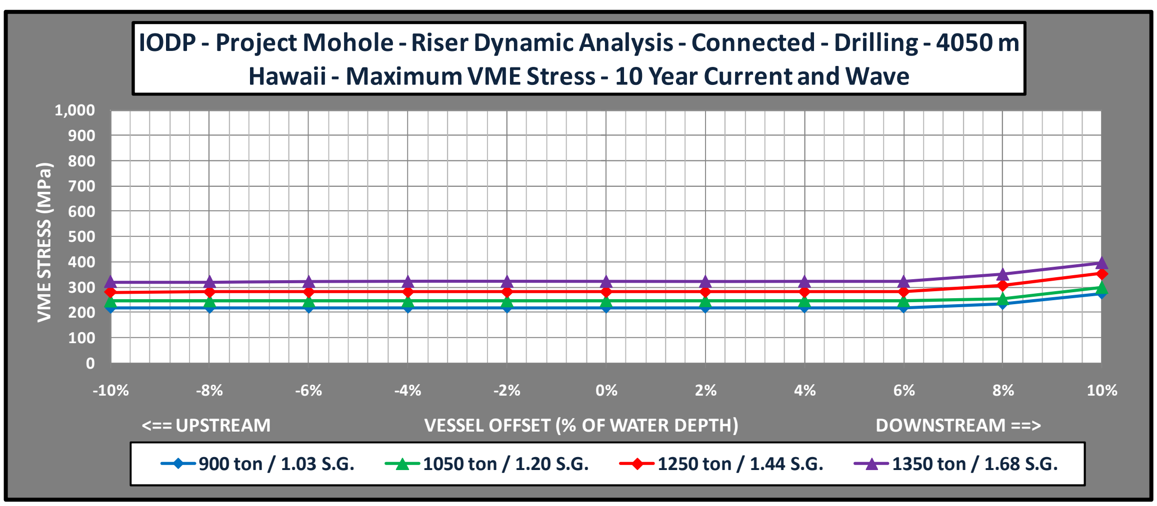

Figure 25—Maximum VME Stress in the Marine Drilling Riser

The maximum VME stress in the marine drilling riser for the 10 year return period ranges between 200 MPa and 400 MPa for the different cases analyzed. However, since per API 16Q, the maximum allowable stress during drilling is 220 MPa when using the current drilling riser, a higher strength material is needed, at least for the deeper section of the marine drilling riser. For instance, if titanium alloy, grade 23 is used, the maximum allowable stress during drilling is 331 MPa which allows keeping the vessel between -10% to +6% vessel offset as shown in Figure 25.

5.7 Subsea Drilling Systems

Four drilling systems are currently available for ultra deepwater environments:

1. Conventional 21-inch riser with an 18-3/4-inch subsea BOP system. This is the most widely used system by operators to drill and access oil and gas reserves.
2. A surface BOP system (SBOP) where the surface BOP stack is located on the drilling rig right below the rotary system. Then, a high pressure riser composed of casing is connecting the SBOP and the seafloor. This concept has essentially been used in Asia and requires calm waters environment.
3. A modified SBOP system with a disconnecting mechanism at the seafloor. The disconnecting system is mainly composed of two hydraulic connectors and two BOP shear rams that are operated through acoustic and electrical signals.
4. A 16-inch slim riser which uses the same 18-3/4-inch subsea BOP system than for conventional ultra deepwater drilling (system 1) and is associated with slim-hole drilling technology.

Because of the relative severe environmental loads that are present in any of the three locations in the Pacific Ocean and the number of unknowns in the pressure regimes in the igneous rocks, both the conventional 21-inch riser (system 1) and the 16-inch slim riser (system 4) which necessitate the same 18-3/4-inch subsea BOP system seem to be the best technical and mature solutions to be used for the 'Mohole Project'. Further detailed studies will need to be carried on to select which one of these two systems will be best suited for the Moho wells.

5.8 Future Work

In the following sections, several input data that would yield more accurate results for the marine drilling riser analyses are discussed and proposed.

5.8.1 Metocean Data Analysis

More detailed marine drilling riser analyses will be required to help determining and selecting the best technical and economical solution discussed in section 5.5. For instance, ocean current velocity profile along the 4000 meters seawater column and Deep Ocean current would be required. Also, for the dynamic analysis, a modified wave spectrum for the Pacific Ocean could be developed to be more representative of environmental conditions over the three well locations. Currently, Pierson-Moskowitz spectrum which represent ocean-wave spectrum for fully developed seas in the North Atlantic Ocean is used by the offshore industry and therefore in these analyses.

5.8.2 Marine Growth

As previously discussed in section 5.2.2, the marine drilling riser is a drag-dominated structure where the riser diameter is very small as compared to the wave length. Thus, the first half of Morrison's equation (Eq. 1) dominates the load calculation and determining accurately the drag coefficient (C_D) is very important for load calculations.

Soft and hard marine growths have been observed in salt water as deep as 1000 meters in the region where photosynthesis can occur. Marine growth sticks to the marine drilling riser and the drilling vessel splash zone and can form a thick layer around the structural components outside diameter. This result in an increase in drag diameter and also mass of the marine drilling riser and therefore increase the hydrodynamic loading as per Morrison's equation, decrease fatigue performance and require additional top tension.

For the project Mohole, marine growth profile estimations for the Pacific Ocean would be useful to collect.

5.8.3 VIV (Fatigue)

Ocean current speed in deepwater environments can trigger a vibratory mode called vortex induced vibration (VIV) where the marine drilling riser vibrates in the direction normal to the main ocean current direction. Thus, fatigue damage can be accumulated at a very fast rate. Therefore, in order to ensure marine drilling riser integrity, both detailed modal and fatigue analysis from both wave action and current VIV must be carried on in future studies. If vortex induced vibrations potential damage is likely to happen, VIV suppression devices such as strakes or fairings can equip the marine drilling riser.

5.8.4 Dynamic Disconnected Analysis

When operating in deepwater environments where high ocean current are present, the dynamically positioned drilling vessel could drift off location. Also, when a storm is forecasted in the vicinity of the well site, systems and procedures to disconnect the marine drilling riser and LMRP from the BOP stack must be put into place. Then, once these 'extreme' events are not considered to be a threat for the safety of the drilling and coring operations, the marine drilling riser will be reconnected to the BOP stack and finally drilling and coring operations can resume. Moreover, data from the National Hurricane Center, USA provided by IODP and CDEX shown in Figure 26 and Figure 27 suggest that numerous storms between the months of July and November are likely to occur in the Eastern Pacific and Central Pacific basins. Therefore, disconnected analyses are required to determine the response characteristics of a marine drilling riser when a controlled or emergency disconnection is needed.

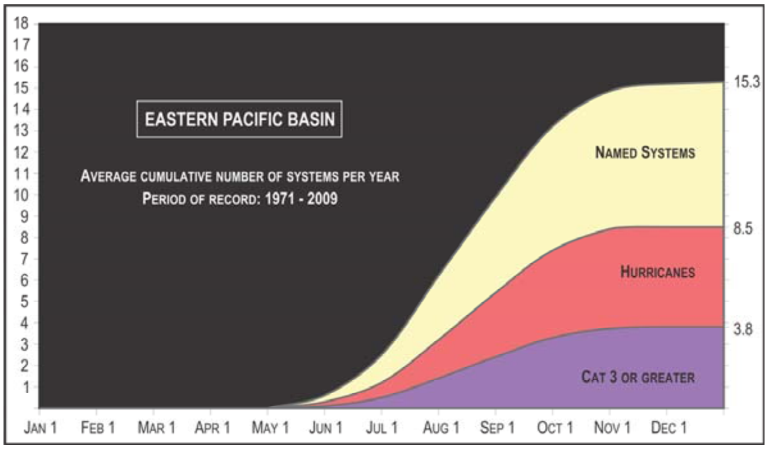

Figure 26—Eastern Pacific Basin Tropical Cyclones

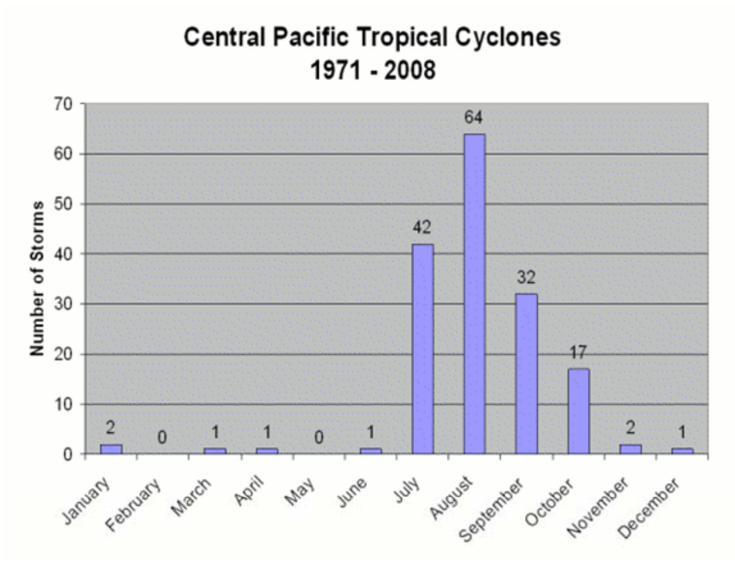

Figure 27—Central Pacific Basin Tropical Cyclones

5.8.5 Conductor Analysis in Sediments

The first string of casing used during offshore operations called conductor casing serves as a foundation for the well. Usually, the conductor diameter ranges between 30-inch and 36-inch. In addition, an in-place conductor analysis that uses as input values the Chikyu vessel offsets, the marine drilling riser system, and the mud weight and vessel top tension would be required to design the conductor casing.

However, soil borings need to be conducted at the targeted well locations. For the design of structural conductor strings, the sediment undrained shear strength is required to develop the non-linear soil characteristics (called P-Y springs for lateral stiffness and T-Z springs for axial stiffness). From a non-linear finite element analysis the point of maximum bending can be determined along with a host of other structural information, i.e., rotations, displacements, stresses, and strains.

6 Well Design Assumptions

A key objective of this feasibility study was to investigate the operational time and cost implications of the main scientific coring methods being considered by the IODP such as continuous coring of the entire hole, long core intervals of key sections, or spot coring. In order to do this, some assumptions had to be made about the fundamental down-hole conditions that impact the design of a well. It is recognized that most of the information about the down-hole conditions is presently unknown. However, after discussions with the IODP, it was agreed that the assumptions discussed below are reasonable, or at least not unreasonable for this feasibility work.

6.1 Stratigraphy

A cross-section showing the general stratigraphy / lithology that can be expected is shown in Figure 28 which is based on information published by the IODP from their 2010 Mohole workshop report.

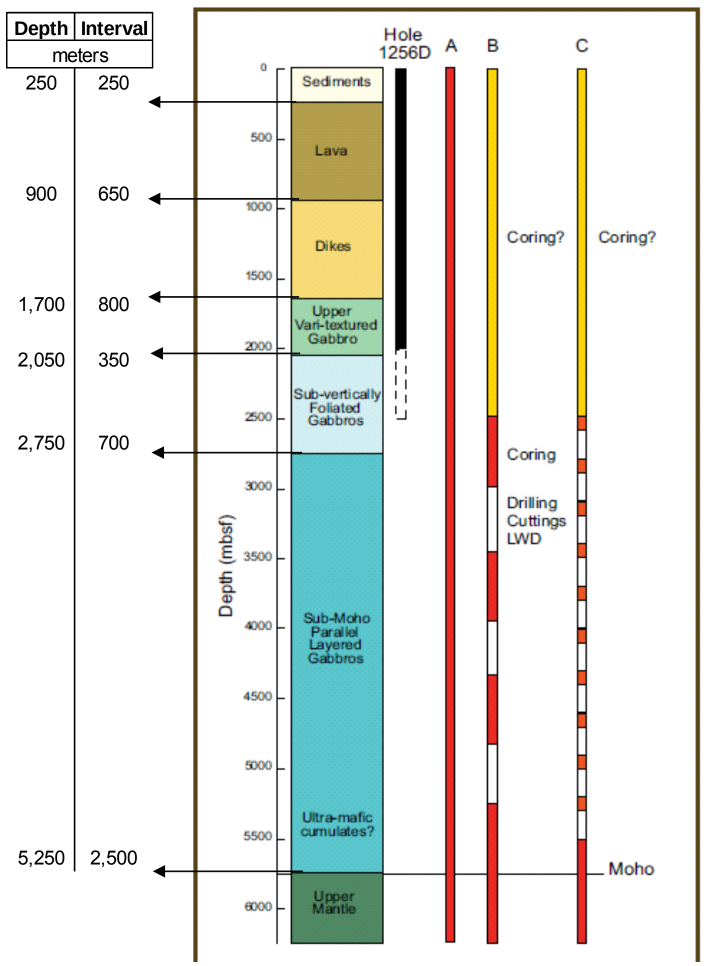

Figure 28—Expected General Stratigraphy for the 3 Well Locations

From this, an assumed stratigraphic / lithologic column was developed for the three prospective locations as shown below in Figure 29.

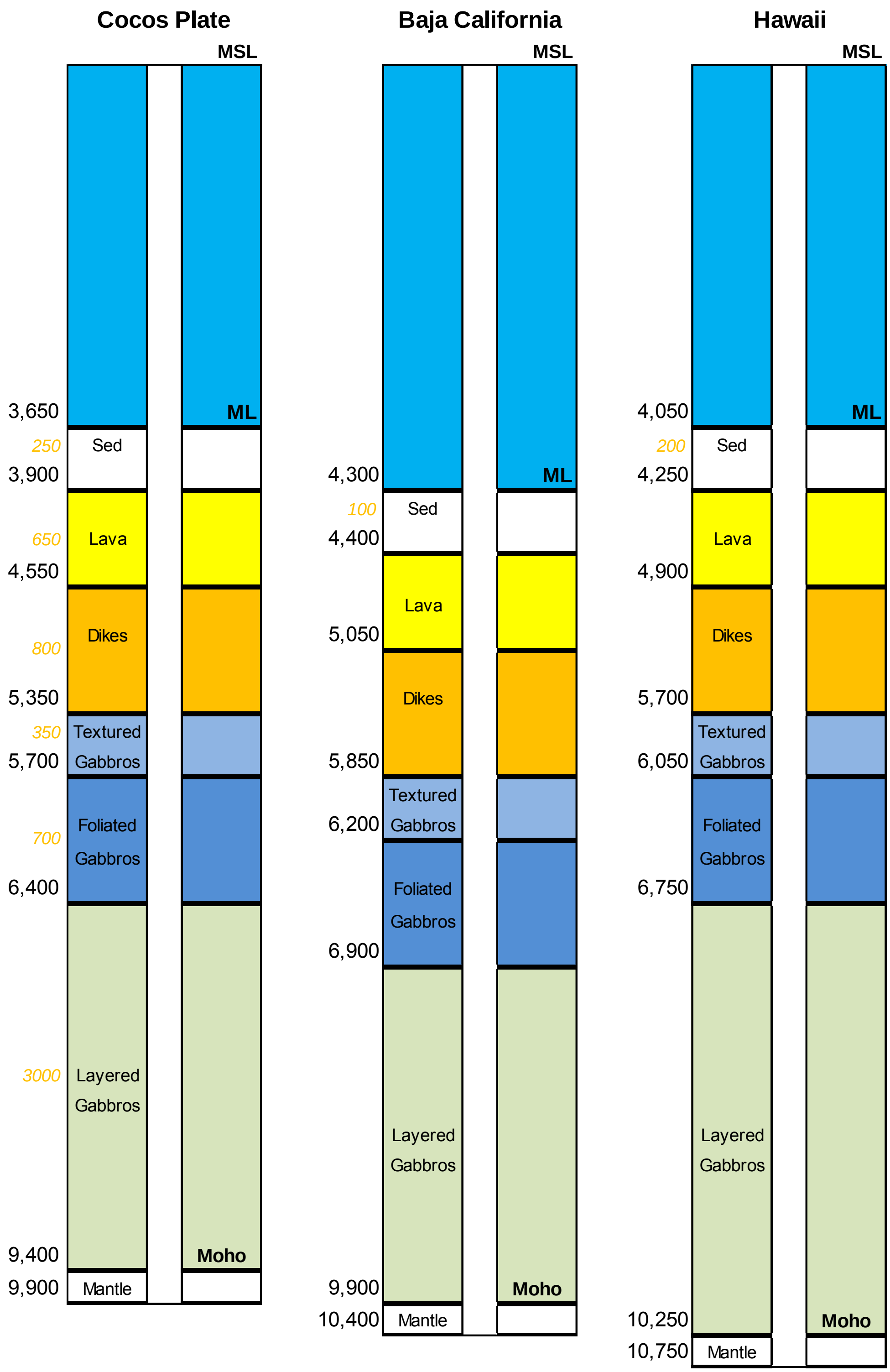

Figure 29—Lithology Comparison of the 3 Prospective Locations

6.2 Downhole Temperature

The assumed downhole temperature profiles for the candidate locations are shown below. The maximum bottom hole temperature (BHT) estimate is based on previous models of formation burial depth and age as provided by the IODP. The profiles are based on the water depth, available temperature measurements made during operations at the 1256D hole, and the estimated BHT. The uncertainly in the BHT estimate is believed to be ±50°C. Therefore, a maximum expected temperature of 300°C should be used for design and planning purposes.

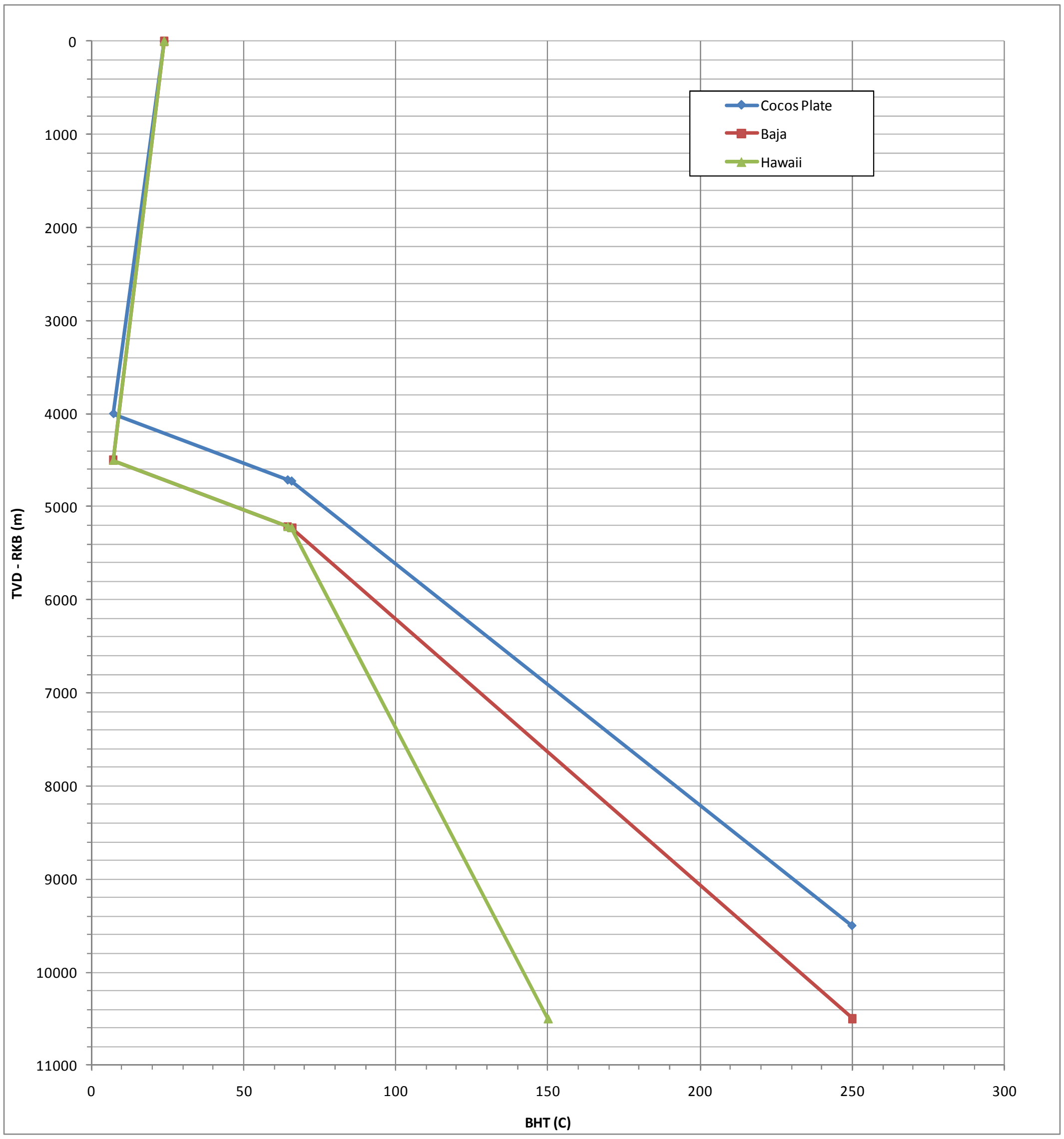

Figure 30—Bottom-Hole Temperature Estimate for Each of the 3 Candidate Locations

6.3 Pore Pressure / Fracture Gradient

The wellbore is "unequivocally" expected to be normally pressured (1.03 SG / 8.66 ppge in oilfield units) to total depth. As such, the presence of abnormally pressured intervals, which is typically a critical design consideration, will not be an issue. Therefore, casing point selection will be done on the basis of wellbore stability. Figure 31 shows the assumed pore pressure (Pform), formation fracture (FG) and overburden gradients that were used for this study. The overburden gradient (OBG) is assumed to be 22.6 kPa/m (1.0 psi/ft) which is a common oilfield assumption for sedimentary basins and represents a conservative minimum case since the OBG in igneous rocks will be higher. The FG was then assumed to be 95% of the OBG.

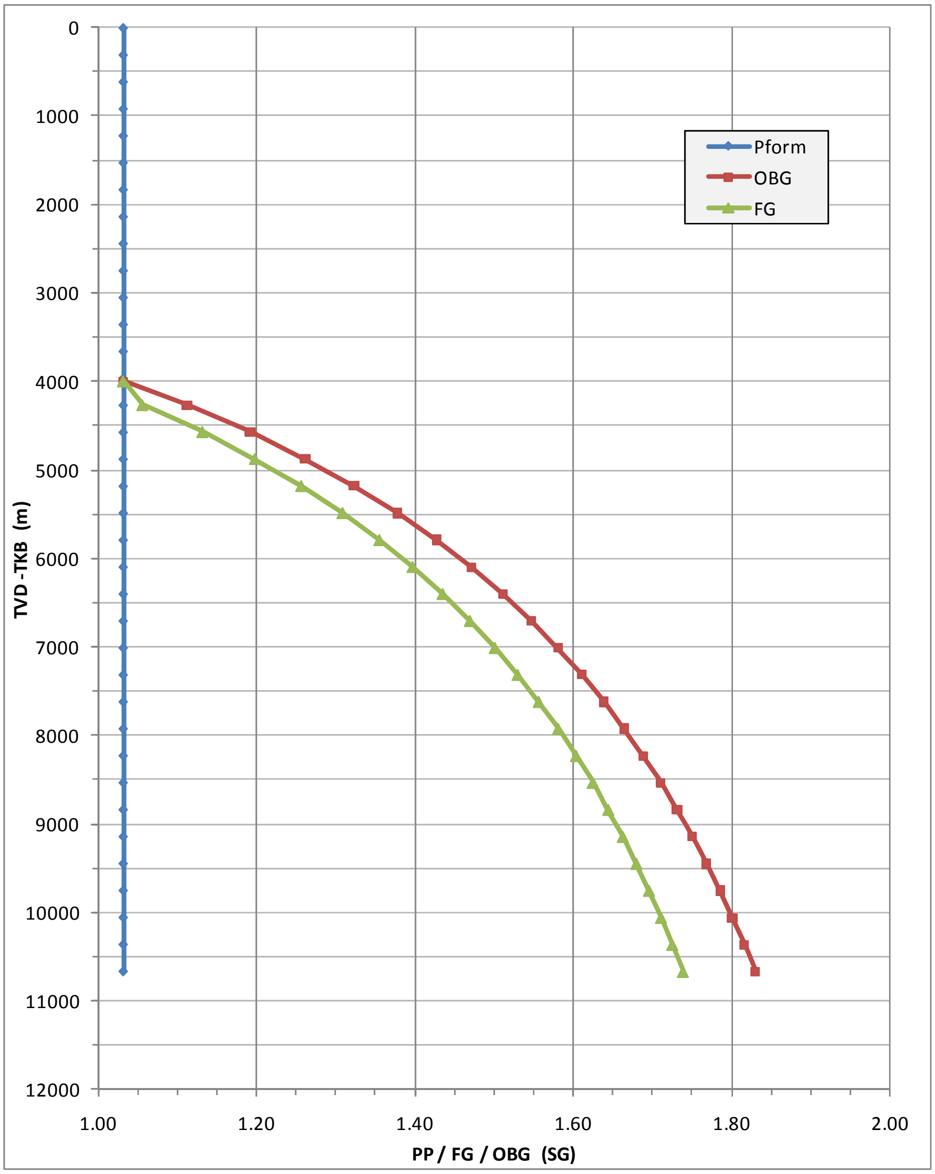

Figure 31—Generic Pore Pressure, Fracture Gradient and Overburden Curves

6.4 General Assumptions

The following are the main assumptions that were used in this study for well planning purposes:

- Structural casing will be jetting to ±61m (200 ft) below the sea floor.
- Surface casing will be set at or near the base of the sediments interval.
- The sediment, lava and dikes intervals do not need to be cored at the Cocos Plate location because of previous IODP experience on the 1256D hole.
- It is assumed that the entire hole will be drilled/cored using a rotary core barrel (RCB) similar to what is being used now in IODP's various ongoing expeditions.
- The minimum borehole size at TD will be 9-7/8". It is assumed that larger size RCB bits will become available for the upper hole sections since drilling and then under-reaming, and/or under-reaming while drilling is not practical from a time and cost standpoint. In addition, developing bits smaller than 9-7/8" is not desirable since the core diameter would be smaller than then the current 5.87 cm (2.312") diameter.
- Coring and drilling ROP's as shown in Table 8 below:

Table 8—Drilling and Coring Rate of Penetration

Stratigraphy	Coring	Drilling	
Sediments	3.0	15.2	m/hr
Lava	1.5	3.0	m/hr
Dikes	1.5	3.0	m/hr
Textured Gabbros	1.2	2.4	m/hr
Foliated Gabbros	1.2	2.4	m/hr
Layered Gabbros	0.9	1.5	m/hr
Mantle	0.9	0.0	m/hr

- The average bit life is 50 hrs in the "upper" part of the well and 35 hrs in the "lower" part of well.
- The bit trip time was assumed to be 305 m/hr (1,000 ft/hr) which is an oilfield rule thumb and probably somewhat conservative a Moho well.
- The RCB wire-line trip time is estimated using the following data (Table 9) provided by IODP.

Table 9—Wire-line Trip Time

Depth (mBRT)	W/L Ops Time for One Core Barrel (hr)
4000	2.45
5000	3.05
6000	3.65
7000	4.25
8000	4.85
9000	5.45
10000	6.05

- Based on previous IODP experience, an average of 5% non-productive time (NPT) or trouble time is assumed to account for expected down-hole related problems when developing operational time estimates. This should exclude weather or rig equipment NPT.

7 Drilling and Coring in High Temperature Igneous Rocks

This section discusses some of the key operational and design issues that will need to be resolved prior to drilling a Moho well. It should be noted that these issues have been understood for some time and were, for example, comprehesively discussed in the IODP report from their June 2010 Moho workshop. Blade's focus was therefore not to re-examine the issues, but rather to evaluate them in terms of current and trending technologies in oilfield and geothermal industries to determine how difficult it will be to resolve the issues.

7.1 Drill-pipe Design

An obvious issue is the drill string design because of the extreme depths of the planned wells. The following discussion looks at whether there is an existing oilfield solution to the drill string design issue that could be used with the existing Chikyu drill string and therefore obviate the need to purchase and/or develop a special non-standard, high strength drill string for the Moho wells.

The following Table 10 shows a representative sample of some of the drill strings that are currently being used in the oilfield for deepwater wells and are readily available for rental or purchase. Also shown are the drill strings currently being used on the Chikyu and the Joides Resolution drilling vessels.

Table 10—Drill-strings Used in the Oilfield Industry and on IODP Drill-ships

DP #	OD	Nom Wt/ft	ID	New Wall	Grade	Tensile Rating New	Tensile Rating Prem	Conn	Adj Wt/ft	Tool Jt OD	Notes
	inches	lbs/ft	inches	inches	ksi	lbs	lbs		lbs/ft	inches	
1	6 5/8	50.00	4.999	0.813	S135	2,004,000	1,558,400	6-5/8 FH	58.58	8.750	
2	6 5/8	40.00	5.375	0.625	S135	1,590,400	1,245,800	6-5/8 FH	48.29	8.500	
3	6 5/8	34.00	5.581	0.522	S135	1,351,000	1,062,000	6-5/8 FH	42.49	8.500	
4	6 5/8	27.70	5.901	0.362	S135	962,000	760,000	6-5/8 FH	34.18	8.500	
5	5 7/8	35.00	4.625	0.625	V150	1,546,300	1,207,500	XT57	39.98	7.125	
6	5 7/8	28.70	4.875	0.500	Z140	1,182,000	928,000	XTM57	3.21	7.000	
7	5 7/8	26.30	5.045	0.415	S135	961,000	757,000	XT57	29.78	7.000	
8	5 7/8	23.40	5.153	0.361	S135	844,000	666,000	XT57	26.48	7.000	
9	5 1/2	24.70	4.670	0.415	S135	895,001	704,314	FH	30.80	7.750	
10	5	19.50	4.276	0.362	S135	712,000	560,765	GPDS50	23.48	6.625	
11	5 1/2	*29.00*	4.488	0.506	S150	1,190,807	933,341	5-3/4 FH	34.31	7.500	Chikyu
12	5 1/2	24.70	4.670	0.415	S140	928,150	730,400	5-1/2 FH	28.72	7.000	Chikyu
13	5	19.50	4.776	0.362	S140	738,445	581,534	5-1/2 FH	24.40	7.000	Chikyu
14	5 1/2	26.67	4.500	0.500	V140	1,099,560	862,055	5-1/2 FH	31.90	7.750	JR
15	5	19.50	4.276	0.362	V140	738,445	581,534	5-1/2 FH	22.10	7.000	JR

Below Figure 32, Figure 33, Table 11 and Table 12 show the results of two basic drill string designs for the Hawaii location which has the deepest TD of the three location candidates (10,750m / 35,269 ft).

Drill String Design Example 1:

Table 11—Drill String Design – Case 1: Hawaii Location

Hawaii Test Case — 35,269 = Total Depth — 12.0 = Mud Wt

DP #	Item	Adj Wt	From	To	Length	Air Wt	Mwt	BF	Buoyed Wt	
5	5.875, 35# 0.625	39.98	0	10,000	10,000	399,800	12.0	0.817	326,498	lbs
11	5.5, 29# 0.506	34.31	10,000	16,000	6,000	205,860	12.0	0.817	168,116	lbs
12	5.5, 24.7# 0.415	28.72	16,000	34,269	18,269	524,686	12.0	0.817	428,487	lbs
	BHA	---	34,269	35,269	1,000	50,000	12.0	0.817	40,833	lbs
					Total Air Wt =	1,180,346		Total Hookload =	**963,934**	lbs

Depth	Tensile Load	Tensile Rating	Overpull Margin	Safety Factor
0	963,934	1,207,500	**243,566**	**1.25**
10,000	637,436	933,341	**295,905**	**1.46**
16,000	469,319	730,400	**261,081**	**1.56**
34,269	40,833	---		

The example 1 shown in Figure 32 below presents a drill string configuration which consists of an "oilfield" 5-7/8" V150 string and two 5-1/2" strings currently being used on the Chikyu in a 12.0 ppg (1.44 SG) mud weight. The buoyed weight at TD is 963,934 lbs (437 ton) which is well within the Chikyu's derrick capacity. The premium class tensile rating of the 5-7/8" is 1,207,500 lbs (548 ton) which provides an over-pull margin of 243,566 lbs (110 ton).

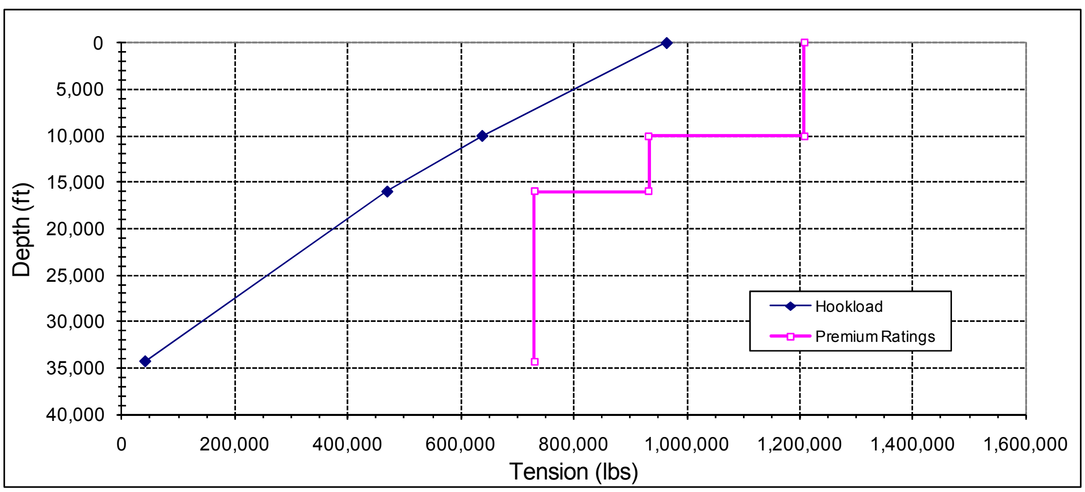

Figure 32—Drill-string Design – Case 1: Hawaii Location

Drill String Design Example 2 :

Table 12—Drill String Design – Case 2: Hawaii Location

	Hawaii Test Case			35,269	= Total Depth		12.0	= Mud Wt		
DP #	Item	Adj Wt	From	To	Length	Air Wt	Mwt	BF	Buoyed Wt	
5	5.875, 35# 0.625	39.98	0	8,000	8,000	319,840	12.0	0.817	261,199	lbs
11	5.5, 29# 0.506	34.31	8,000	17,000	9,000	308,790	12.0	0.817	252,175	lbs
13	5, 19.5# 0.362	24.40	17,000	34,269	17,269	421,364	12.0	0.817	344,108	lbs
	BHA	---	34,269	35,269	1,000	50,000	12.0	0.817	40,833	lbs
					Total Air Wt =	1,099,994		Total HKLD =	**898,314**	lbs

Depth	Tensile Load	Tensile Rating	Overpull Margin	Safety Factor
0	898,314	1,207,500	**309,186**	**1.34**
8,000	637,116	933,341	**296,225**	**1.46**
17,000	384,941	581,534	**196,593**	**1.51**
34,269	40,833	---		

The example 2 drill string configuration consists of the same 5-7/8" V150 string and the Chikyu's 5-1/2" 0.506" wall and 5.0" strings in a 12.0 ppg (1.44 SG) mud weight. The buoyed weight at TD is lower at 898,314 lbs (407 ton) providing an over-pull margin of 309,186 lbs (140 ton).

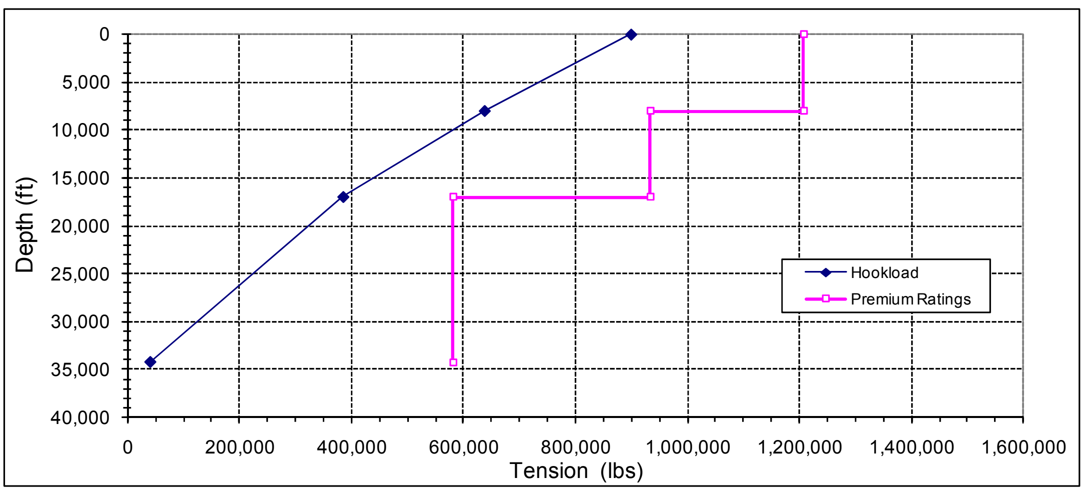

Figure 33—Drill-string Design – Case 2: Hawaii Location

The main point of this exercise is to demonstrate that the Moho wells could be drilled today with a combination of readily available oilfield drill pipe and the Chilyu's existing drill pipe, and therefore a non-standard, special high strength drill string is not needed.

This is not intended to be a definitive drill string design and further work will be required to optimize the design in order to maximize the over-pull margin and address the issues around slip crushing. Nevertheless, the point remains the same. In addition, there are also some non-standard oilfield options currently available such as the new UD165 grade string.

7.2 Well Design

In most deepwater wells the presence of abnormal pressure is a fundamental criteria for determining casing points and the drilling mud density required to reach TD. Because abnormal pressure is not an issue for a Moho well, the selection of casing points and mud weights will be based on wellbore stability considerations. In other words, a safe operating mud weight window needs to be defined that will offset the stress concentrations that are generated in the surrounding rock as it is drilled which can cause mechanical instability of the rock. If the mud weight is too low the hole will essentially collapse due to a compressive shear failure in the rock. Too high a mud weight will cause lost circulation due to a tensile fracturing of the rock. The operating mud window can be modeled using offset well data and seismic data, but is presently unknown. However, the pore pressure estimate previously discussed can be used to provide some initial insight around possible mud weights that could be used and the selection of casing points.

In general, higher mud weights are needed to prevent the hole from collapsing so casing points need to be selected that maximize the fracture pressure of the formation allowing higher mud weights to be used. However a trade-off must be made between the allowable mud weights and the number of casing strings that are used. There are only so many casing strings that can fit in a well, and running multiple strings is time consuming, costly and complicates the geometry of the well. It would certainly be advantageous to minimize the number of casing strings used for the Moho well if only to minimize the sizes of the RCB bits that would need to be developed.

The casing points assumed in for this study are shown in Figure 34. The basic logic is that the surface casing needs to be set near the base of the sediments in order to help provide structural support for the well. Furthermore, experience from IODP's operations on the 1256D hole has shown that the lava and dikes interval can be successfully drilled / cored with seawater so arguably, there is no need to set casing in this interval. Therefore, setting the second string of casing at the base of the dikes would allow the subsequent interval to be drilled with a higher mud weight. The depth needed for the next casing string is speculative, but arguably, at least a third string would be need to be set into the layered gabbros section in order to case off and protect the upper part of the hole, and allow a higher mud weight to be used to TD the well. Note that the point where the horizontal dashed lines intersect the FG curve represents the maximum allowable mud weight for the subsequent borehole interval. Exceeding this maximum would result in a risk of lost returns, so the actual mud weight used to drill/core with would be somewhat less than the maximum.

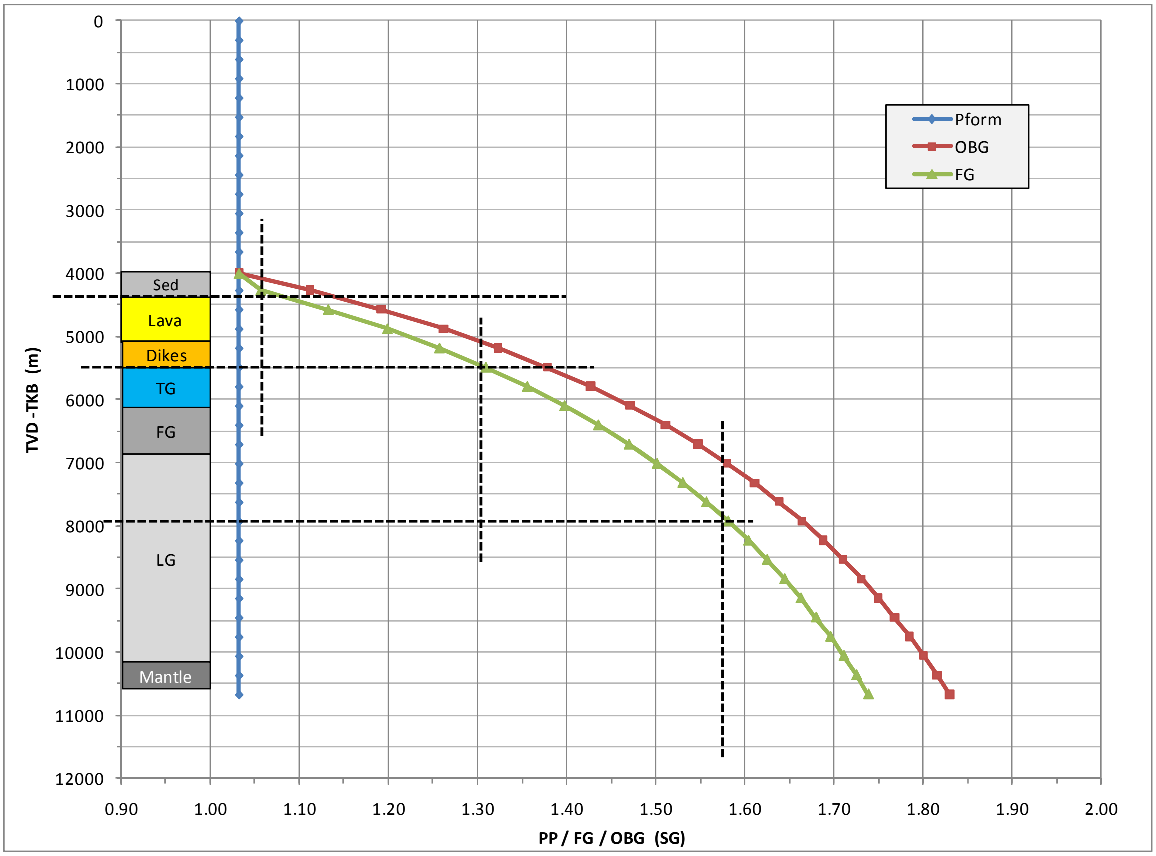

Figure 34—Casing Points Selection for a Base Case

As can be seen from Figure 34 above, while the casing points selected seem reasonable at this stage, there are any number of permutations of casing points and mud weights. As such, the mud weight requirements are probably the single most important variable impacting the well design. Mud weight also has a significant impact on the riser design as was discussed in Section 6.

7.3 Base Case Well Configuration

After selecting the casing points, a base case wellbore configuration shown in Figure 35 below was developed as shown below. Standard size casing diameters are used and the well is 'TD'd' with a 9-7/8" hole size.

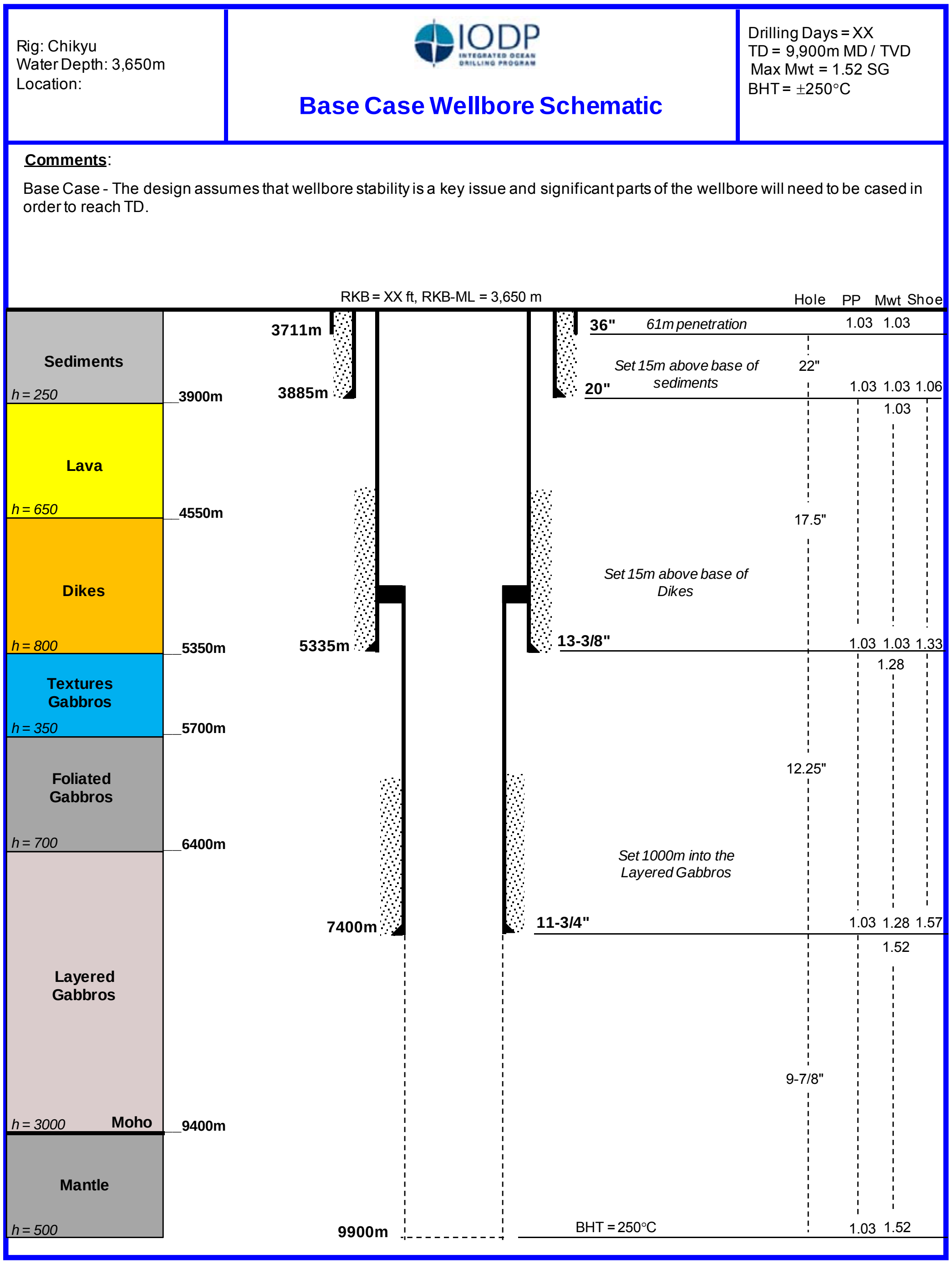

Figure 35—Base Case – Wellbore Schematic

7.3.1 Slim Riser and Slim Wellbore

A "slimmed" casing configuration that has same casing points as the base case is shown in Figure 36 below. While this is a viable configuration that offers some advantages from the standpoint of the riser design as previously discussed, it does limit the operational flexibility and results in a smaller hole size at TD.

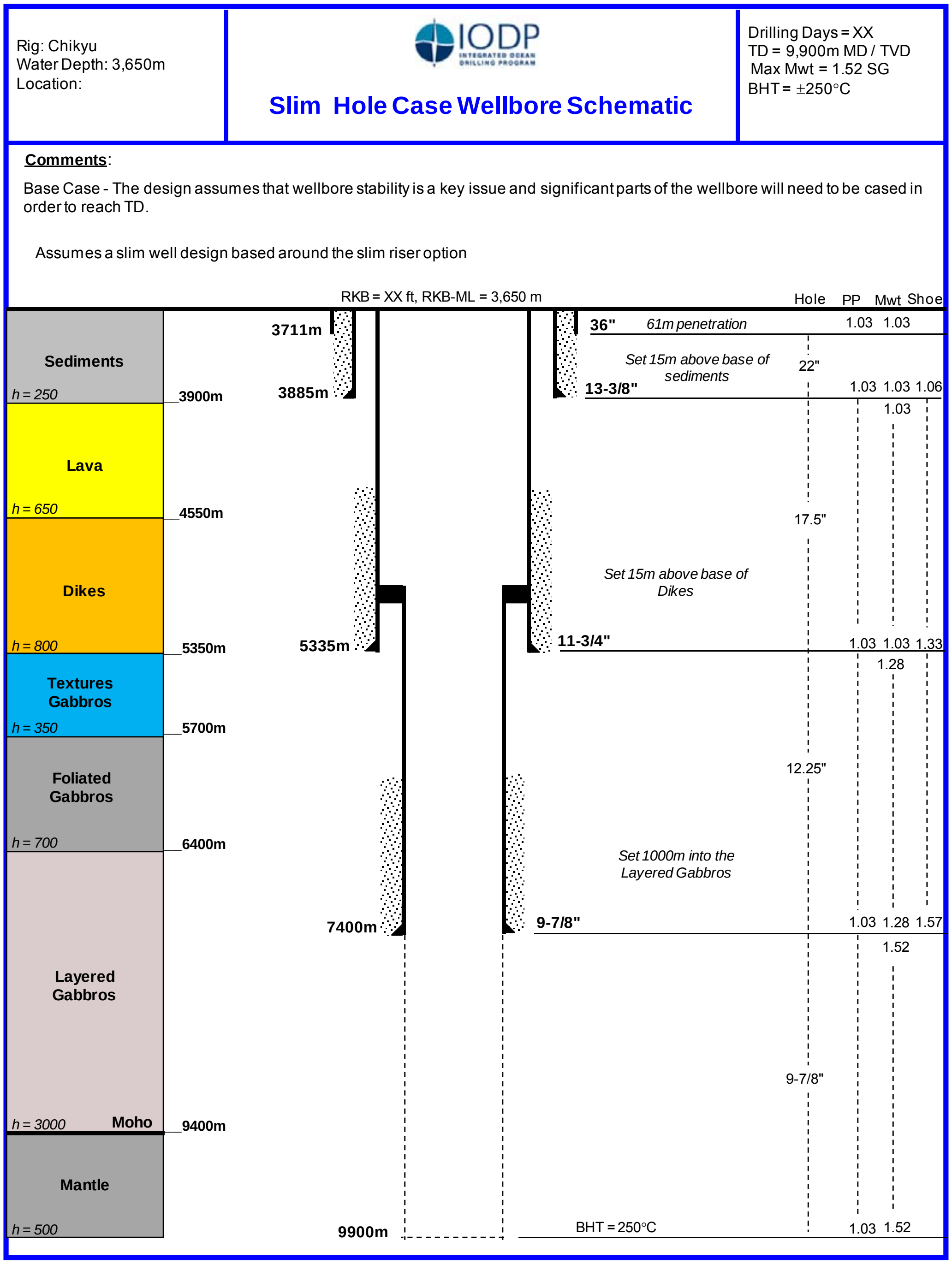

Figure 36—Slim Hole Case – Wellbore Schematic

7.4 Operational Time Estimation

As described below, operational time estimates for four different scientific drilling cases were developed for each of the candidate locations. The cases are similar to the IODP's options A, B and C as described in their 2011 Mohole workshop report.

- Case 1: Assumes that the hole is continuously cored to TD. This would be the ideal situation as it would maximize the amount of scientific information obtained from the hole. It is also the most expensive.
- Case 2: Assumes that long sections of continuous core are taken across the major lithologic and geophysical transition intervals of key sections. For the time estimate it was assumed that the upper third of each main stratigraphic interval was cored, the middle third was drilled and the lower third was cored.
- Case 3: Assumes that only spot coring is done during the last 10m of hole before each bit trip.
- Case 4: Assumes that the hole is drilled to the Moho and that the mantle is cored. This was done as a comparison to Case 1 since it represents the least expensive case.

The assumptions used for the time estimates were discussed in Section 6.

7.4.1 Summary

The following Table 13 is a summary of the operational time estimates for each of the 12 cases that were prepared. Operational days exclude the rig mobilization and positioning time.

Table 13—Operational Time Estimates Summary for the 3 Locations

Candidate Location	Water Depth	Total Depth	TD BSF	Operational Time (days)					Ops Time	Project Time
				Core/Drill	Bit Trip	W/L	Flat	NPT		
Cocos Location										
Case 1	3650	9900	6250	216	261	186	33	34	696	756
Case 2	3650	9900	6250	184	234	112	34	28	564	617
Case 3	3650	9900	6250	155	187	51	40	21	433	480
Case 4	3650	9900	6250	144	172	26	33	18	374	418
Baja Location										
Case 1	4300	10400	6100	236	300	238	33	40	807	866
Case 2	4300	10400	6100	197	259	147	38	32	642	693
Case 3	4300	10400	6100	157	160	58	31	20	405	445
Case 4	4300	10400	6100	143	183	27	33	19	386	425
Hawaii Location										
Case 1	4050	10750	6700	260	319	264	33	43	876	934
Case 2	4050	10750	6700	214	285	155	34	34	688	737
Case 3	4050	10750	6700	172	177	63	36	22	448	485
Case 4	4050	10750	6700	157	204	28	33	21	422	443

7.4.2 Cocos Operational Time Estimates

Figure 37 below is the base case wellbore schematic for a hole drilled at the Cocos location.

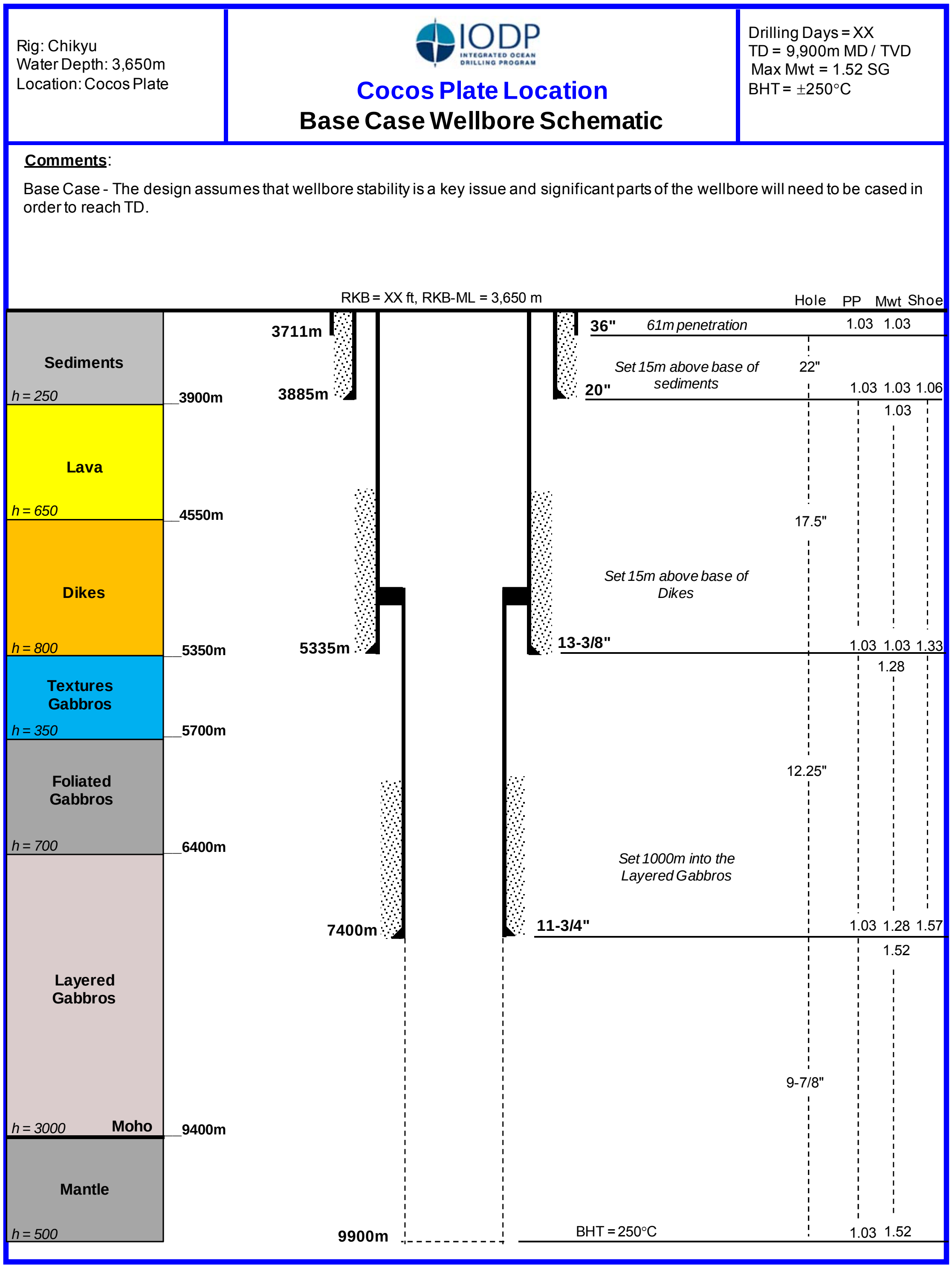

Figure 37—Cocos Plate Location – Base Case – Wellbore Schematic

Case 1 Results

This case is based on continuous coring from the seafloor to TD. However for the Cocos location it is assumed that the sediments, lava and dike intervals do not need to be cored because of previous IODP experience on the 1256D hole. It is further assumed that the Chikyu is mobilized from Tokyo and that the transit distance to the location is approximately 10,600 km. A summary of the time estimate for this case is shown in Table 14 below.

Table 14—Cocos Plate – Case 1 – Breakdown of Operational Time Required to Reach Total Depth

Phase	Interval Days	Cum Days	From (m)	To (m)	Interval (m)	Avg m/day
Move in rig	23.9	23.9				
Position Rig	1.5	25.4				
Jet 36"	0.5	25.9	3,650	3,711	61	122
Drill Sediments	1.5	27.4	3,711	3,885	174	116
Set 20" casing	2.1	29.5				
Run BOP & Riser	3.0	32.5				
Drill Sediments	1.2	33.7	3,885	3,900	15	12.6
Drill Lava	13.6	47.3	3,900	4,550	650	47.7
Drill Dikes	17.6	64.9	4,550	5,335	785	44.6
Set 13-3/8" Casing	5.0	69.9				
Core Dikes	2.6	72.5	5,335	5,350	15	6.0
Core Textured Gabbros	31.6	104.0	5,350	5,700	350	11.1
Core Foliated Gabbros	70.1	174.2	5,700	6,400	700	10.0
Core Layered Gabbros	55.4	229.6	6,400	6,857	457	8.3
Core Layered Gabbros	74.7	304.3	6,857	7,400	543	7.3
Run 11-3/4" Casing	7.0	311.3				
Core Layered Gabbros	323.3	634.6	7,400	9,400	2,000	6.2
Core Mantle	78.6	713.1	9,400	9,900	500	6.4
TA hole	5.0	718.1				
Pull BOP/Riser	3.0	721.1				
5% Operational NPT	34.4	755.5				

Total Core/Drill Days = **696**

Total Project Days = **756**

For this case, 73% of the hole is cored, and 27% is drilled as shown in Table 15 below.

Table 15—Cocos Plate – Case 1 – Projected Days for Drilling and Coring

	Interval	%	Days
Coring =	4,565	73.0%	196
Drilling =	1,685	27.0%	21
	6,250	100%	216

The following pie chart (Figure 38) shows a breakdown of the key operations in terms of total days and percentage of the total time. Flat time is defined as the time spent running BOP's running wire-line, logs and running casing. Note that 261 days, or 37% of the time was spent on bit trips.

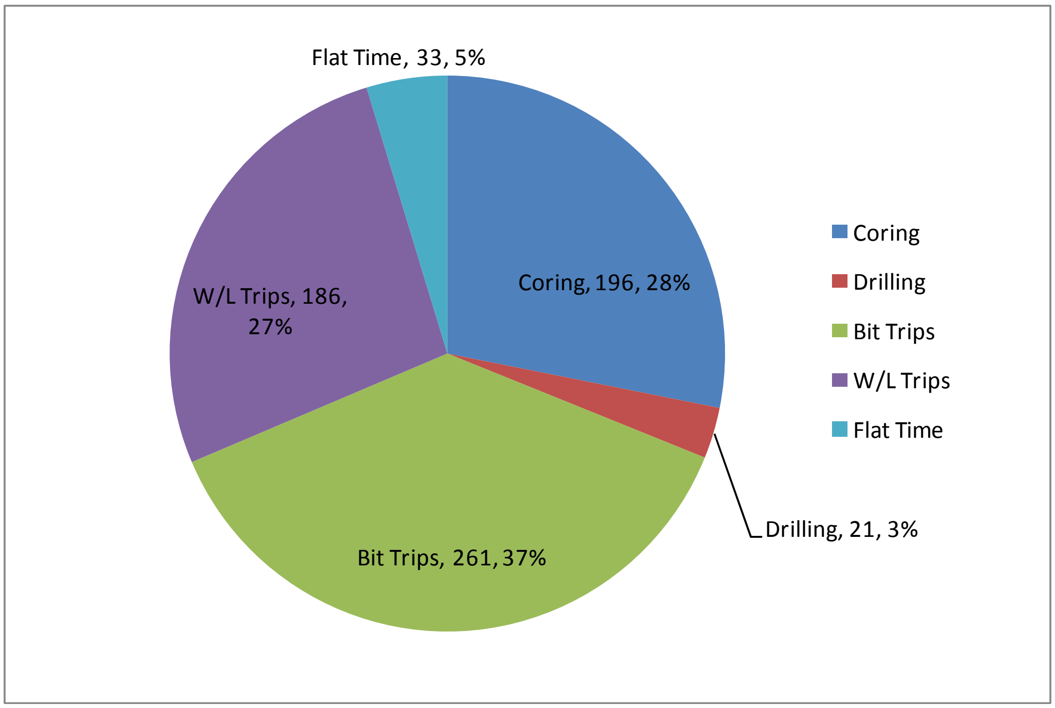

Figure 38—Cocos Plate – Case 1 – Operations Breakdown Comparison

A drilling curve for Case 1 is shown in Figure 39 below.

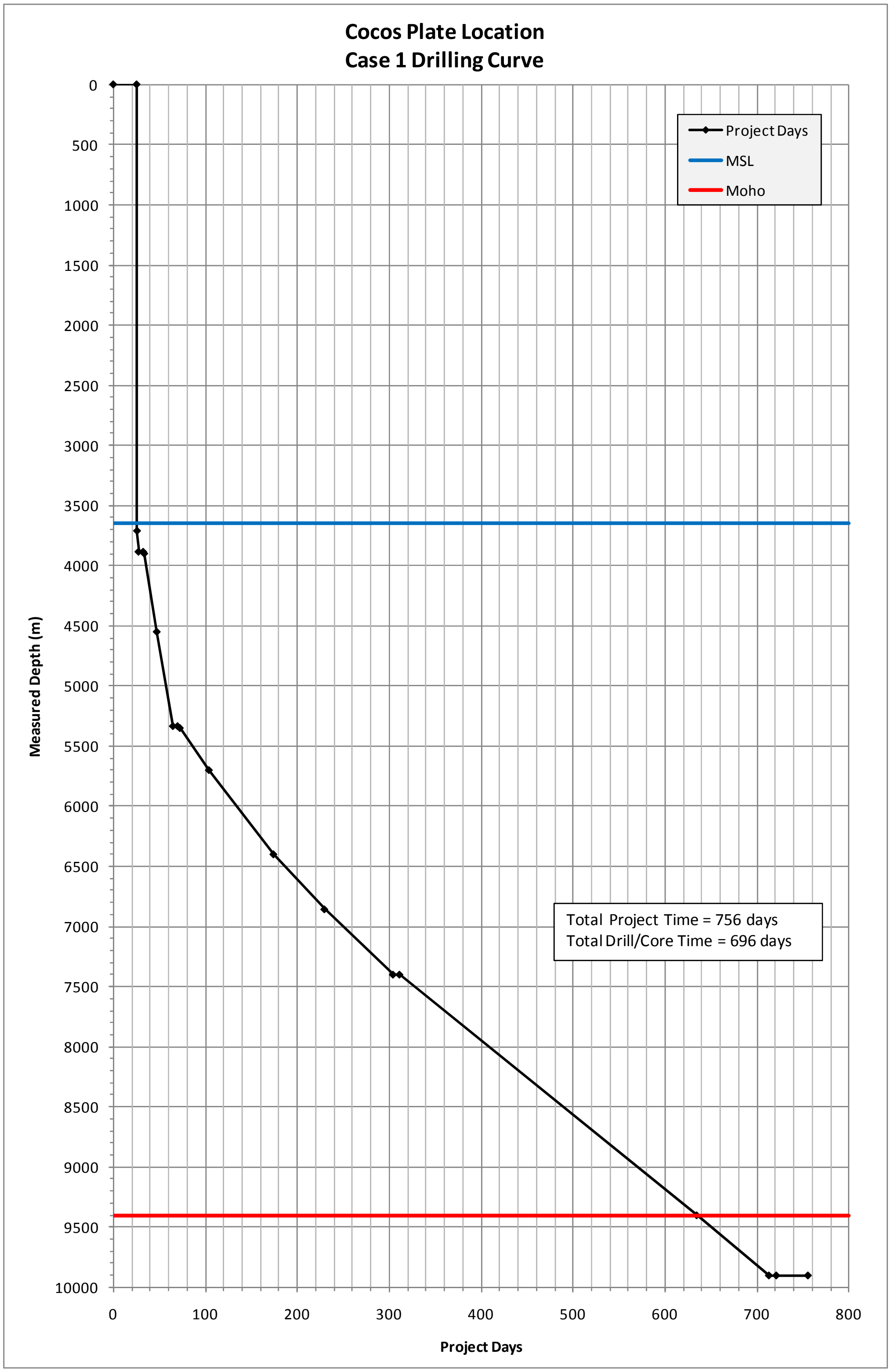

Figure 39—Cocos Plate – Case 1 – Drilling Curve

Case 2 Results

This case is based on coring the upper third of stratigraphic section, drilling the middle third, and then coring the bottom third. A summary of the time estimate for this case is shown in Table 16 below.

Table 16—Cocos Plate – Case 2 – Breakdown of Operational Time Required to Reach Total Depth

Phase	Interval Days	Cum Days	From (m)	To (m)	Interval (m)	Avg m/day
Move in rig	23.9	23.9				
Position Rig	1.5	25.4				
Jet 36"	0.5	25.9	3,650	3,711	61	121.9
Drill Sediments	1.5	27.4	3,711	3,885	174	116
Set 20" casing	2.1	29.5				
Run BOP & Riser	3.0	32.5				
Drill Sediments	1.2	33.7	3,885	3,900	15	12.6
Drill Lava	13.6	47.3	3,900	4,550	650	47.7
Drill Dikes	17.6	64.9	4,550	5,335	785	44.6
Set 13-3/8" Casing	5.0	69.9			0	0.0
Core Dikes	2.6	72.5	5,335	5,350	15	6.0
Core Textured Gabbros	10.4	82.9	5,350	5,467	117	11.2
Drill Textured Gabbros	8.8	91.6	5,467	5,583	117	13.3
Core Textured Gabbros	10.8	102.4	5,583	5,700	117	10.8
Core Foliated Gabbros	21.9	124.3	5,700	5,933	233	10.7
Drill Foliated Gabbros	7.4	131.7	5,933	6,167	233	31.3
Core Foliated Gabbros	23.1	154.9	6,166	6,400	233	10.1
Core Layered Gabbros	55.2	210.1	6,400	6,857	457	8.3
Drill Layered Gabbros	32.6	242.7	6,857	7,400	543	16.7
Set 11-3/4" Liner	7.0	249.7				
Core Layered Gabbros	68.9	318.6	7,400	7,857	457	6.6
Drill Layered Gabbros	32.6	351.2	7,857	8,314	457	14.0
Core Layered Gabbros	74.5	425.7	8,314	8,772	457	6.1
Drill Layered Gabbros	34.9	460.6	8,772	9,229	457	13.1
Core Layered Gabbros	29.2	489.8	9,229	9,400	171	5.9
Core Mantle	91.8	581.6	9,400	9,900	500	5.4
TA hole	5.0	586.6				
Pull BOP/Riser	3.0	589.6				
5% Operational NPT	27.8	617.4				

Total Core/Drill Days = **564**

Total Project Days = **617**

For this case, 44% of the hole is cored, and 56% is drilled as shown in Table 17 below.

Table 17—Cocos Plate – Case 2 – Projected Days for Drilling and Coring

	Interval	%	Days
Coring =	2,758	44.1%	117
Drilling =	3,492	55.9%	66
	6,250	100%	184

The following pie chart (Figure 40) shows a breakdown of the key operations in terms of total days and percentage of the total time. Note that 234 days, or 41% of the time was spent on bit trips.

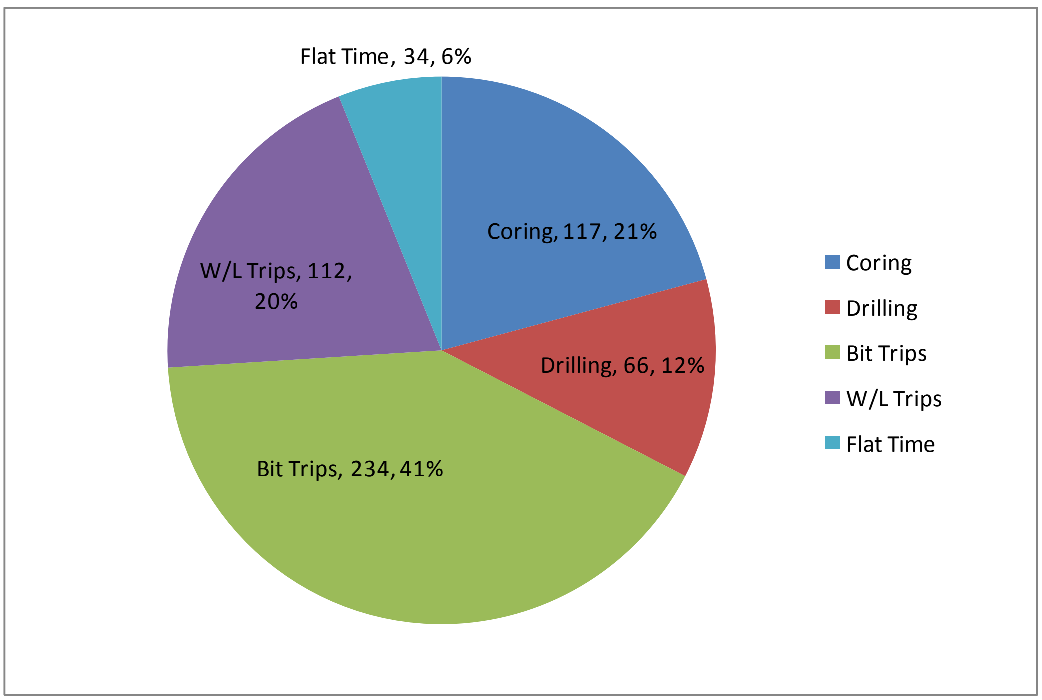

Figure 40—Cocos Plate – Case 2 – Operations Breakdown Comparison

A drilling curve for Case 2 is shown in Figure 41 below.

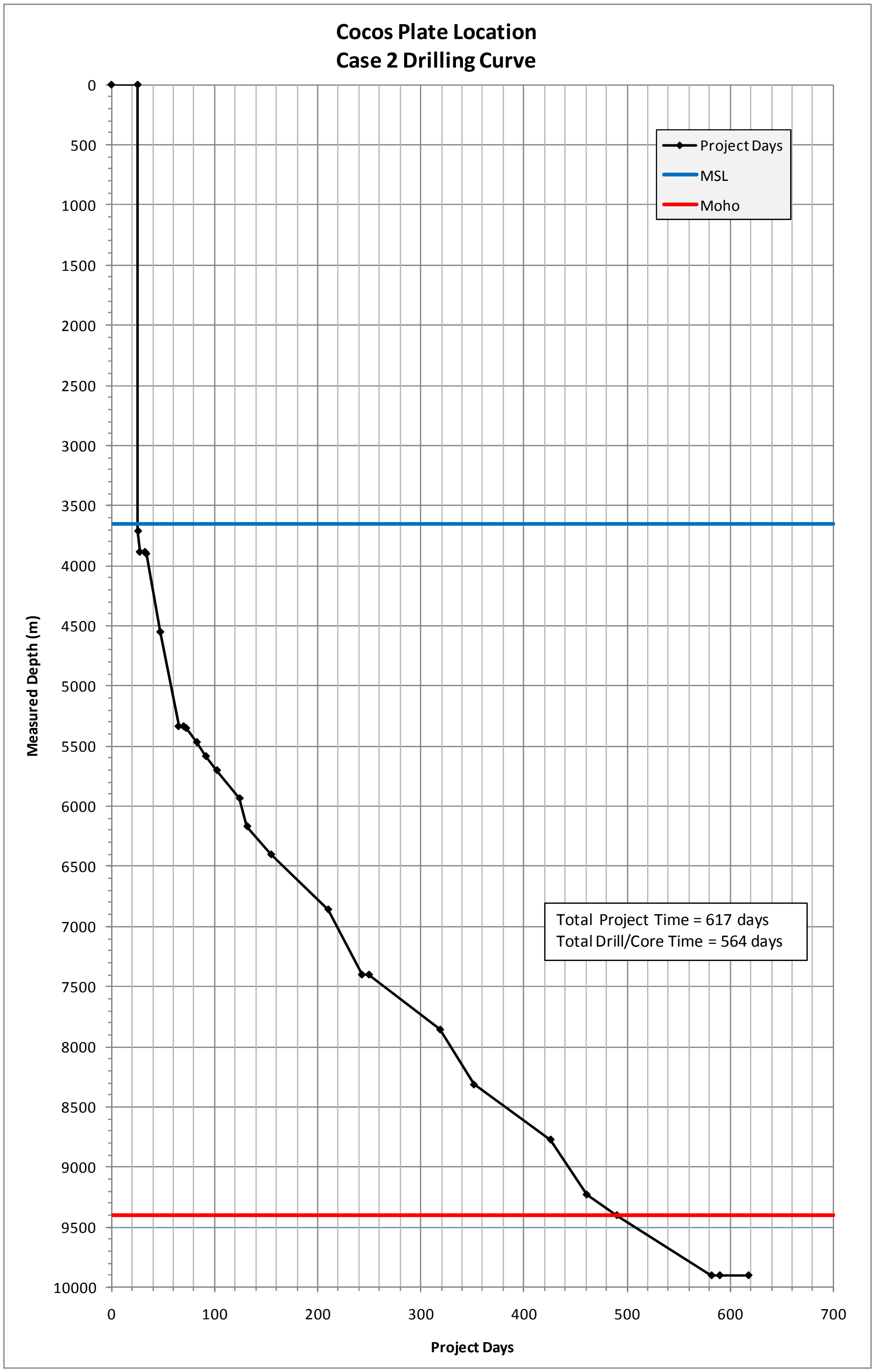

Figure 41—Cocos Plate – Case 2 – Drilling Curve

Case 3 Results

This case is based on spot coring the last 10m of hole before each bit trip. A summary of the time estimate for this case is shown in Table 18 below.

Table 18—Cocos Plate – Case 3 – Breakdown of Operational Time Required to Reach Total Depth

Phase	Interval Days	Cum Days	From (m)	To (m)	Interval (m)	Avg m/day
Move in rig	23.9	23.9				
Position Rig	1.5	25.4				
Jet 36"	0.5	25.9	3,650	3,711	61	122
Drill Sediments	1.5	27.4	3,711	3,885	174	116
Set 20" casing	2.1	29.5				
Run BOP & Riser	3.0	32.5				
Drill Sediments	1.2	33.7	3,885	3,900	15	12.6
Drill Lava	13.6	47.3	3,900	4,550	650	47.7
Drill Dikes	17.6	64.9	4,550	5,335	785	44.6
Set 13-3/8" Casing	5.0	69.9				
Core Dikes	1.7	71.6	5,335	5,350	15	9.0
Drill/Core Textured Gabbros	17.3	88.9	5,350	5,700	350	20.3
Drill/Core Foliated Gabbros	26.0	114.9	5,700	6,400	700	26.9
Drill/Core Layered Gabbros	62.8	177.6	6,400	7,400	1,000	15.9
Set 11-3/4" Liner	7.0	184.6				
Drill/Core Layered Gabbros	174.2	358.9	7,400	9,400	2,000	11.5
Core Mantle	91.8	450.7	9,400	9,900	500	5.4
TA hole	5.0	455.7				
Pull BOP/Riser	3.0	458.7				
5% Operational NPT	21.3	479.9				

Total Core/Drill Days = **433**

Total Project Days = **480**

For this case,18% of the hole is cored, and 82% is drilled as shown in Table 19.

Table 19—Cocos Plate – Case 3 – Projected Days for Drilling and Coring

	Interval	%	Days
Coring =	1,155	18.5%	51
Drilling =	5,095	81.5%	104
	6,250	100%	155

The following pie chart (Figure 42) shows a breakdown of the key operations in terms of total days and percentage of the total time. Note that 187 days, or 43% of the time was spent on bit trips.

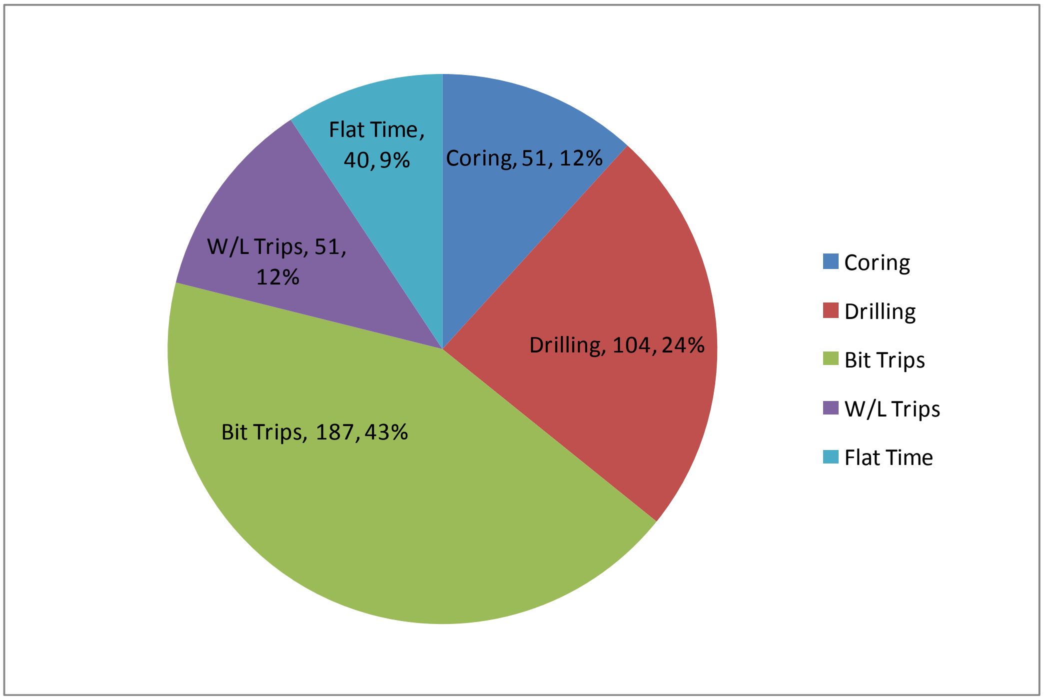

Figure 42—Cocos Plate – Case 3 – Operations Breakdown Comparison

A drilling curve for Case 3 is shown in Figure 43 below.

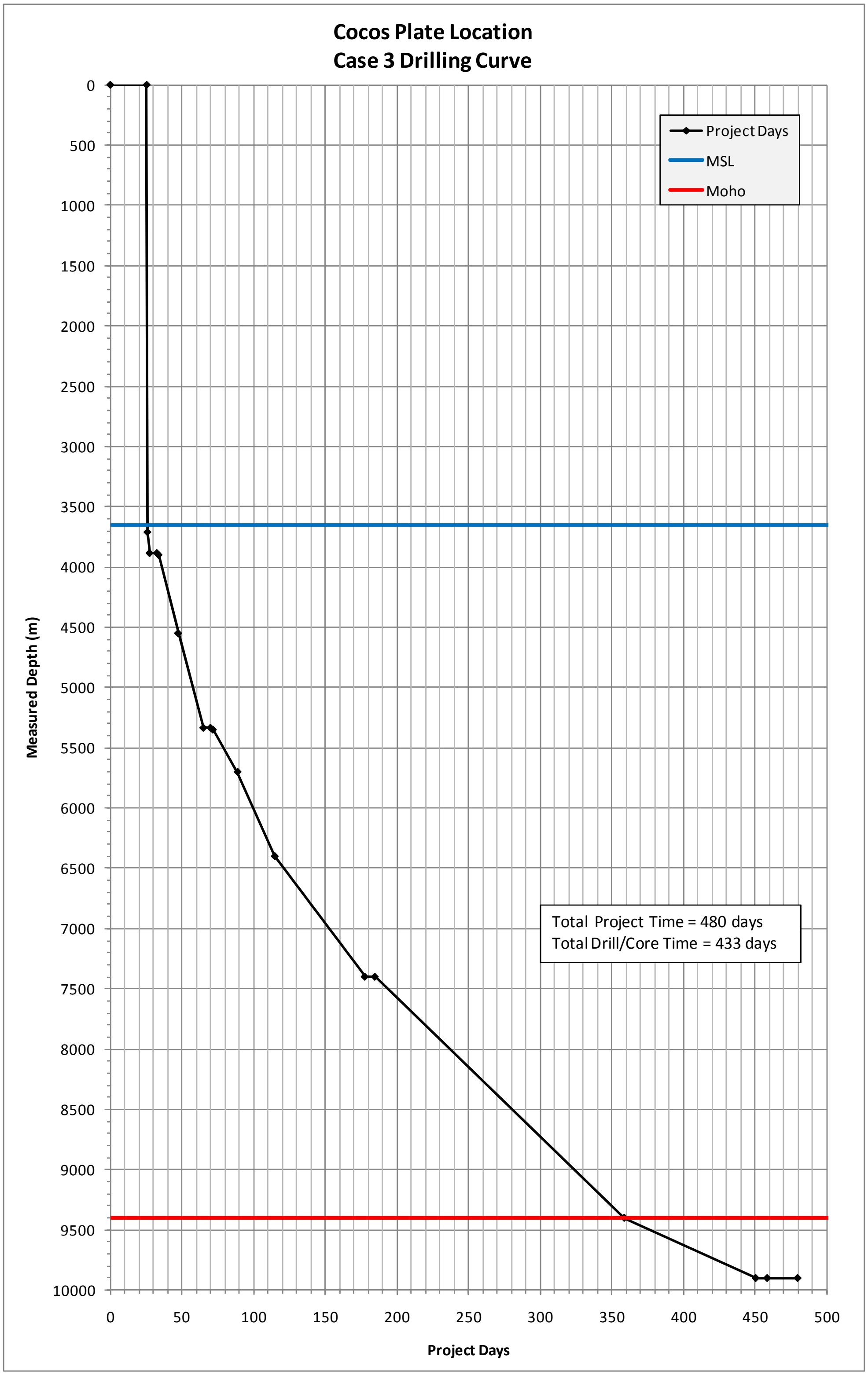

Figure 43—Cocos Plate – Case 3 – Drilling Curve

Case 4 Results

This case is based on drilling the entire hole to the Moho and the coring the mantle. A summary of the time estimate for this case is shown in Table 20 below.

Table 20—Cocos Plate – Case 4 – Breakdown of Operational Time Required to Reach Total Depth

Phase	Interval Days	Cum Days	From (m)	To (m)	Interval (m)	Avg m/day
Move in rig	23.9	23.9				
Position Rig	1.5	25.4				
Jet 36"	0.5	25.9	3,650	3,711	61	122
Drill Sediments	1.5	27.4	3,711	3,885	174	116
Set 20" casing	2.1	29.5				
Run BOP & Riser	3.0	32.5				
Drill Sediments	1.2	33.7	3,885	3,900	15	12.6
Drill Lava	13.6	47.3	3,900	4,550	650	47.7
Drill Dikes	17.6	64.9	4,550	5,335	785	44.6
Set 13-3/8" Casing	5.0	69.9				
Drill Dikes	1.8	71.7	5,335	5,350	15	8.4
Drill Textured Gabbros	10.7	82.4	5,350	5,700	350	32.9
Drill Foliated Gabbros	27.2	109.6	5,700	6,400	700	25.7
Drill Layered Gabbros	23.7	133.3	6,400	6,857	457	19.3
Drill Layered Gabbros	32.6	165.9	6,857	7,400	543	16.7
Run 11-3/4' Liner	7.0	172.9				
Drill Layered Gabbros	139.9	312.8	7,400	9,400	2,000	14.3
Core Mantle	78.6	391.3	9,400	9,900	500	6.4
TA hole	5.0	396.3				
Pull BOP/Riser	3.0	399.3				
5% Operational NPT	18.3	417.6				

Total Core/Drill Days = **374**
Total Project Days = **418**

For this case 8% of the hole is cored, and 92% is drilled as shown in Table 21 below.

Table 21—Cocos Plate – Case 4 – Projected Days for Drilling and Coring

	Interval	%	Days
Coring =	500	8.0%	23
Drilling =	5,750	92.0%	121
	6,250	100%	144

The following pie chart (Figure 44) shows a breakdown of the key operations in terms of total days and percentage of the total time. Note that 172 days, or 46% of the time was spent on bit trips.

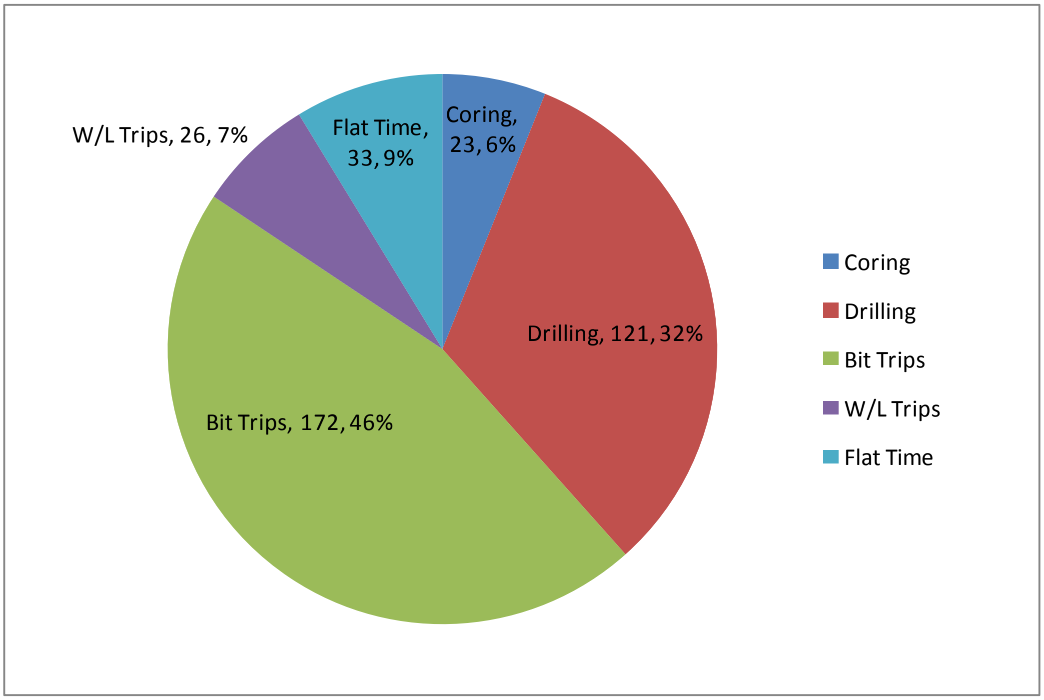

Figure 44—Cocos Plate – Case 4 – Operations Breakdown Comparison

A drilling curve for Case 4 is shown in Figure 45 below.

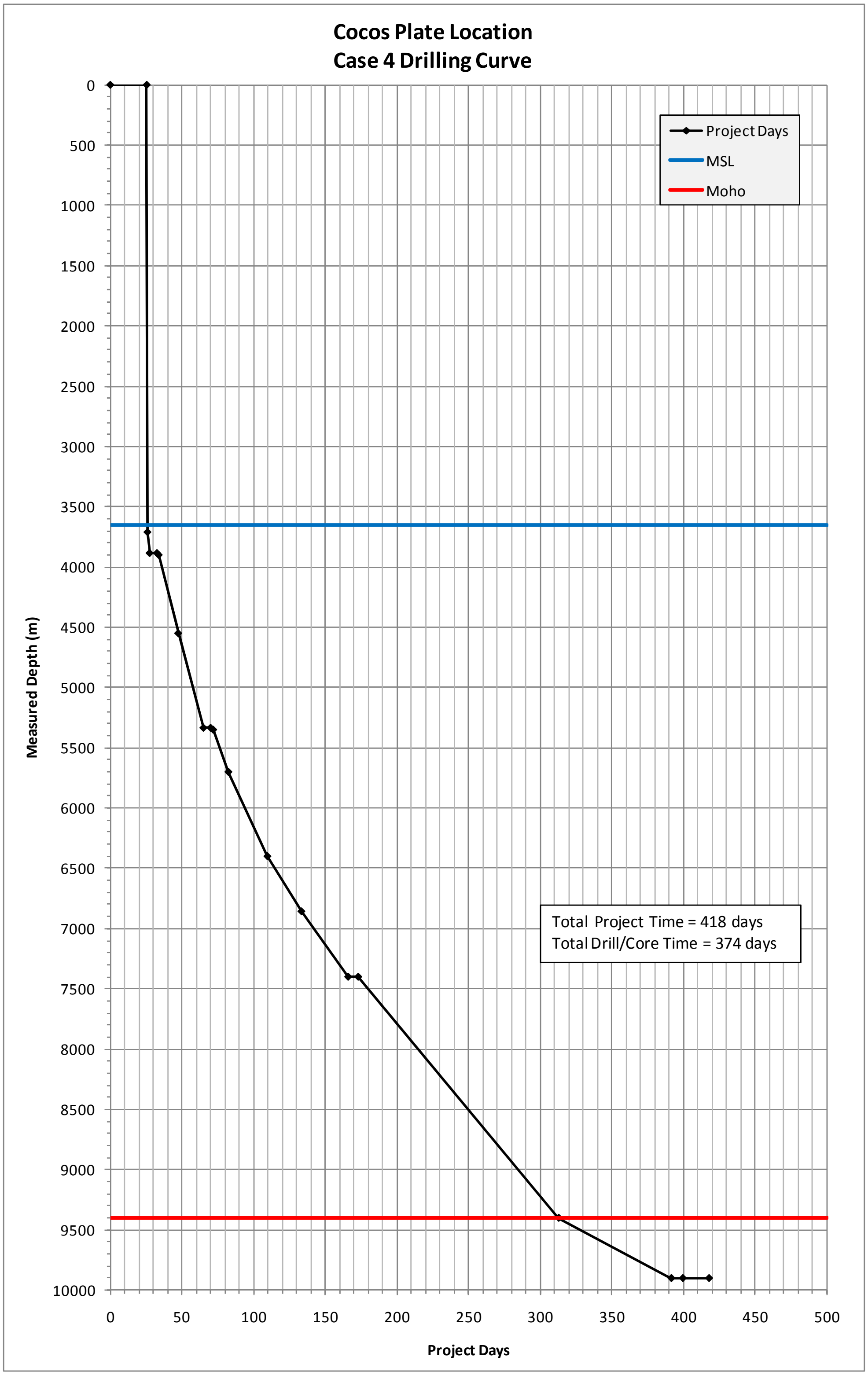

Figure 45—Cocos Plate – Case 4 – Drilling Curve

Case Comparison

The following Figure 46 shows a comparison of the drilling curves for all four cases.

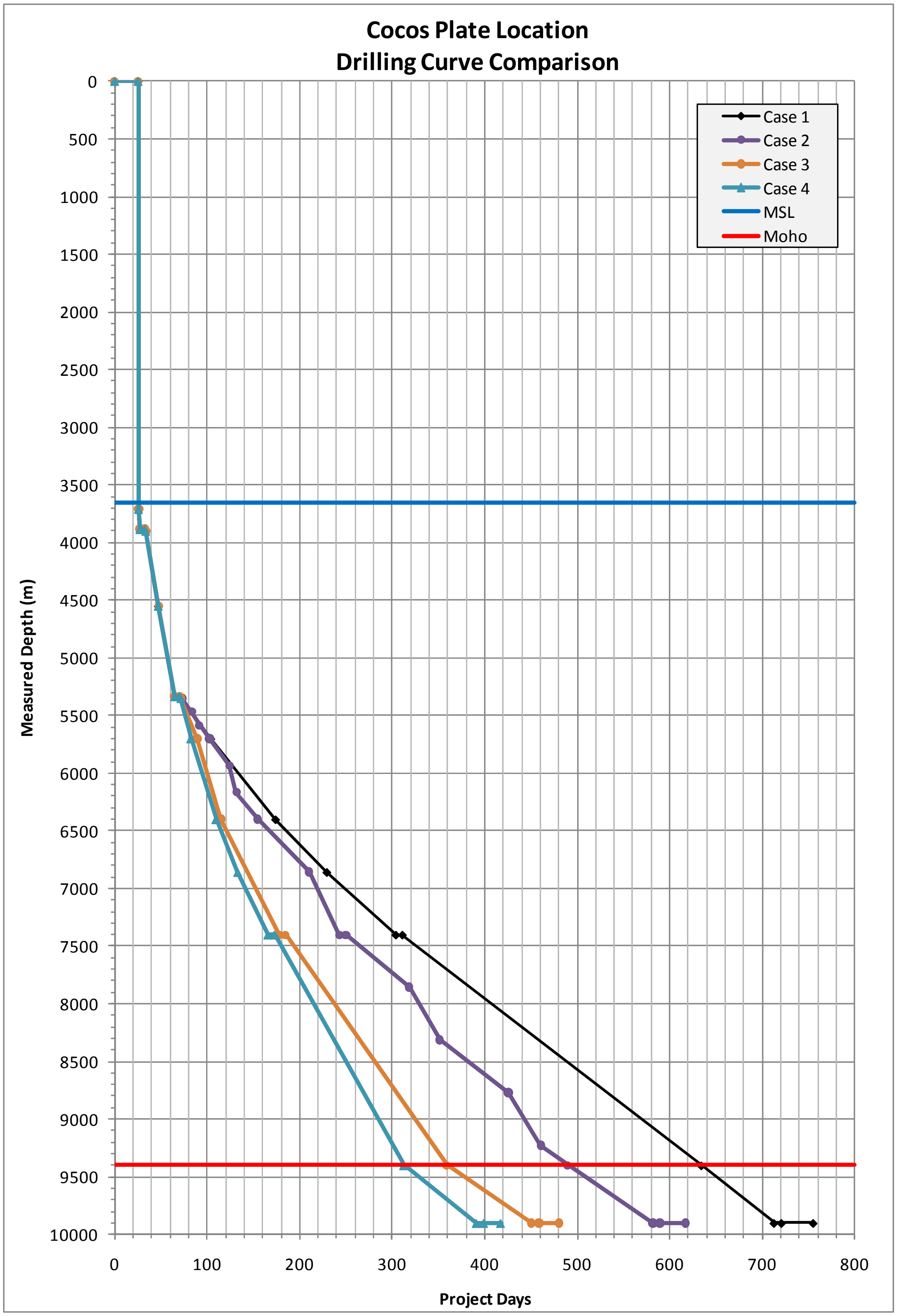

Figure 46—Cocos Plate – Case Comparison – Drilling Curve

7.4.3 Baja Operational Time Estimates

Figure 47 below is the base case wellbore schematic for a hole drilled at the Baja location.

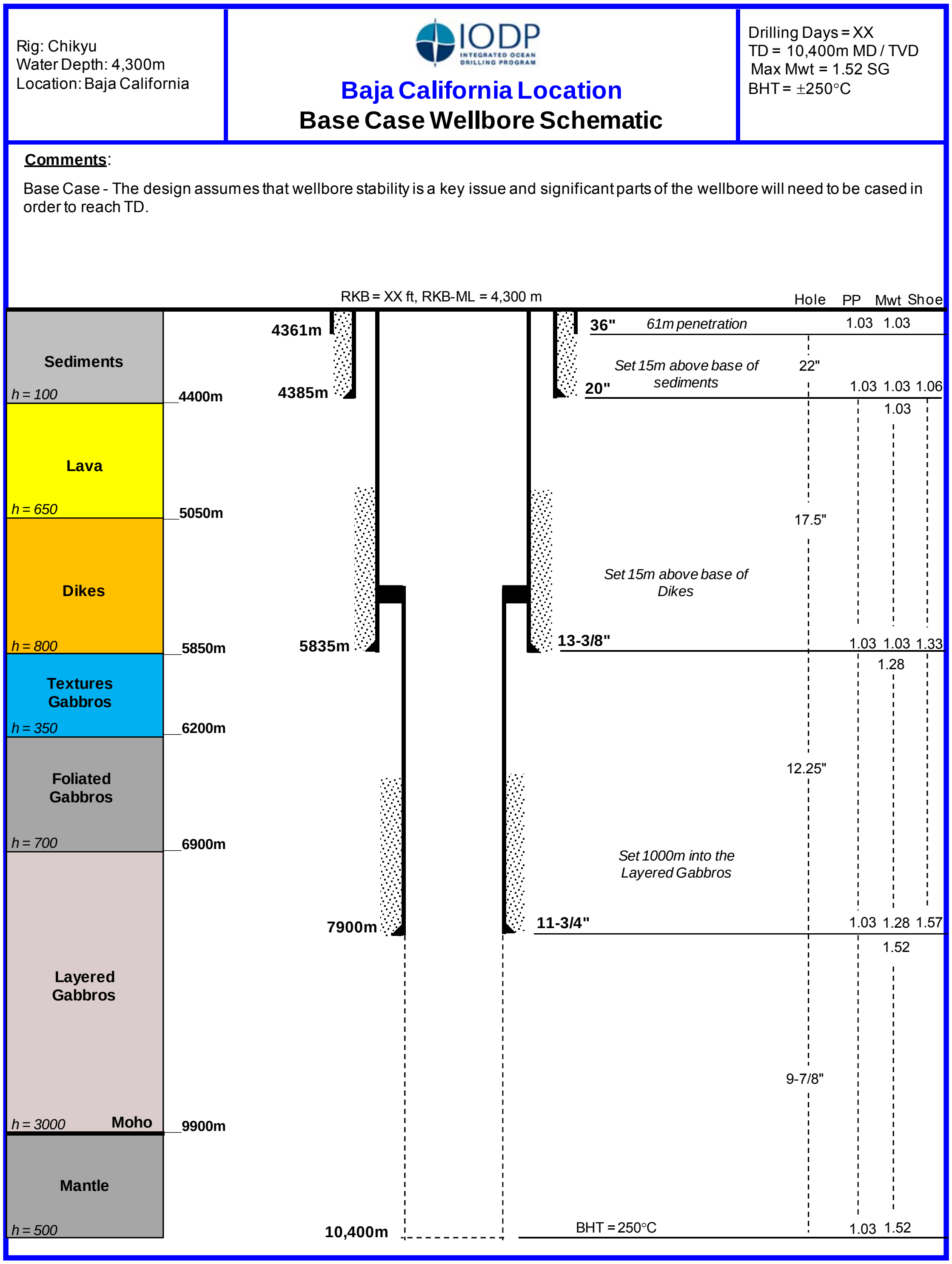

Figure 47—Baja California Location – Base Case – Wellbore Schematic

Case 1 Results

This case is based on continuous coring from the seafloor to TD. It is further assumed that the Chikyu is mobilized from Tokyo and that the transit distance to the location is approximately 8,000 km. A summary of the time estimate for this case is shown in Table 22 below.

Table 22—Baja California – Case 1 – Breakdown of Operational Time Required to Reach Total Depth

Phase	Interval Days	Cum Days	From (m)	To (m)	Interval (m)	Avg m/day
Move in rig	18.1	18.1				
Position Rig	1.5	19.6				
Jet 36"	0.5	20.1	4,300	4,361	61	122
Core Sediments	2.2	22.3	4,361	4,385	24	11
Set 20" casing	2.1	24.4				
Run BOP & Riser	3.0	27.4				
Core Sediments	2.0	29.4	4,385	4,400	15	7.7
Core Lava	45.9	75.2	4,400	5,050	650	14.2
Core Dikes	59.4	134.6	5,050	5,835	785	13.2
Set 13-3/8" Casing	5.0	139.6				
Core Dikes	2.8	142.4	5,835	5,850	15	5.5
Core Textured Gabbros	33.3	175.7	5,850	6,200	350	10.5
Core Foliated Gabbros	73.5	249.2	6,200	6,900	700	9.5
Core Layered Gabbros	129.8	379.0	6,900	7,900	1,000	7.7
Run 11-3/4" Liner	7.0	386.0				
Core Layered Gabbros	337.0	723.0	7,900	9,900	2,000	5.9
Core Mantle	95.3	818.4	9,900	10,400	500	5.2
TA hole	5.0	823.4				
Pull BOP/Riser	3.0	826.4				
5% Operational NPT	39.9	866.3				

Total Core/Drill Days = **807**
Total Project Days = **866**

For this case, 99% of the hole is cored, and 1% is drilled as shown in Table 23 below.

Table 23—Baja California – Case 1 – Projected Days for Drilling and Coring

	Interval	%	Days
Coring =	6,039	99.0%	236
Drilling =	61	1.0%	1
	6,100	100%	236

The following pie chart (Figure 48) shows a breakdown of the key operations in terms of total days and percentage of the total time. Flat time is defined as the time spent running BOP's running wire-line, logs and running casing. Note that 300 days, or 37% of the time was spent on bit trips.

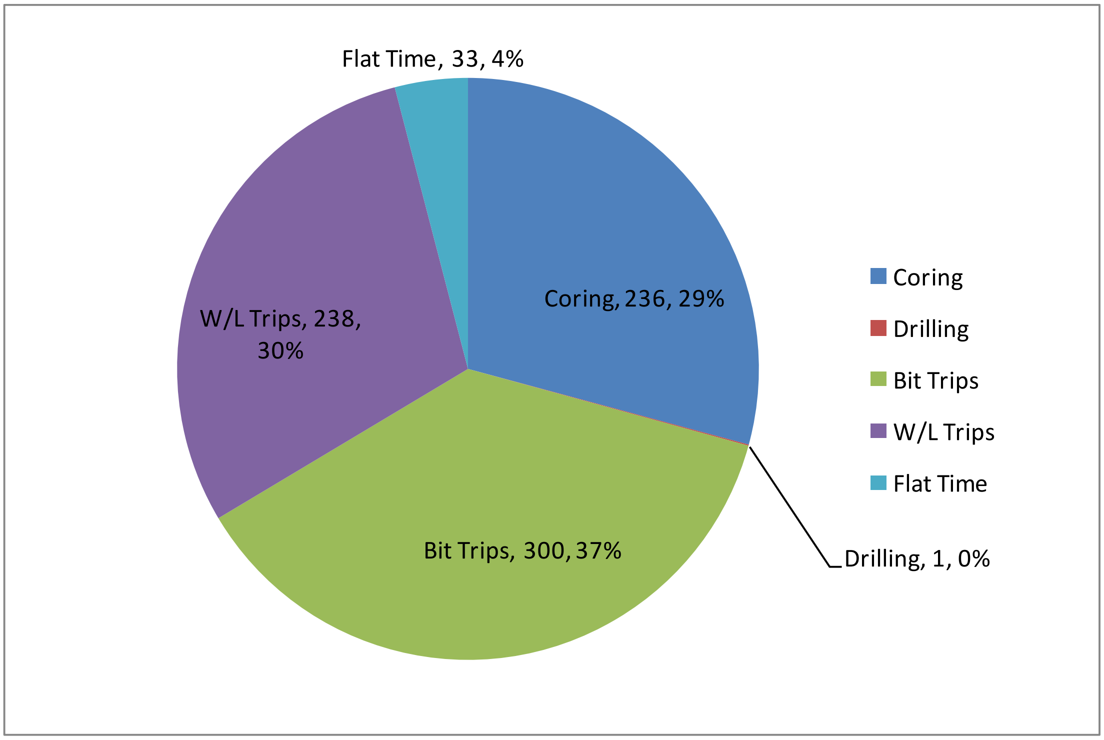

Figure 48—Baja California – Case 1 – Operations Breakdown Comparison

A drilling curve for Case 1 is shown in Figure 49 below.

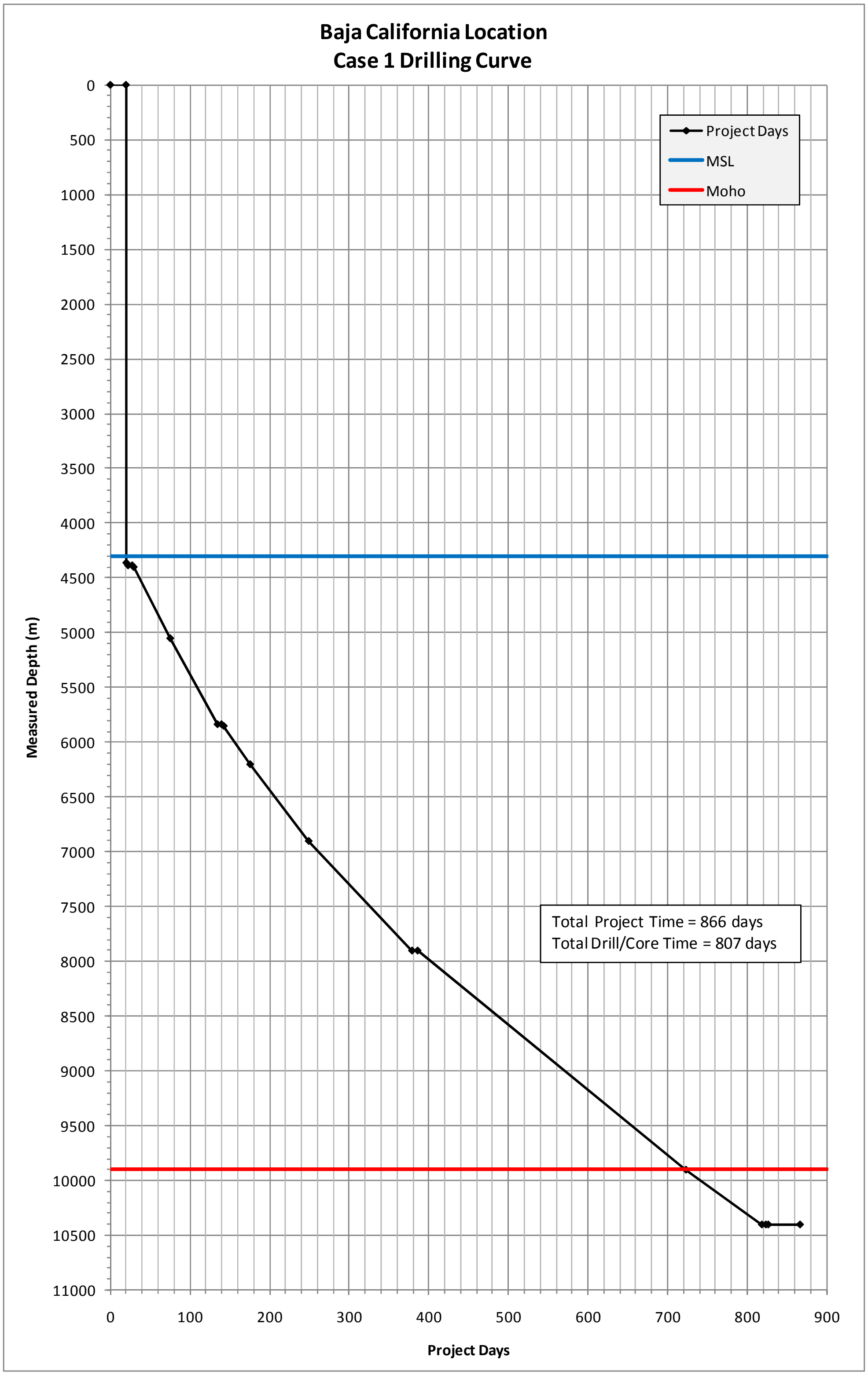

Figure 49—Baja California – Case 1 – Drilling Curve

Case 2 Results

This case is based on coring the upper third of stratigraphic section, drilling the middle third, and then coring the bottom third. A summary of the time estimate for this case is shown in Table 24 below.

Table 24—Baja California – Case 2 – Breakdown of Operational Time Required to Reach Total Depth

Phase	Interval Days	Cum Days	From (m)	To (m)	Interval (m)	Avg m/day
Move in rig	18.1	18.1				
Position Rig	1.5	19.6				
Jet 36"	0.5	20.1	4,300	4,361	61	122
Core Sediments	3.3	23.4	4,361	4,385	24	7
Set 20" casing	2.1	25.5				
Run BOP & Riser	3.0	28.5				
Core Sediments	2.0	30.5	4,385	4,400	15	7.7
Core Lava	15.0	45.5	4,400	4,617	217	14.4
Drill Lava	4.4	49.9	4,617	4,834		
Core Lava	15.9	65.7	4,834	5,050	216	13.6
Core Dikes	20.5	86.2	5,050	5,317	267	13.0
Drill Dikes	11.9	98.1	5,314	5,580	267	22.4
Core Dikes	19.8	117.9	5,580	5,835	255	12.9
Set 13-3/8" Casing	5.0	122.9				
Core Dikes	2.8	125.7	5,835	5,850	15	5.5
Core Textured Gabbros	11.0	136.6	5,850	5,967	116	10.6
Drill Textured Gabbros	3.9	140.6	5,967	6,083	116	29.5
Core Textured Gabbros	11.3	151.8	6,083	6,200	117	10.4
Core Foliated Gabbros	23.1	174.9	6,200	6,433	233	10.1
Drill Foliated Gabbros	7.9	182.8	6,433	6,667	233	29.5
Core Foliated Gabbros	24.1	206.9	6,667	6,900	233	9.7
Core Layered Gabbros	57.8	264.7	6,900	7,357	457	7.9
Drill Layered Gabbros	33.8	298.5	7,357	7,900	543	16.1
Run 11-3/4" Liner	7.0	305.5				
Core Layered Gabbros	71.9	377.4	7,900	8,357	457	6.4
Drill Layered Gabbros	34.5	411.9	8,357	8,815	457	13.3
Core Layered Gabbros	78.3	490.2	8,815	9,272	457	5.8
Drill Layered Gabbros	36.8	527.0	9,272	9,729	457	12.4
Core Layered Gabbros	31.1	558.1	9,729	9,900	171	5.5
Core Mantle	95.3	653.5	9,900	10,400	500	5.2
TA hole	5.0	658.5				
Pull BOP/Riser	3.0	661.5				
5% Operational NPT	31.7	693.2				

Total Core/Drill Days = **642**

Total Project Days = **693**

For this case, 61% of the hole is cored, and 39 % is drilled as shown in Table 25 below.

Table 25—Baja California – Case 2 – Projected Days for Drilling and Coring

	Interval	%	Days
Coring =	3,752	61.5%	144
Drilling =	2,352	38.5%	53
	6,103	100%	197

The following pie chart (Figure 50) shows a breakdown of the key operations in terms of total days and percentage of the total time. Note that 259 days, or 40% of the time was spent on bit trips.

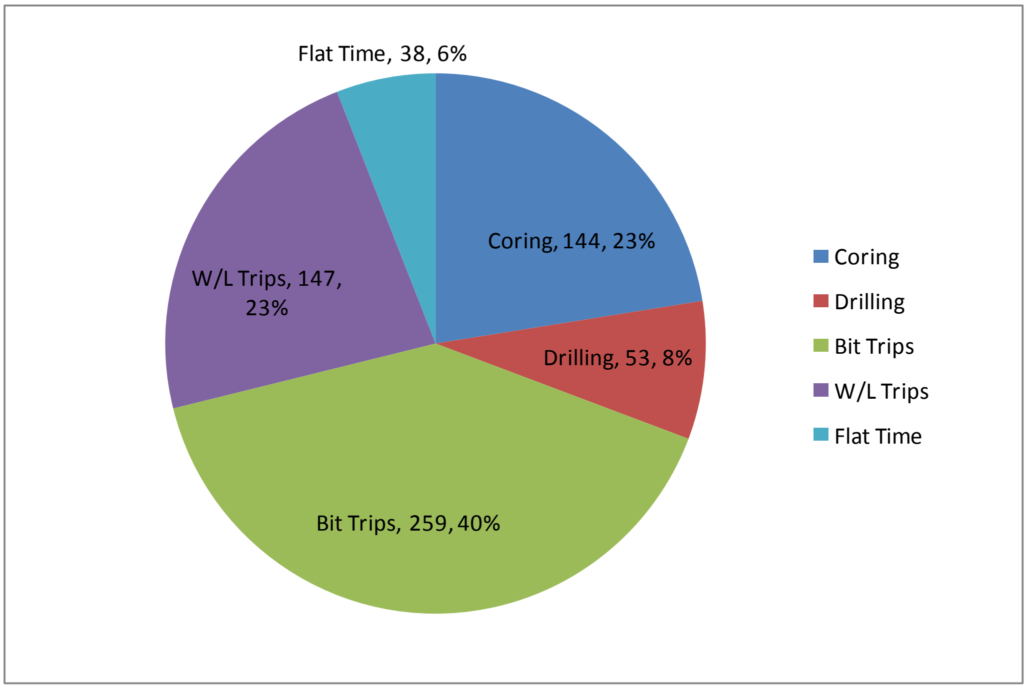

Figure 50—Baja California – Case 2 – Operations Breakdown Comparison

A drilling curve for Case 2 is shown in Figure 51 below.

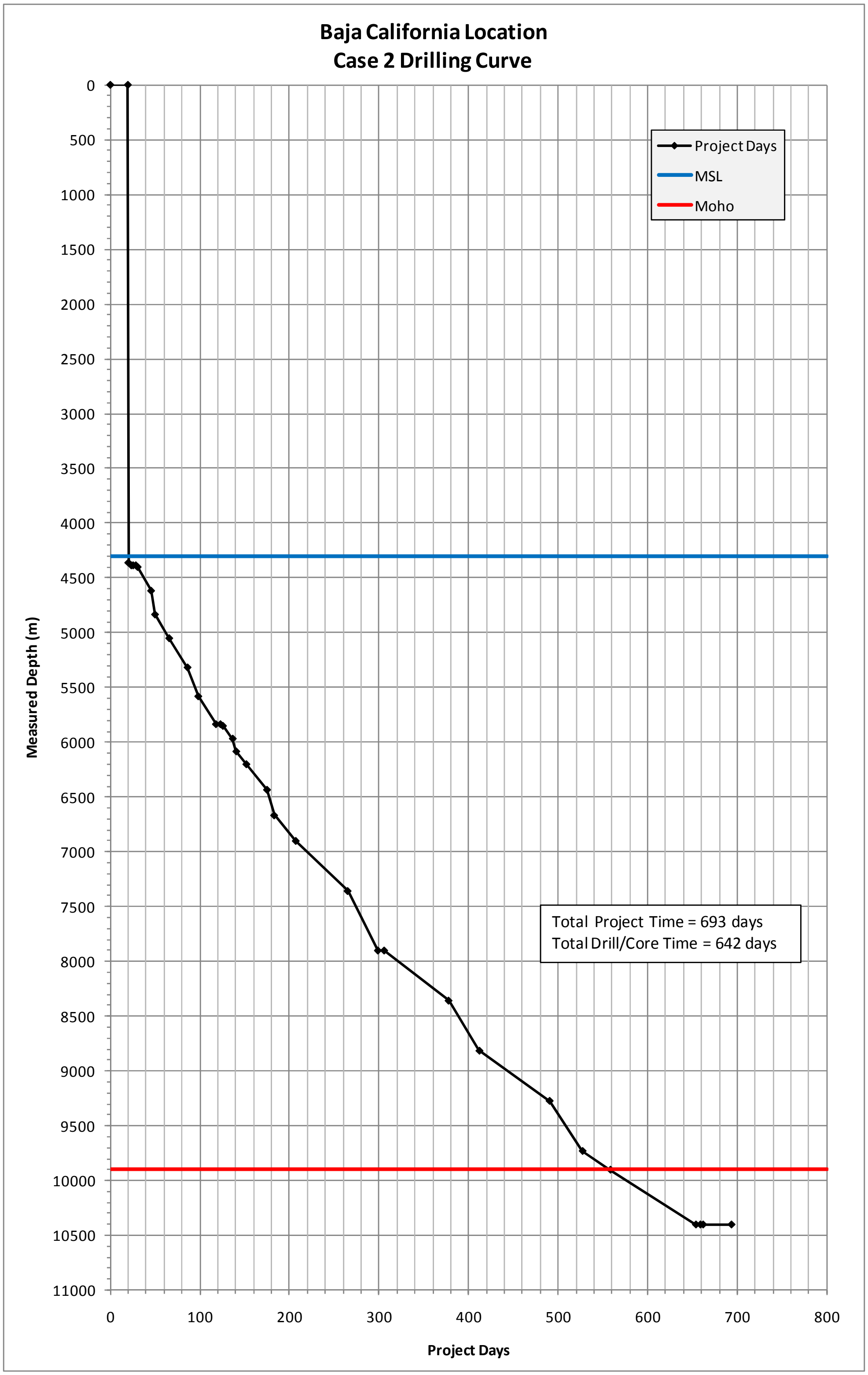

Figure 51—Baja California – Case 2 – Drilling Curve

Case 3 Results

This case is based on spot coring the last 10m of hole before each bit trip. A summary of the time estimate for this case is shown in Table 26 below.

Table 26—Baja California – Case 3 – Breakdown of Operational Time Required to Reach Total Depth

Phase	Interval Days	Cum Days	From (ft)	To (ft)	Interval (ft)	Avg ft/day
Move in rig	18.1	18.1				
Position Rig	1.5	19.6				
Jet 36"	0.5	20.1	4,300	4,361	61	122
Drill Sediments	1.3	21.4	4,361	4,385	24	19
Set 20" casing	2.1	23.5				
Run BOP & Riser	3.0	26.5				
Core Sediments	2.0	28.5	4,385	4,400	15	7.7
Drill/Core Lava	18.1	46.6	4,400	5,035	635	35.0
Drill/Core Dikes	24.7	71.3	5,035	5,835	800	32.4
Set 13-3/8" Casing	7.0	78.3				
Drill/Core Textured Gabbros	11.8	90.1	5,835	6,200	365	30.9
Drill/Core Foliated Gabbros	27.3	117.4	6,200	6,900	700	25.6
Drill/Core Layered Gabbros	65.5	183.0	6,900	7,900	1,000	15.3
Set 11-3/4" Liner	7.0	190.0				
Drill/Core Layered Gabbros	173.4	363.4	7,900	9,900	2,000	11.5
Core Mantle	53.7	417.0	9,900	10,400	500	9.3
TA hole	5.0	422.0				
Pull BOP/Riser	3.0	425.0				
5% Operational NPT	19.9	444.9				

Total Core/Drill Days =	**405**
Total Project Days =	**445**

For this case, 21% of the hole is cored, and 79% is drilled as shown in Table 27 below.

Table 27—Baja California – Case 3 – Projected Days for Drilling and Coring

	Interval	%	Days
Coring =	1,301	21.3%	55
Drilling =	4,799	78.7%	102
	6,100	100%	157

The following pie chart (Figure 50) shows a breakdown of the key operations in terms of total days and percentage of the total time. Note that 160 days, or 39% of the time was spent on bit trips.

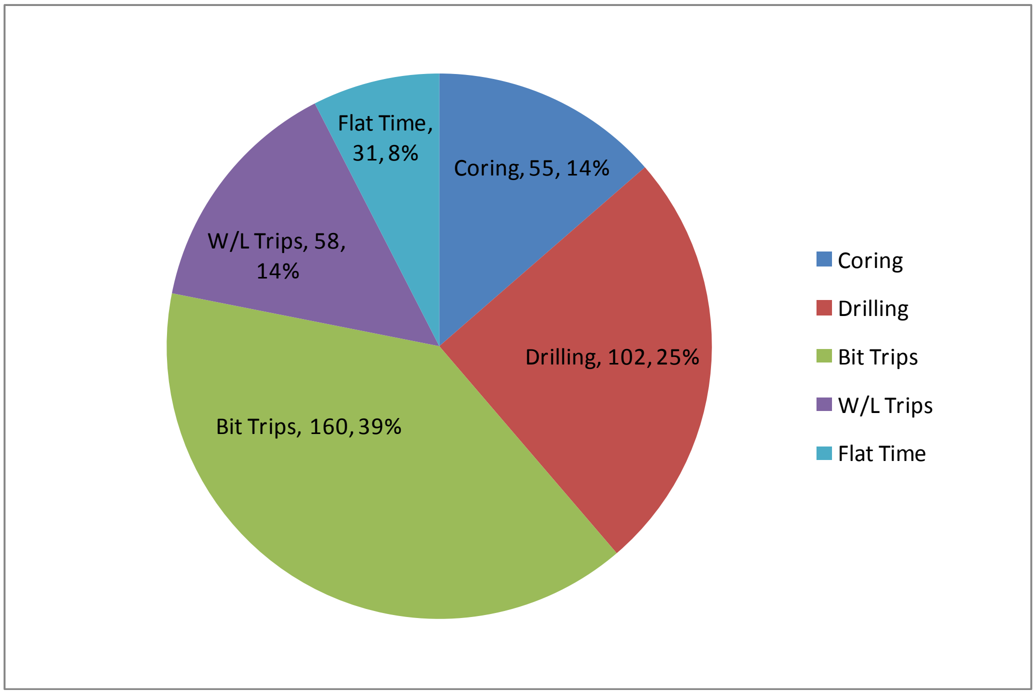

Figure 52—Baja California – Case 3 – Operations Breakdown Comparison

A drilling curve for Case 3 is shown in Figure 53 below.

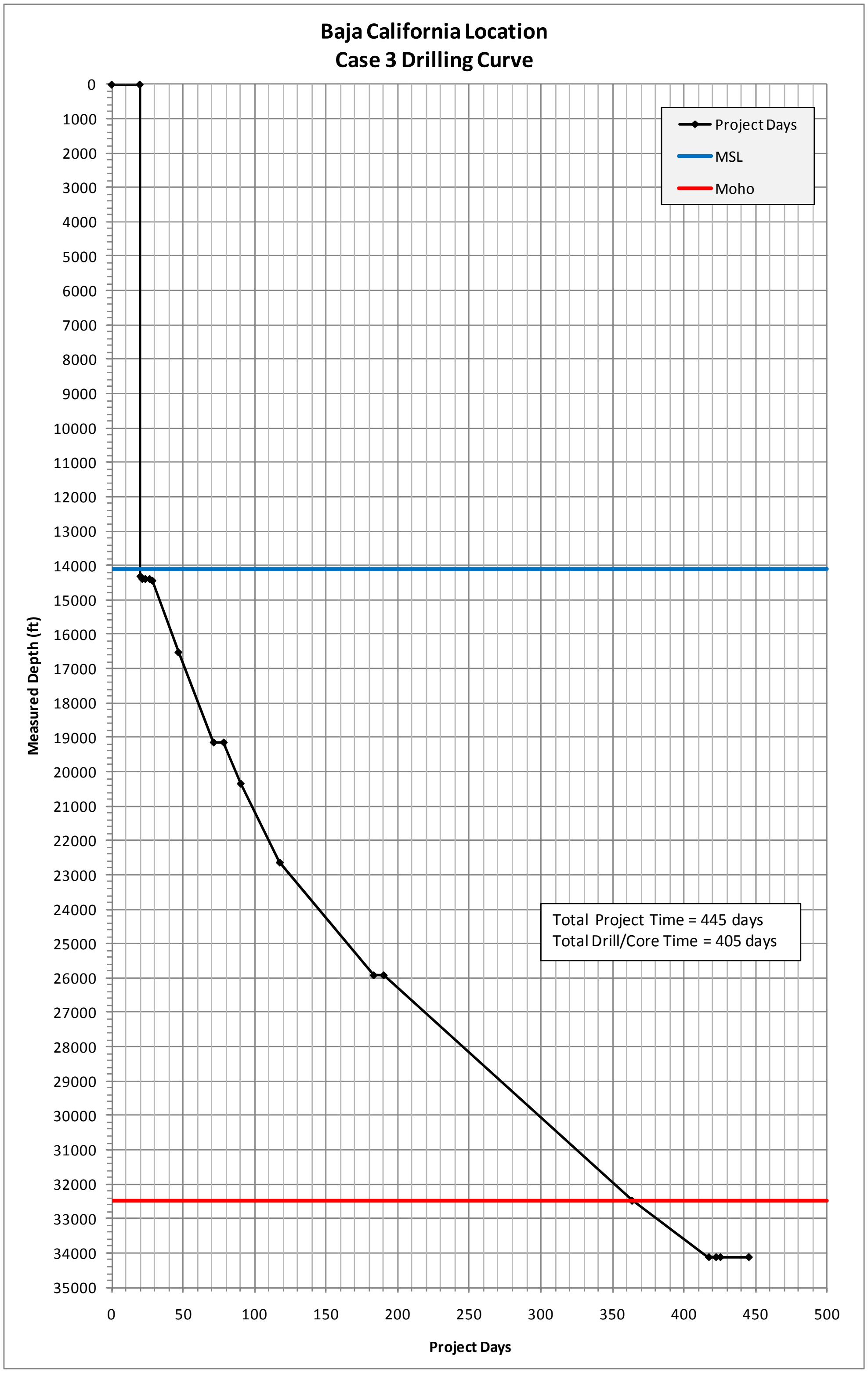

Figure 53—Baja California – Case 3 – Drilling Curve

Case 4 Results

This case is based on drilling the entire hole to the Moho and the coring the mantle. A summary of the time estimate for this case is shown in Table 28 below.

Table 28—Baja California – Case 4 – Breakdown of Operational Time Required to Reach Total Depth

Phase	Interval Days	Cum Days	From (m)	To (m)	Interval (m)	Avg m/day
Move in rig	18.1	18.1				
Position Rig	1.5	19.6				
Jet 36"	0.5	20.1	4,300	4,361	61	122
Drill Sediments	1.2	21.3	4,361	4,385	24	20
Set 20" casing	2.1	23.4				
Run BOP & Riser	3.0	26.4				
Drill Sediments	1.4	27.8	4,385	4,400	15	11.3
Drill Lava	3.4	31.2	4,400	4,550	150	44.1
Drill Dikes	29.0	60.2	4,550	5,835	1,285	44.3
Set 13-3/8" Casing	5.0	65.2				
Drill Dikes	2.0	67.1	5,835	5,850	15	7.8
Drill Textured Gabbros	11.1	78.2	5,850	6,200	350	31.6
Drill Foliated Gabbros	28.0	106.2	6,200	6,900	700	25.0
Drill Layered Gabbros	24.6	130.8	6,900	7,357	457	18.6
Drill Layered Gabbros	33.6	164.4	7,357	7,900	543	16.2
Run 11-3/4" Liner	7.0	171.4				
Drill Layered Gabbros	144.9	316.3	7,900	9,900	2,000	13.8
Core Mantle	81.5	397.8	9,900	10,400	500	6.1
TA hole	5.0	402.8				
Pull BOP/Riser	3.0	405.8				
5% Operational NPT	18.9	424.7				

Total Core/Drill Days = **386**
Total Project Days = **425**

For this case 8% of the hole is cored, and 92% is drilled as shown in Table 29 below.

Table 29—Baja California – Case 4 – Projected Days for Drilling and Coring

	Interval	%	Days
Coring =	500	8.2%	123
Drilling =	5,600	91.8%	20
	6,100	100%	143

The following pie chart (Figure 54) shows a breakdown of the key operations in terms of total days and percentage of the total time. Note that 183 days, or 47% of the time was spent on bit trips.

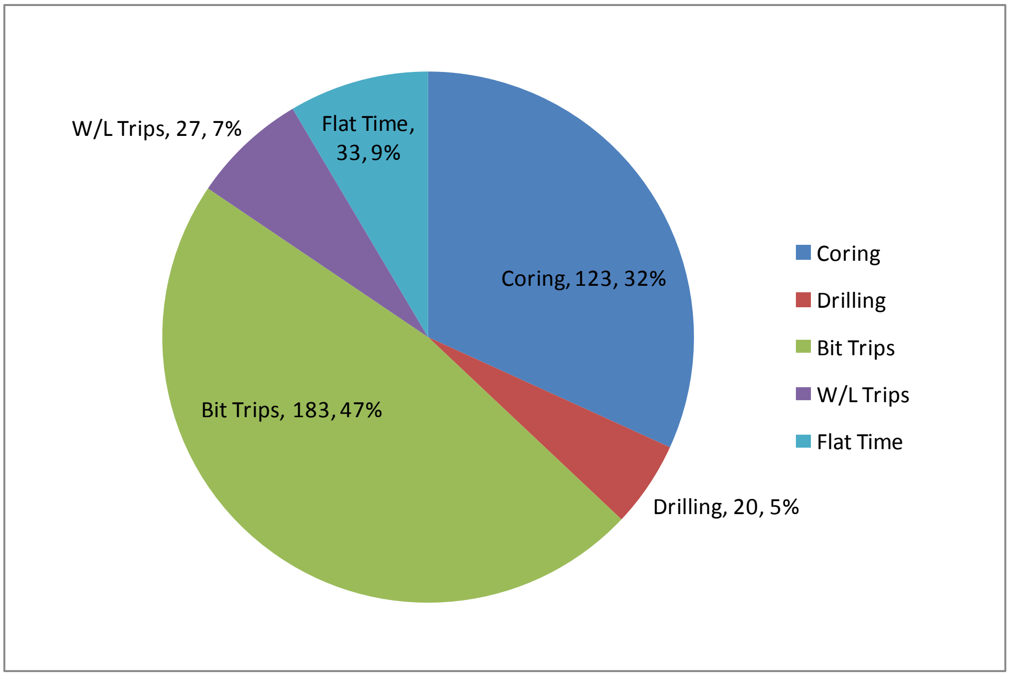

Figure 54—Baja California – Case 4 – Operations Breakdown Comparison

A drilling curve for Case 4 is shown in Figure 55 below.

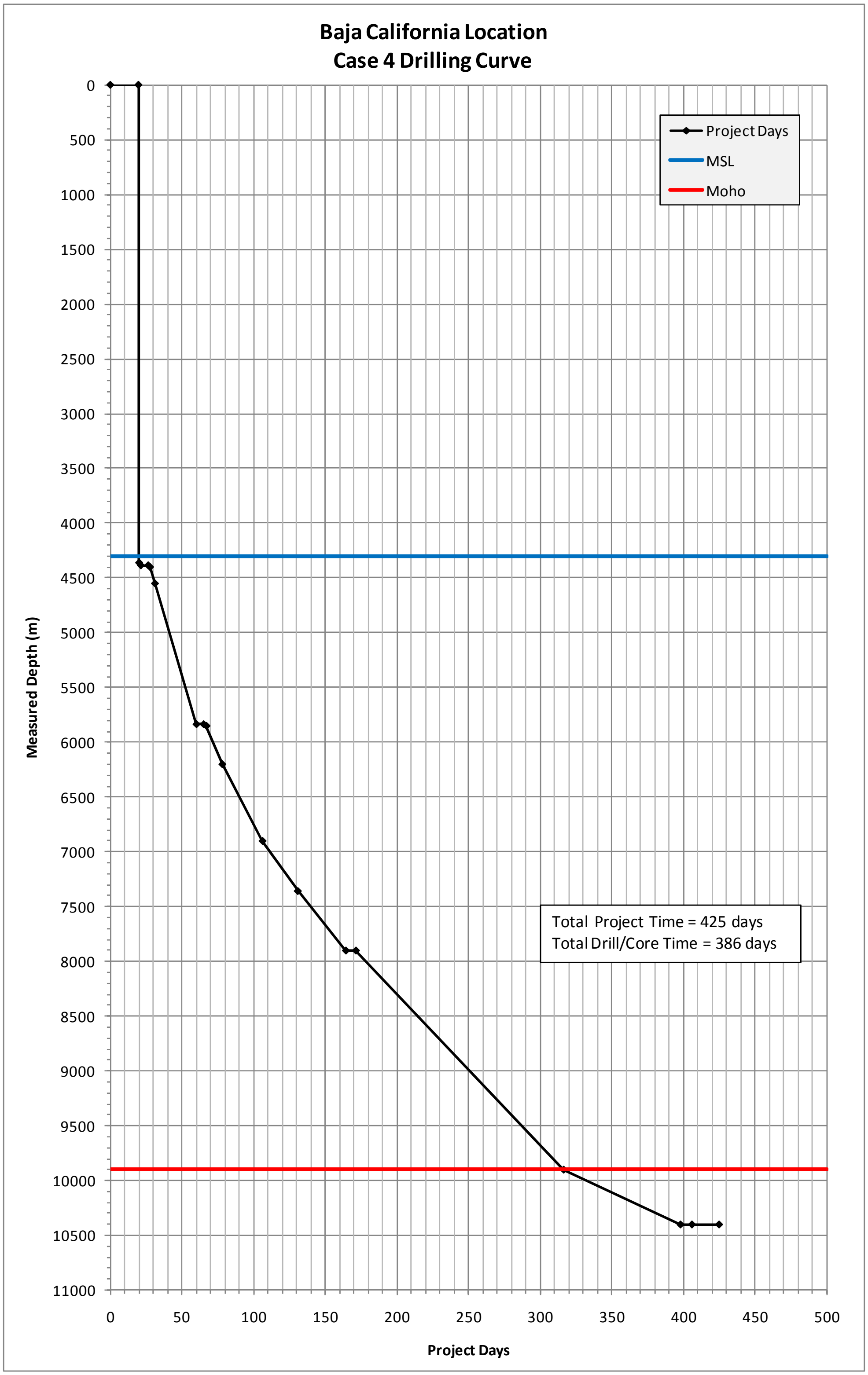

Figure 55—Baja California – Case 4 – Drilling Curve

Case Comparison

The following Figure 56 shows a comparison of the drilling curves for all four cases.

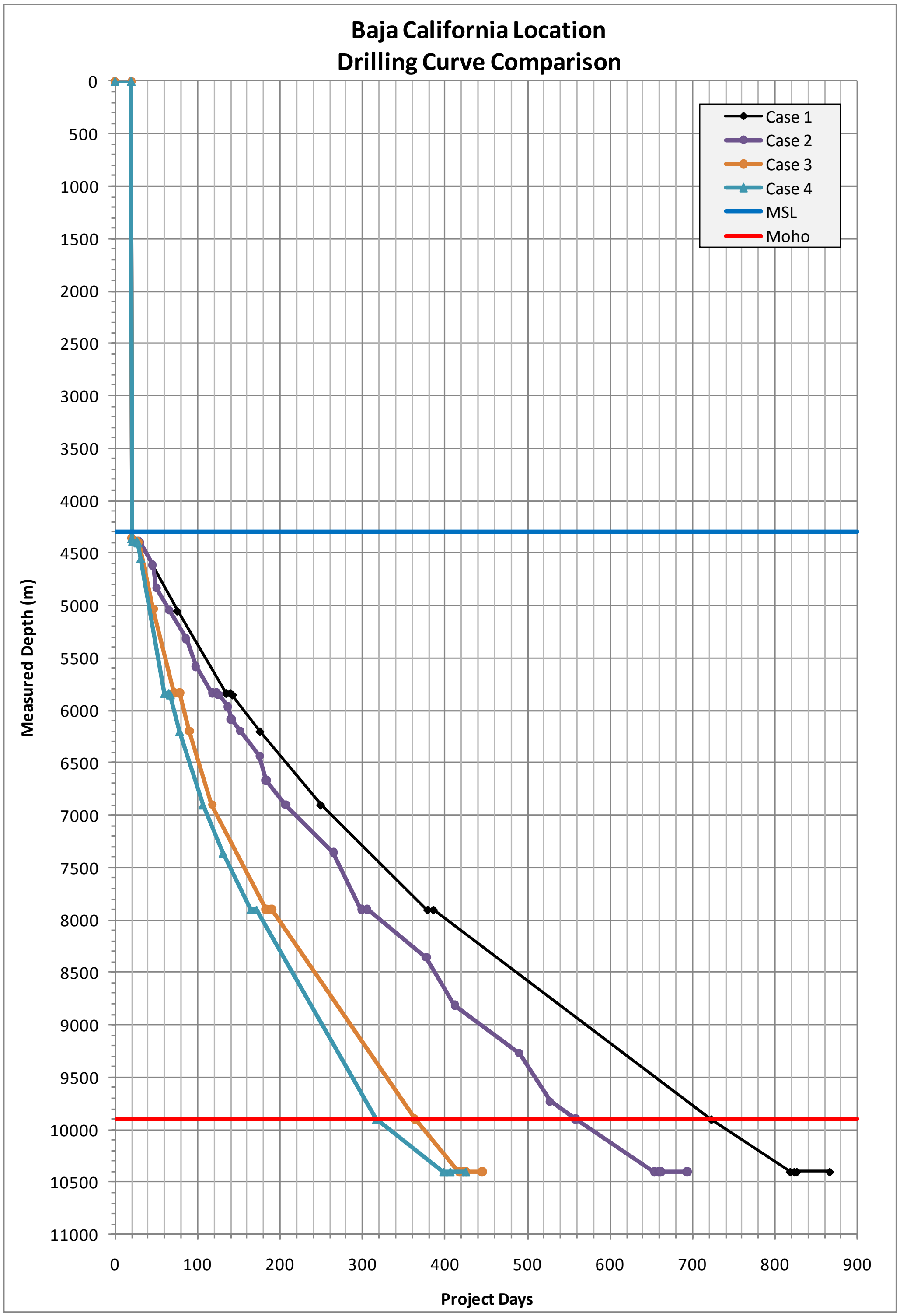

Figure 56—Baja California – Case Comparison – Drilling Curve

7.4.4 Hawaii Operational Time Estimates

Figure 57 below is the base case wellbore schematic for a hole drilled at the Hawaii location.

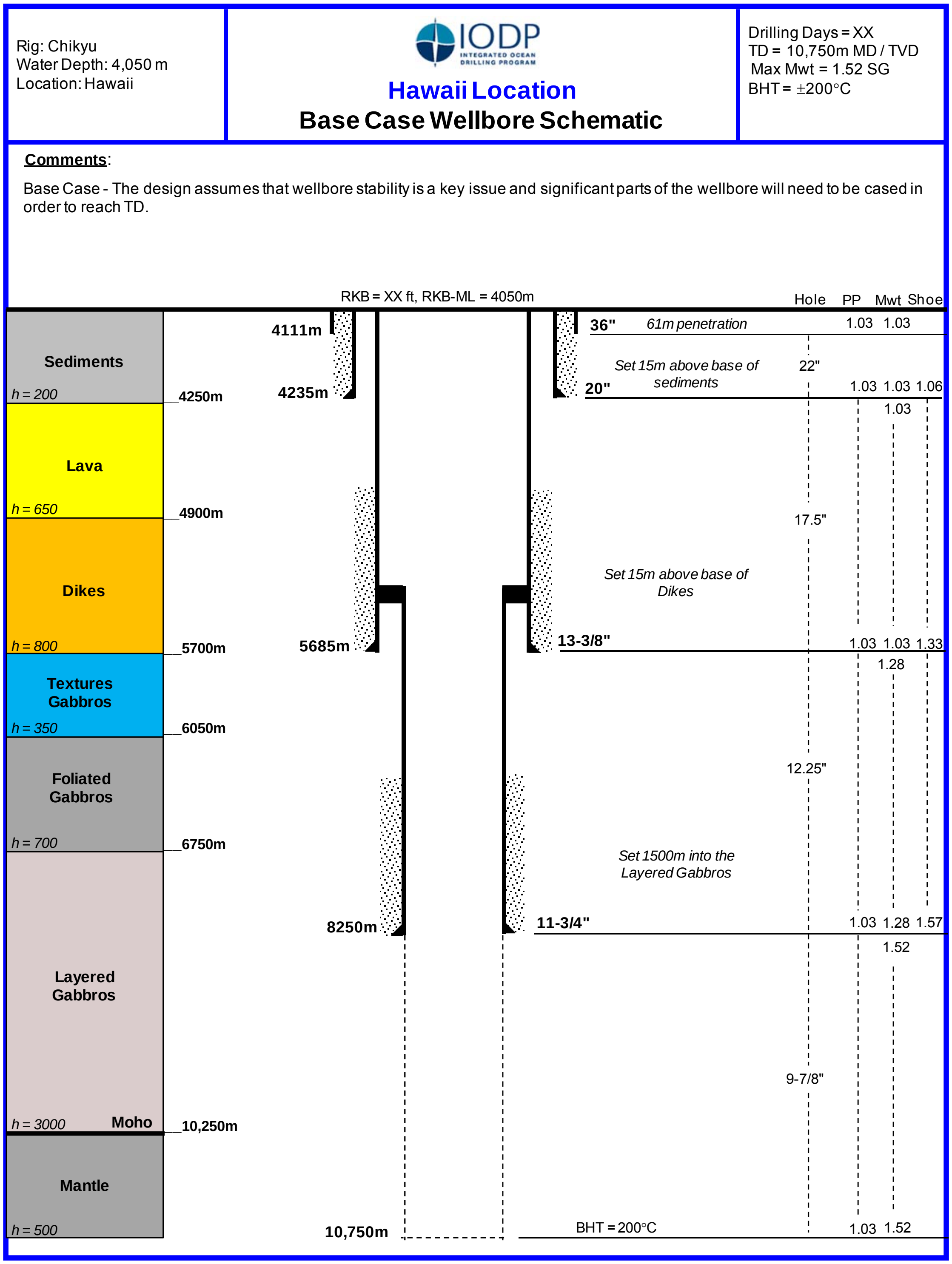

Figure 57—Hawaii Location – Base Case – Wellbore Schematic

Case 1 Results

This case is based on continuous coring from the seafloor to TD. It is further assumed that the Chikyu is mobilized from Tokyo and that the transit distance to the location is approximately 5,900 km. A summary of the time estimate for this case is shown in Table 30 below.

Table 30—Hawaii – Case 1 – Breakdown of Operational Time Required to Reach Total Depth

Phase	Interval Days	Cum Days	From (m)	To (m)	Interval (m)	Avg m/day
Move in rig	13.4	13.4				
Position Rig	1.5	14.9				
Jet 36"	0.5	15.4	4,050	4,111	61	122
Core Sediments	5.6	21.0	4,111	4,235	124	22
Set 20" casing	2.1	23.1				
Run BOP & Riser	3.0	26.1				
Core Sediments	1.9	28.0	4,235	4,250	15	8.0
Core Lava	45.0	73.0	4,250	4,900	650	14.4
Core Dikes	58.3	131.3	4,900	5,685	785	13.5
Set 13-3/8" Casing	5.0	136.3				
Core Dikes	2.7	139.0	5,685	5,700	15	5.7
Core Textured Gabbros	32.8	171.8	5,700	6,050	350	10.7
Core Foliated Gabbros	72.5	244.3	6,050	6,750	700	9.7
Core Layered Gabbros	147.7	392.0	6,750	7,900	1,150	7.8
Core Layered Gabbros	53.3	445.3	7,900	8,250	350	6.6
Run 11-3/4" Liner	7.0	452.3				
Core Layered Gabbros	346.7	799.0	8,250	10,250	2,000	5.8
Core Mantle	83.5	882.5	10,250	10,750	500	6.0
TA hole	5.0	887.5				
Pull BOP/Riser	3.0	890.5				
5% Operational NPT	43.4	933.8				

Total Core/Drill Days = **876**

Total Project Days = **934**

For this case, 99% of the hole is cored, and 1% is drilled as shown in Table 31 below.

Table 31—Hawaii – Case 1 – Projected Days for Drilling and Coring

	Interval	%	Days
Coring =	6,639	99.1%	219
Drilling =	61	0.9%	42
	6,700	100%	260

The following pie chart (Figure 58) shows a breakdown of the key operations in terms of total days and percentage of the total time. Flat time is defined as the time spent running BOP's running wire-line, logs and running casing. Note that 319 days, or 36% of the time was spent on bit trips.

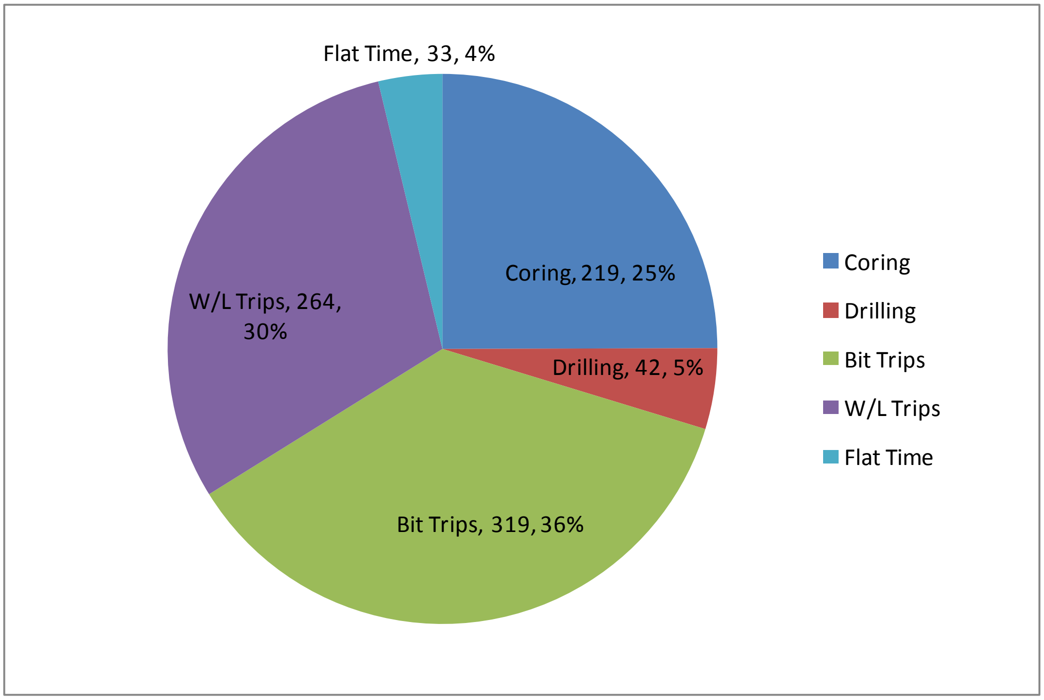

Figure 58—Hawaii – Case 1 – Operations Breakdown Comparison

A drilling curve for Case 1 is shown in Figure 59 below.

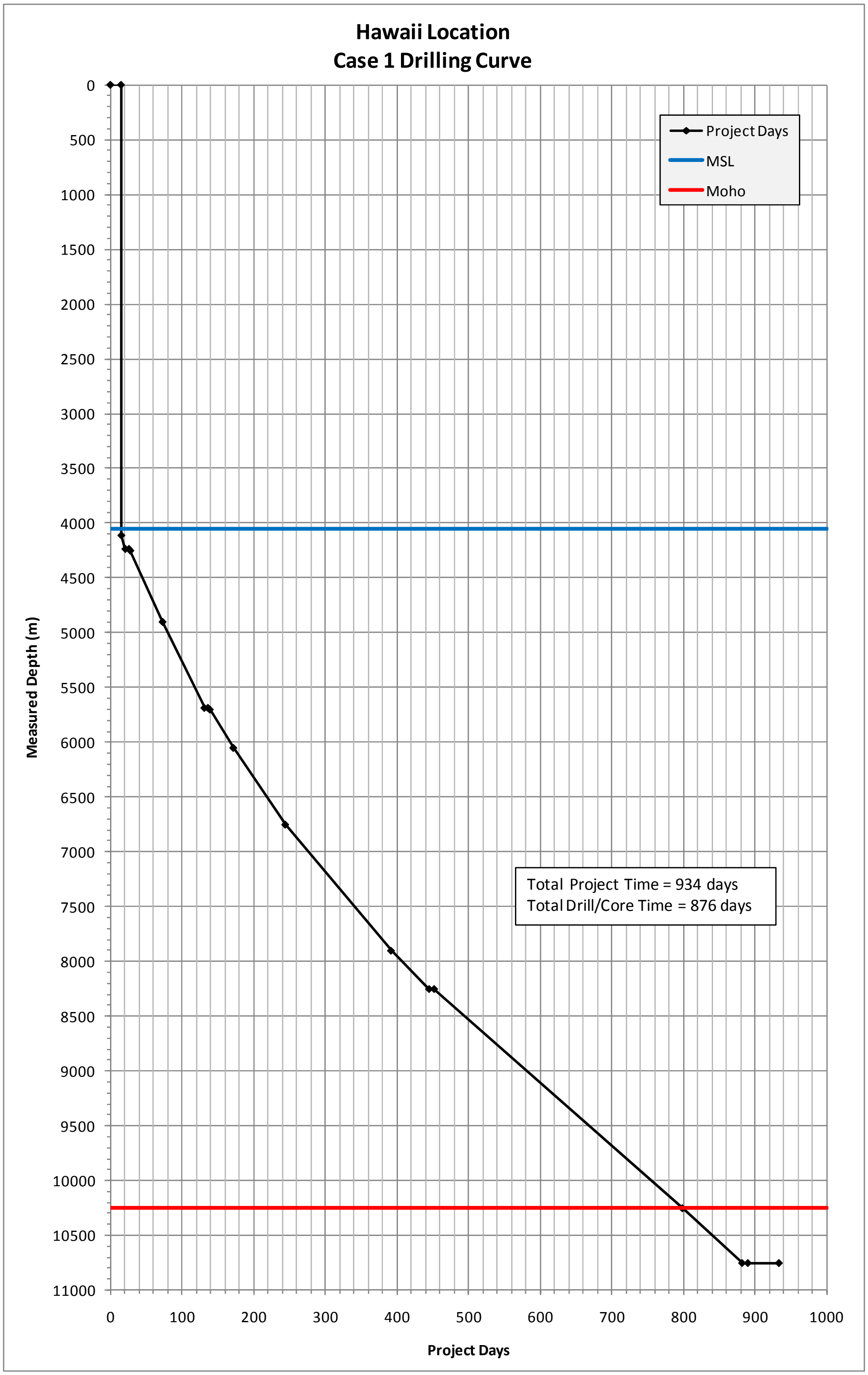

Figure 59—Hawaii – Case 1 – Drilling Curve

Case 2 Results

This case is based on coring the upper third of stratigraphic section, drilling the middle third, and then coring the bottom third. A summary of the time estimate for this case is shown in Table 32 below.

Table 32—Hawaii – Case 2 – Breakdown of Operational Time Required to Reach Total Depth

Phase	Interval Days	Cum Days	From (m)	To (m)	Interval (m)	Avg m/day
Move in rig	13.4	13.4				
Position Rig	1.5	14.9				
Jet 36"	0.5	15.4	4,050	4,111	61	
Core Sediments	5.6	21.0	4,111	4,235	124	22
Set 20" casing	2.1	23.1				
Run BOP & Riser	3.0	26.1				
Core Sediments	1.9	28.0	4,235	4,250	15	8.0
Core Lava	14.7	42.7	4,250	4,467	217	14.7
Drill Lava	4.3	47.1	4,467	4,683		
Core Lava	15.6	62.6	4,683	4,900	217	13.9
Core Dikes	20.1	82.7	4,900	5,167	267	13.3
Drill Dikes	6.8	89.6	5,167	5,433	267	39.1
Core Dikes	19.1	108.7	5,433	5,685	251	13.2
Set 13-3/8" Casing	5.0	113.7				
Core Dikes	2.7	116.3	5,685	5,700	15	5.7
Core Textured Gabbros	10.8	127.1	5,700	5,817	116	10.8
Drill Textured Gabbros	3.9	131.0	5,817	5,933	116	29.9
Core Textured Gabbros	11.1	142.1	5,933	6,050	117	10.6
Core Foliated Gabbros	22.7	164.8	6,050	6,284	233	10.3
Drill Foliated Gabbros	7.8	172.6	6,284	6,517	233	29.9
Core Foliated Gabbros	23.8	196.4	6,517	6,750	233	9.8
Core Layered Gabbros	57.0	253.4	6,750	7,207	457	8.0
Drill Layered Gabbros	41.7	295.1	7,207	7,894	687	16.5
Core Layered Gabbros	55.8	350.9	7,894	8,250	355	6.4
Run 11-3/4" Liner	7.0	357.9				
Drill Layered Gabbros	42.4	400.3	8,250	8,829	579	13.7
Core Layered Gabbros	78.4	478.7	8,829	9,286	457	5.8
Drill Layered Gabbros	45.6	524.3	9,286	9,865	579	12.7
Core Layered Gabbros	61.4	585.7	9,865	10,201	335	5.5
Core Layered Gabbros	11.5	597.2	10,201	10,250	49	4.3
Core Mantle	97.8	695.0	10,250	10,750	500	5.1
TA hole	5.0	700.0				
Pull BOP/Riser	3.0	703.0				
5% Operational NPT	34.0	737.0				

Total Core/Drill Days = **688**

Total Project Days = **737**

For this case, 59% of the hole is cored, and 41% is drilled as shown in Table 33 below.

Table 33—Hawaii – Case 2 – Projected Days for Drilling and Coring

	Interval	%	Days
Coring =	3,960	59.1%	150
Drilling =	2,740	40.9%	64
	6,700	100%	214

The following pie chart (Figure 60) shows a breakdown of the key operations in terms of total days and percentage of the total time. Note that 285 days, or 41% of the time was spent on bit trips.

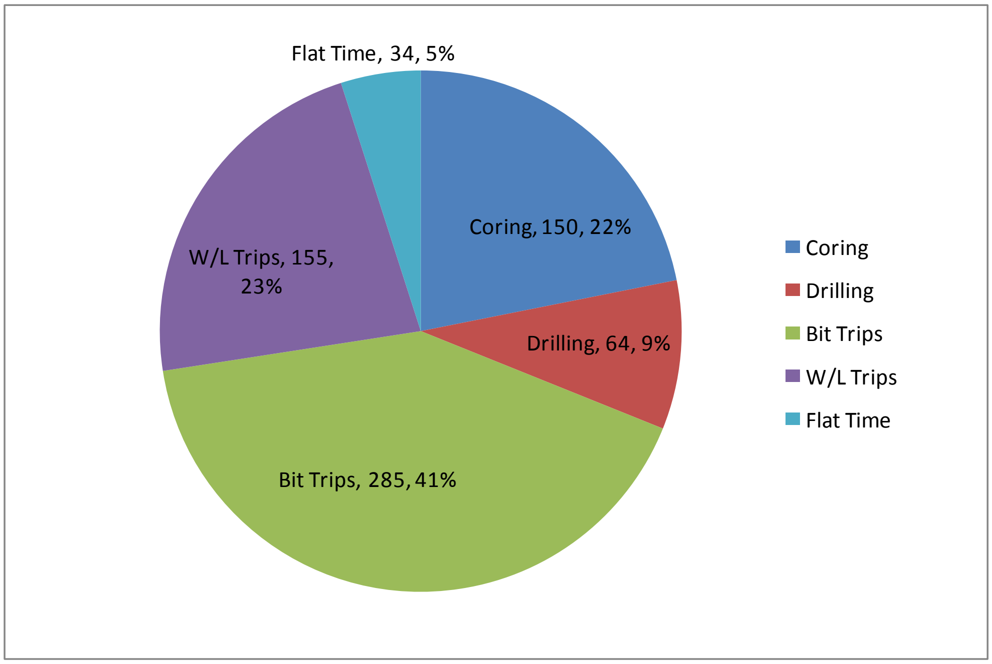

Figure 60—Hawaii – Case 2 – Operations Breakdown Comparison

A drilling curve for Case 2 is shown in Figure 61 below.

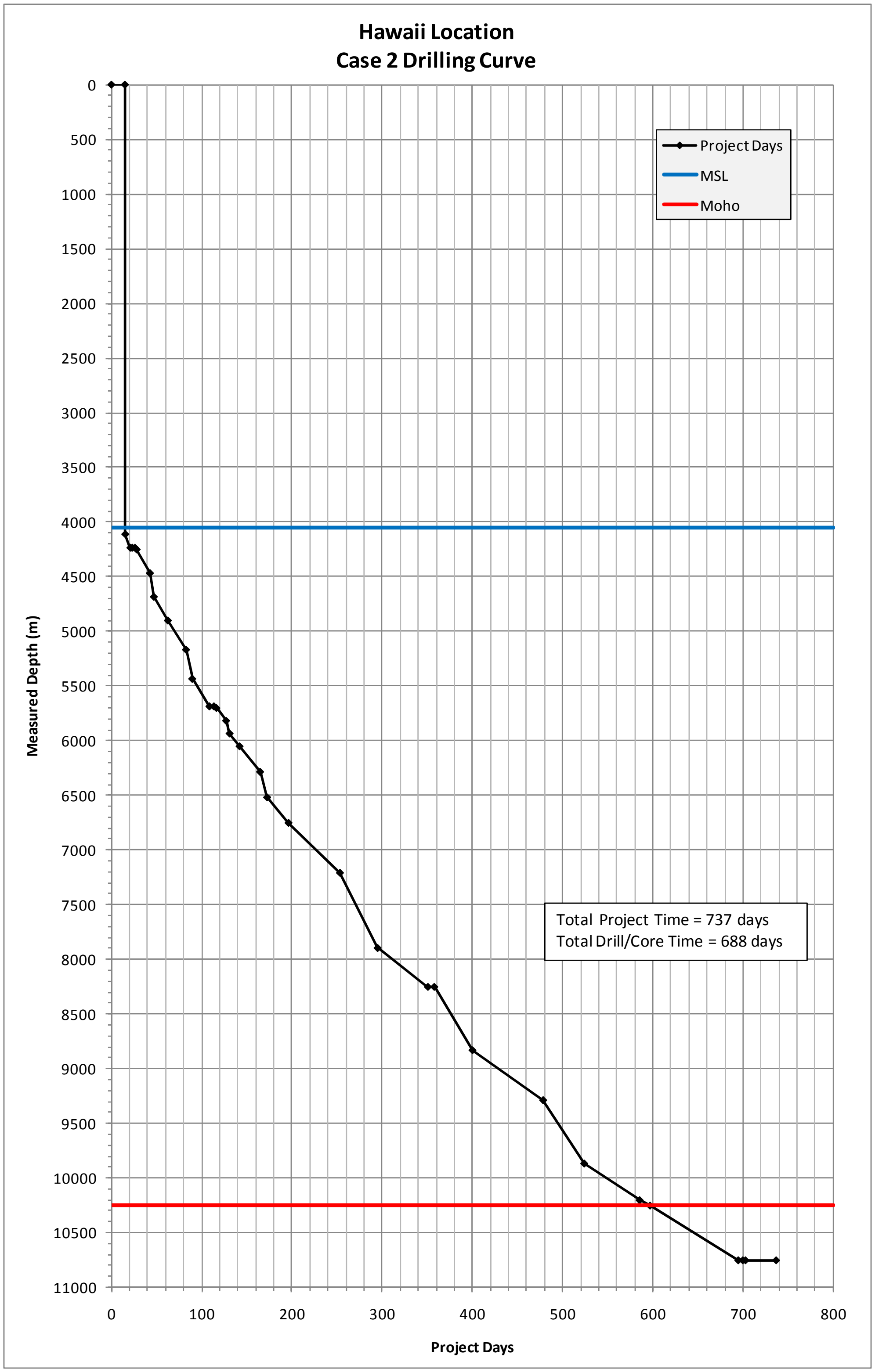

Figure 61—Hawaii – Case 2 – Drilling Curve

Case 3 Results

This case is based on spot coring the last 10m of hole before each bit trip. A summary of the time estimate for this case is shown in Table 34 below.

Table 34—Hawaii – Case 3 – Breakdown of Operational Time Required to Reach Total Depth

Phase	Interval Days	Cum Days	From (ft)	To (ft)	Interval (ft)	Avg ft/day
Move in rig	13.4	13.4				
Position Rig	1.5	14.9				
Jet 36"	0.5	15.4	4,050	4,111	61	122
Drill Sediments	1.5	16.9	4,111	4,235	124	83
Set 20" casing	2.1	19.0				
Run BOP & Riser	3.0	22.0				
Core Sediments	1.9	23.9	4,235	4,250	15	8.0
Drill/Core Lava	24.5	48.4	4,250	4,900	650	26.6
Drill/Core Dikes	22.2	70.5	4,900	5,685	785	35.4
Set 13-3/8" Casing	7.0	77.5				
Core Lava	1.8	79.3	5,685	5,700	15	8.6
Drill/Core Textured Gabbros	14.1	93.4	5,700	6,050	350	24.8
Drill/Core Foliated Gabbros	24.1	117.6	6,050	6,750	700	29.0
Drill/Core Layered Gabbros	99.3	216.9	6,750	8,250	1,500	15.1
Set 11-3/4" Liner	7.0	223.9				
Drill/Core Layered Gabbros	177.6	401.5	8,250	10,250	2,000	11.3
Core Mantle	53.3	454.8	10,250	10,750	500	9.4
TA hole	5.0	459.8				
Pull BOP/Riser	3.0	462.8				
5% Operational NPT	22.0	484.8				

Total Core/Drill Days = **448**

Total Project Days = **485**

For this case, 21% of the hole is cored, and 79% is drilled as shown in Table 35 below.

Table 35—Hawaii – Case 3 – Projected Days for Drilling and Coring

	Interval	%	Days
Coring =	1,389	20.7%	59
Drilling =	5,311	79.3%	114
	6,700	100%	172

The following pie chart (Figure 62) shows a breakdown of the key operations in terms of total days and percentage of the total time. Note that 177 days, or 40% of the time was spent on bit trips.

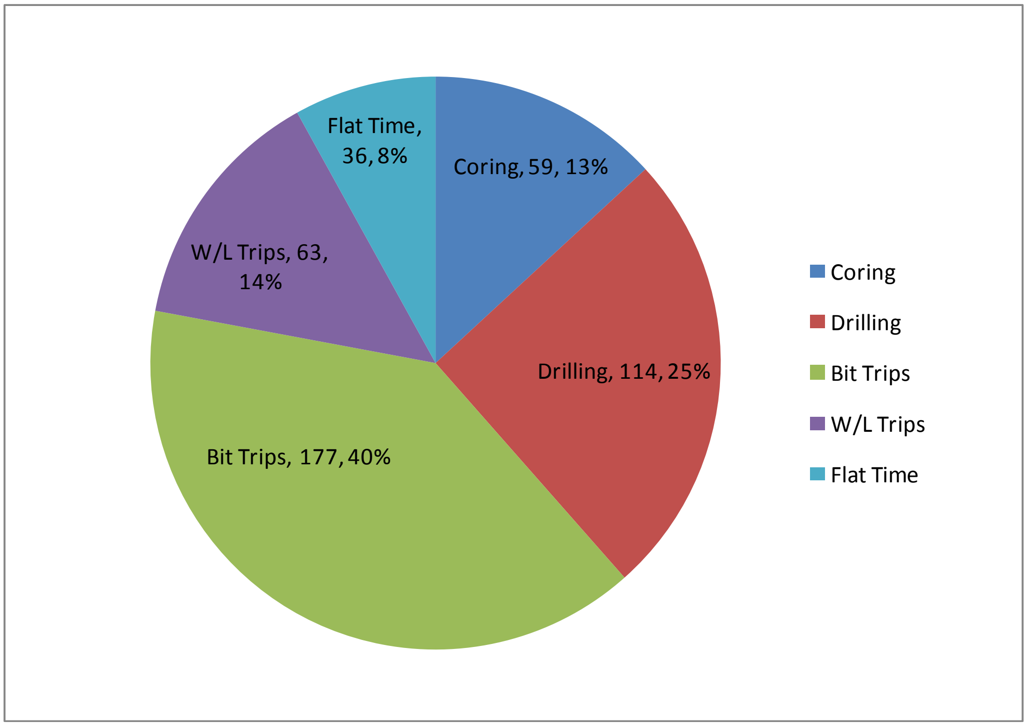

Figure 62—Hawaii – Case 3 – Operations Breakdown Comparison

A drilling curve for Case 3 is shown in Figure 63 below.

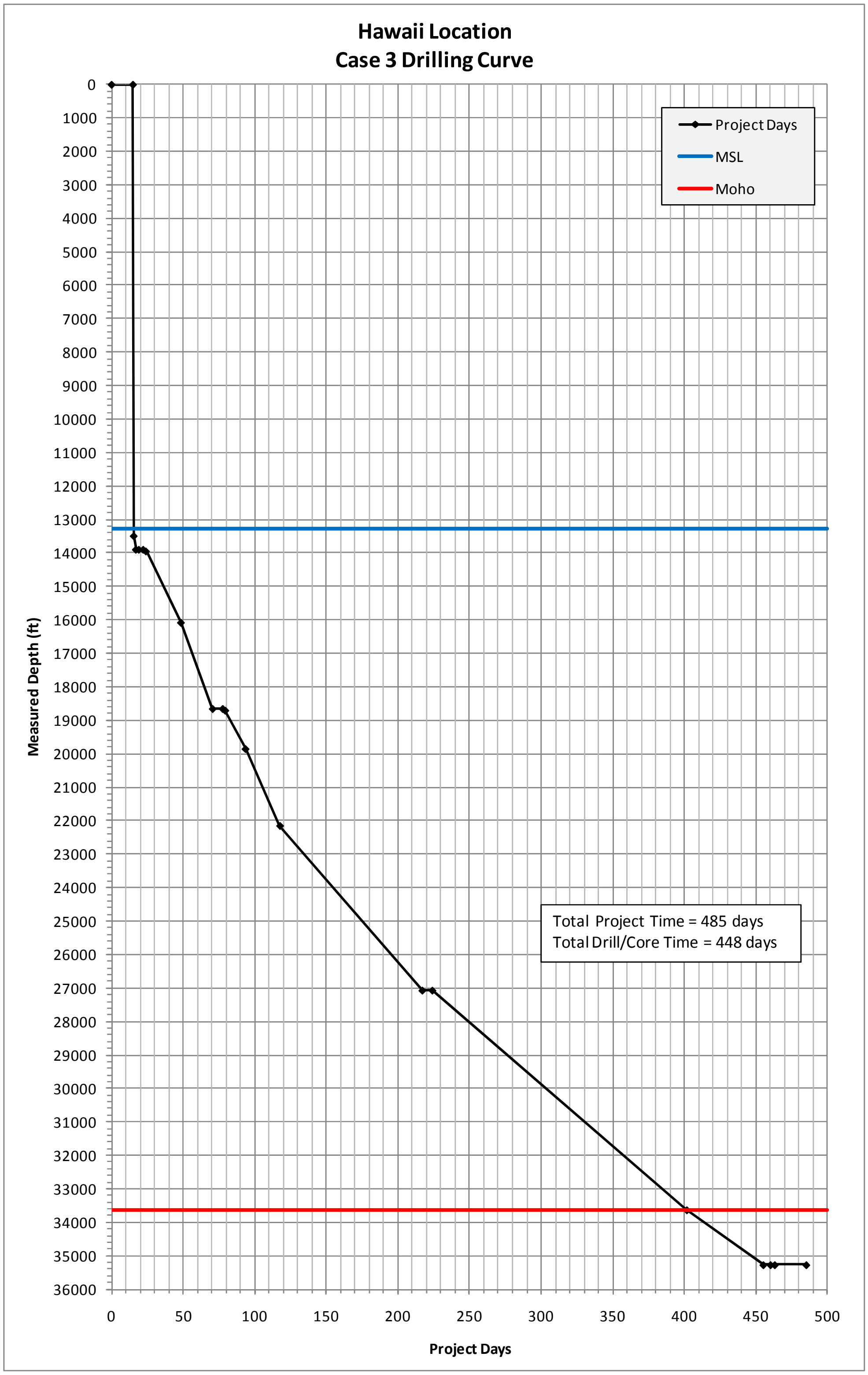

Figure 63—Hawaii – Case 3 – Drilling Curve

Case 4 Results

This case is based on drilling the entire hole to the Moho and the coring the mantle. A summary of the time estimate for this case is shown in Table 36 below.

Table 36—Hawaii – Case 4 – Breakdown of Operational Time Required to Reach Total Depth

Phase	Interval Days	Cum Days	From (m)	To (m)	Interval (m)	Avg m/day
Move in rig	13.4	13.4				
Position Rig	1.5	14.9				
Jet 36"	0.5	15.4	4,050	4,111	61	122
Drill Sediments	1.5	16.9	4,111	4,235	124	83
Set 20" casing	2.1	19.0				
Run BOP & Riser	3.0	22.0				
Drill Sediments	1.3	23.3	4,235	4,250	15	11.6
Drill Lava	14.0	37.3	4,250	4,900	650	46.4
Drill Dikes	18.1	55.4	4,900	5,685	785	43.4
Set 13-3/8" Casing	5.0	60.4				
Drill Dikes	1.9	62.3	5,685	5,700	15	8.0
Drill Textured Gabbros	10.9	73.3	5,700	6,050	350	32.0
Drill Foliated Gabbros	27.8	101.1	6,050	6,750	700	25.2
Drill Layered Gabbros	24.3	125.4	6,750	7,207	457	18.8
Drill Layered Gabbros	41.9	167.3	7,207	8,250	1,043	24.9
Run 11-3/4"Liner	7.0	174.3				
Drill Layered Gabbros	148.5	322.7	8,250	10,250	2,000	13.5
Core Mantle	83.5	406.2	10,250	10,750	500	6.0
TA hole	5.0	411.2				
Pull BOP/Riser	3.0	414.2				
5% Operational NPT	19.6	433.8				

Total Core/Drill Days = **399**
Total Project Days = **434**

For this case 8% of the hole is cored, and 92% is drilled as shown in Table 37 below.

Table 37—Hawaii – Case 4 – Projected Days for Drilling and Coring

	Interval	%	Days
Coring =	500	7.5%	23
Drilling =	6,200	92.5%	134
	6,700	100%	157

The following pie chart (Figure 64) shows a breakdown of the key operations in terms of total days and percentage of the total time. Note that 204 days, or 48% of the time was spent on bit trips.

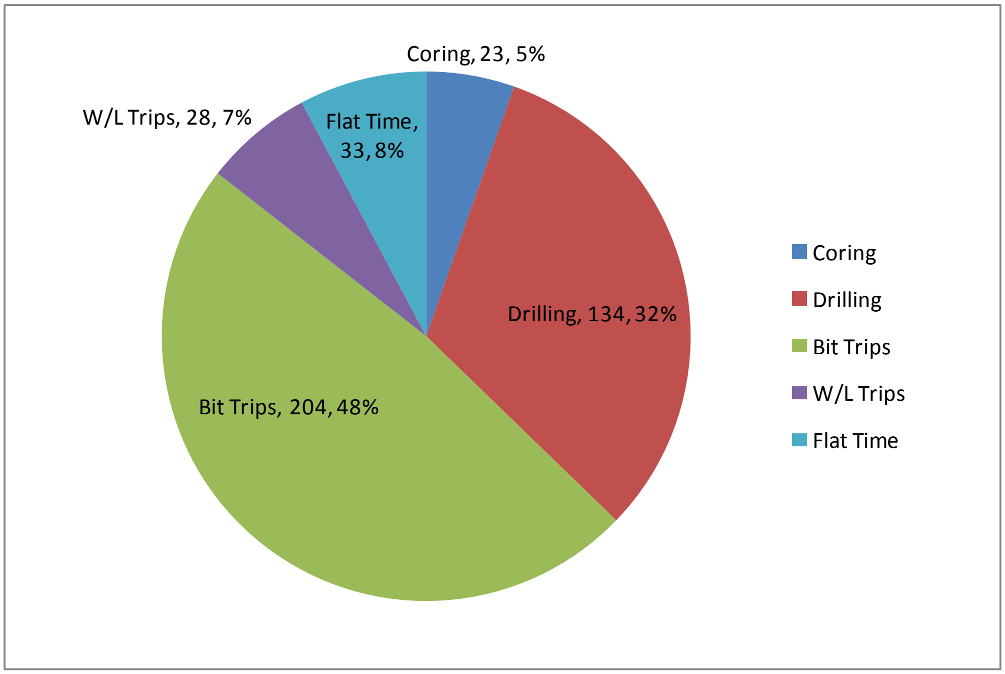

Figure 64—Hawaii – Case 4 – Operations Breakdown Comparison

A drilling curve for Case 4 is shown in Figure 65 below.

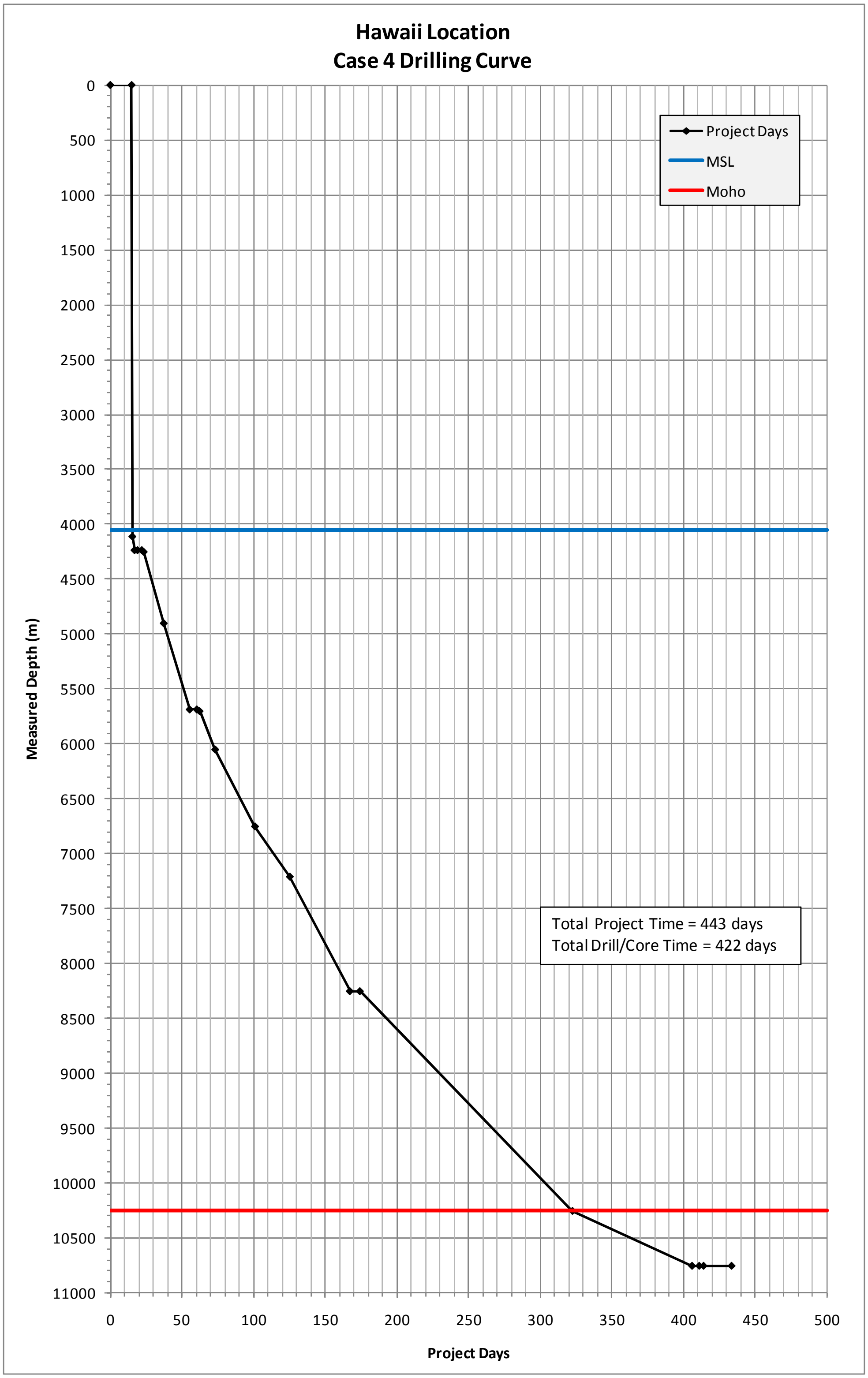

Figure 65—Hawaii – Case 4 – Drilling Curve

Case Comparison

The following Figure 66 shows a comparison of the drilling curves for all four cases.

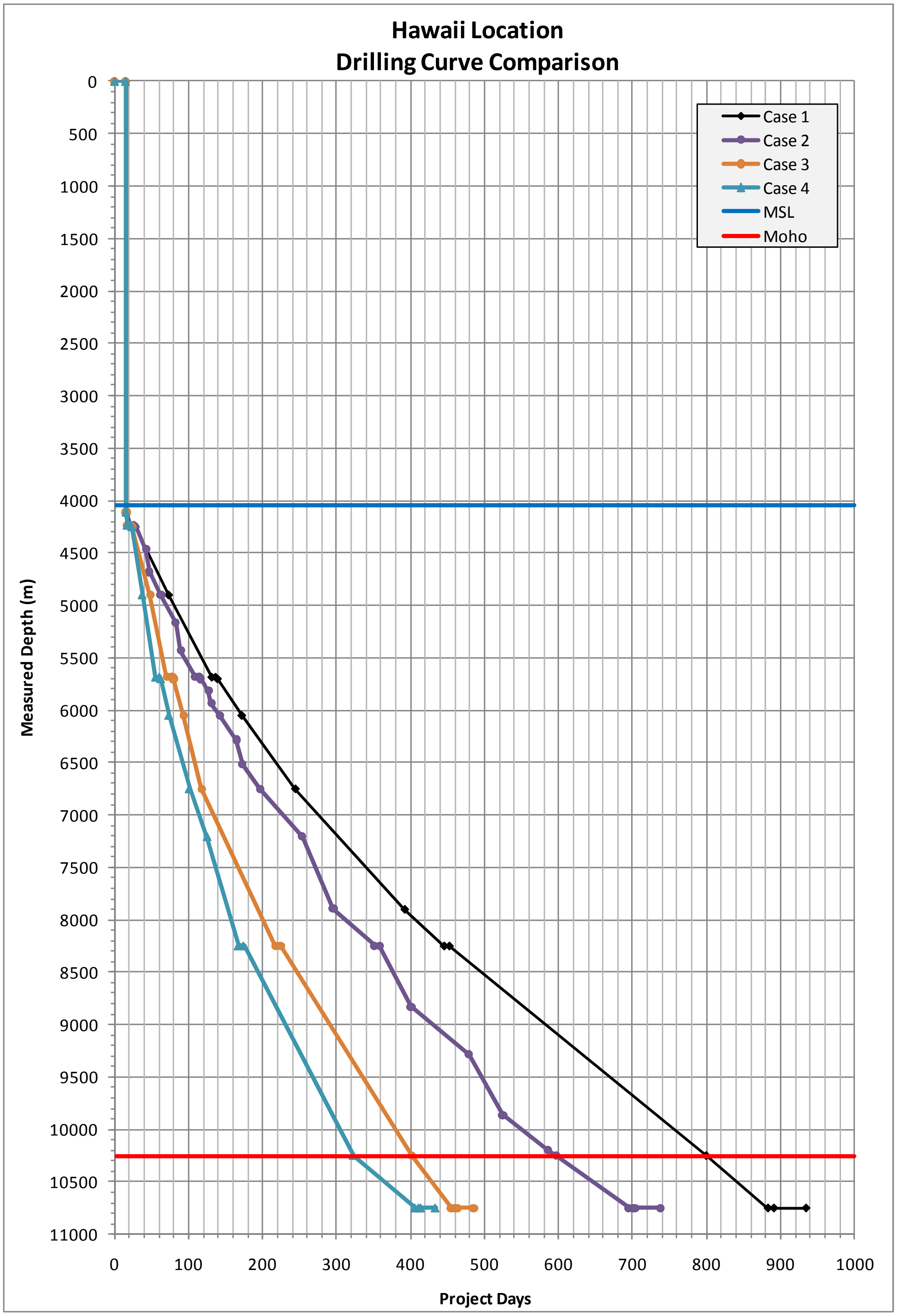

Figure 66—Hawaii – Case Comparison – Drilling Curve

7.5 High Temperature

7.5.1 Circulating Temperature

The following chart Figure 67 show the results of some down-hole circulating temperature modeling that was done for several circulation rates using the Case 1 drill string described in Section 6. The modeling was done using WellFlow, a commercially available fluid flow modeling simulator. The intent was to look at the effect of circulation rate on the down-hole temperature and get an idea of what the magnitude of the down-hole circulating temperatures might be.

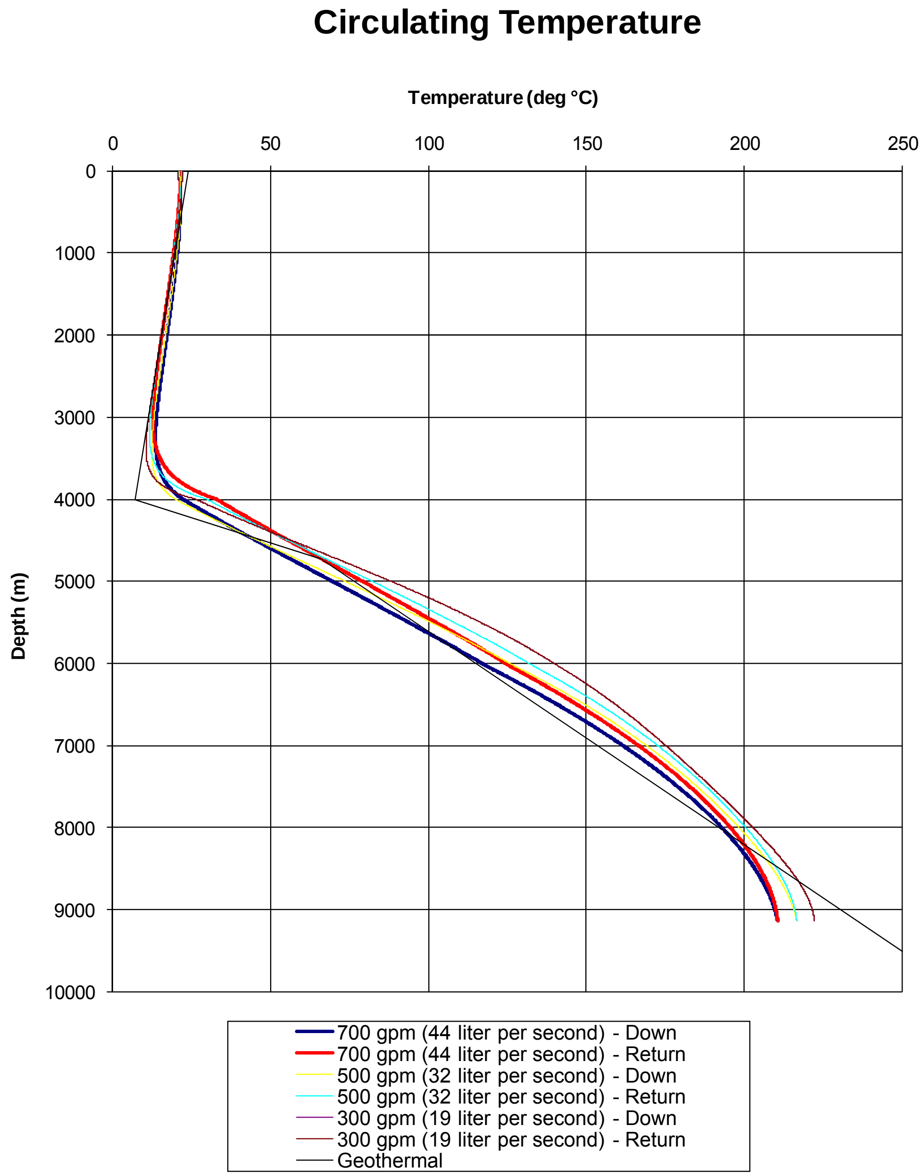

Figure 67—Circulating Temperature

As can be seen, the circulating temperatures are between 25-40°C less than the static temperature and the inlet temperature cools down through the water column to a value close to the static seafloor temperature. Of particular note is the fact that the return temperature values are very close to the inlet values from a few hundred meters below the mud line back to the surface, which is also seen in geothermal wells.

The significance of this is that the primary technique used on geothermal wells to deal with the down-hole temperatures is to cool the mud at the surface and adjust the circulation rate so that the resulting circulating temperatures are less than the temperature rating of the down-hole tools that are being used. However, because of the cooling effect of the water column, there will be no additional benefit to cooling the mud at the surface for the Moho well.

7.5.2 Down-hole Tools

The down-hole circulating temperatures discussed in section 7.5.1 above exceed the temperature ratings of most down-hole tools that are commercially available today, although there is ongoing work by the equipment providers to improve the temperature rating of their tools. Increasing the temperature rating of the down-hole tools that will be needed for the Moho well is a significant issue that will need to be addressed.

Another significant issue is bit design. As was shown in Section 6, the time spent tripping for a new but was a much as 40% of the overall operational time. The development of bits that can stay on bottom longer will therefore have a tremendous impact on the time and cost it will take to drill/core the Moho well. Increasing the rate of penetration would also be beneficial, but this has less of an impact than improving bit life.

7.5.3 Drilling Fluids

There are drilling fluid systems available today that can successfully cope the down-hole temperatures seen on geothermal wells. For example, a thin water base mud with 3% bentonite, 1% lubricant, 0.1% high temperature dispersant and caustic soda associated with a mud cooling system was used to drill geothermal wells with temperature as high as 500°C (Saito and Sakuma, 2000). As such, while additional design work will be needed to develop a fluids system for the Moho well, it is not expected to be a significant obstacle.

7.5.4 Cementing

A typical cement design currently used in geothermal wells consists of conventional Class G Portland cement, retardants and 40% silica flour with a density of around 1,6 SG. As with drilling fluids, the development of a cement design for the Moho well is not expected to be a significant problem The biggest issue will be designing the retarder system that will provide sufficient pump time to get the cement in place. Moreover, research and development efforts led by services and operating companies produced new cement types such as phosphate-bonded and polymers (calcium aluminates and sodium silicates) that were successfully implemented in geothermal wells in South-east Asia (Kalyoncu et al., 1981; Kukacka, 1997; Sugama, 2006).

7.6 Costs Estimation ($1 Million / day)

The following Table 38 shows the order of magnitude costs for the various cases that were evaluated for the three candidate locations. It was assumed that the intangible daily operating costs for a typical commercial drill-ship are $1 million/day. An estimate of the tangible costs which range between $7 to $10 million for a high-pressure deepwater well in the Gulf of Mexico requiring multiple casing strings were not considered for this study.

Table 38—Project Cost for Each Case and Each Location

Candidate Location	Water Depth	Total Depth	TD BSF	Ops Time	Project Time	Project Cost
Cocos Location						
Case 1	3650	9900	6250	696	756	$756,000,000
Case 2	3650	9900	6250	564	617	$617,000,000
Case 3	3650	9900	6250	433	480	$480,000,000
Case 4	3650	9900	6250	374	418	$418,000,000
Baja Location						
Case 1	4300	10400	6100	807	866	$866,000,000
Case 2	4300	10400	6100	642	693	$693,000,000
Case 3	4300	10400	6100	405	445	$445,000,000
Case 4	4300	10400	6100	386	425	$425,000,000
Hawaii Location						
Case 1	4050	10750	6700	876	934	$934,000,000
Case 2	4050	10750	6700	688	737	$737,000,000
Case 3	4050	10750	6700	448	485	$485,000,000
Case 4	4050	10750	6700	422	443	$443,000,000

Note: For accounting purposes (depreciation and taxes), the costs for oil and gas wells are classified as being either intangible or tangible. Intangible costs are basically for non-salvageable items such as labor, drilling rig time, drilling fluids, services, etc. These costs, which are typically charged on a daily basis, account for some 70 to 80% of the total well cost. Tangible costs are basically salvageable items such as the wellhead and tubulars.

8 Conclusions

Offshore drilling and coring are mature technologies and many commercial tools are currently available from several industries (drilling, mining, and aerospace). However, to reach extreme depths in the oceanic crust, drilling and coring in very hard hot rocks and operating in ultra-deep water requires the use of the most recent tools and techniques, and the development or modification of new tools and. In addition, driven by operators and governments, technologies and techniques are continuously advancing and can be expected to continue to close the gap between what is required for the 'Mohole Project' and what is currently possible.

The results of this study show that drilling/coring a scientific hole into the upper mantle is certainly feasible, and there are existing solutions to many of the technological challenges based on work being done in the oilfield and geothermal industries. In fact, a hole could be drilled 'today' at the Hawaii location because it has the lowest bottom-hole temperature of the three candidate locations.

The key conclusions from the study are:

1. There are existing solutions to the riser design issues.
2. There are existing solutions to the drill-string design issues.
3. A key issue would be the development of down-hole tools capable of withstanding the extreme down-hole temperatures.
4. A key issue would be the development of bits with improved bit life since this will have a huge impact on the operational costs and also improved core techniques that could result in faster coring rate.

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