

Seismogenic Zone Deep Drilling and Measurement

Report of Detailed Planning Group

JOIDES, Ocean Drilling Program,

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SUMMARY

Most of the world's great earthquakes and tsunamis are generated by rupture on the "seismogenic zone" of subduction thrust faults. An important project in future scientific ocean drilling, especially of the OD21 riser ship scientific program, is to drill through and make detailed measurements and recording in the parts of subduction thrust faults that generate great earthquakes.

The objectives are an improved understanding of the physical and chemical processes responsible for earthquakes, and seismic hazard reduction for the very destructive great earthquakes that occur on these faults. Some of the important questions are:

1. What controls the earthquake cycle of elastic strain build-up and sudden rupture: stress, pore pressure and chemical changes?
2. Are there changes with time, of stress, pore pressure, pore fluid chemistry or other parameters that define times of increasing probability of great earthquakes?
3. What controls the parts of subduction thrusts that are seismic and aseismic, especially the seaward updip and landward downdip limits?
4. What is the nature of asperities on the megathrust fault that are inferred to be stronger and generate large earthquake slip compared to areas that may have significant aseismic creep?
5. What is the nature of "tsunami earthquakes"? Why do some large slip events have most stress release in the seismic motion of great earthquakes, whereas others have slower slip that generates only moderate earthquakes but large tsunamis?

The SEIZE Detailed Planning Group (DPG) addressed mainly scientific questions, but there was extensive discussion of the technical capabilities required to meet the scientific objectives, and of likely technical limitations to drilling and measurement.

Several previous workshops and reports dealt with studies of the subduction seismogenic zone in general ⁽¹⁾. Important relevant information also is found in the proposal for drilling the San Andreas Fault ⁽¹⁾ and the German KTB well ⁽¹⁾. This report of the DPG deals primarily with drilling by the OD21 riser drill ship, especially the first phase in the Japan area. However, shallower penetration drilling by the present JOIDES Resolution and future non-riser drill ships was also considered. Transects across subduction zone margins including deep riser holes and shallower non-riser holes near the trench are needed to meet the scientific objectives. A drill ship with a riser that allows return circulation and sealing the hole during drilling is necessary both for deep drilling and for the required extensive downhole measurement and recording, especially, (a) to allow circulation of drill mud and thus maintain hole stability in unstable overpressured accretionary prism sediments; (b) to provide ready and long-term access to the borehole for larger instruments. It is noted that at least as important as the possibility of greater hole depth with OD21 compared to the JOIDES Resolution are:

1. The increased hole stability possible by circulation of drilling mud,
2. The balancing of formation pressure with mud weight, especially where overpressured,
3. The blowout preventer for drilling areas that may contain hydrocarbons,
4. The continuous cuttings sample return, and much higher quality core,
5. The much higher quality downhole geophysical logs because of constant diameter (gauge) hole that is possible through stabilization by drilling mud,
6. The access to the hole through large diameter casing pipe; i.e., for larger diameter logging tools, instruments and experiments that are not possible on the JOIDES Resolution.

The planned OD21 riser drill ship has an initial capability of 2,500 m water depth (i.e., riser length), to be extended in later development phases, and a 10,000 m drill string. The first OD21 drilling is to be in the Japan area; initial study shows that most sites around Japan where the water depths are less than 2,500 m, require over 5 km penetration to the seismogenic zone. Such penetration involves potential technical difficulties and drilling times of several years. However, several sites off SW Japan (Nankai Trough) appear to require less penetration although they may have atypical structure. Careful study is needed to find suitable sites requiring the minimum penetration to reach the seismogenic zone. The search for the best initial site will require additional

2D and 3D multichannel and other seismic data. The formation expected to be penetrated off SW Japan is a young elastic accretionary sedimentary prism. The main technical concerns for drilling the subduction thrust and seismogenic zone are (other hazards are noted below): (a) difficult formation conditions, i.e., unconsolidated unstable sediments, high formation pressure, and high temperatures; (b) storms, especially typhoons, (c) strong ocean currents, such as the Kuroshiro current along most of the Nankai Trough. Careful engineering design, and planning are needed to deal with the typhoons and strong currents. Additional thermal data and modelling, geotechnical studies etc. are needed to predict and design for the formation conditions in a deep accretionary prism borehole.

The planning and scientific operations for long duration OD21 programs will be very different from the 2-month drilling leg experience of ODP/DSDP. The DPG recommends that an expert scientific team be set up for each major OD21 program such as SEIZE to develop detailed scientific and operational plans, and to carry through to the scientific program onboard the ship during drilling and measurement. The team should have subgroups for each of the main scientific components, including the required site surveys and studies. The scientific team must work closely with the JAMSTEC drilling engineering and science groups who are responsible for design, construction and operation of the OD21 drill ship. An outline of the proposed scientific team needed for a SEIZE drilling and measurement program is given below. It may be appropriate to have an initial competition for the most qualified and most motivated participants based upon proposals for each component of the project (about 5 scientific components). These proponents then would prepare detailed science plans for their part of the scientific program. A small committee with representation from all of the components would provide oversight to the science for the whole SEIZE project. It is desirable for the critical aspects of the project to be funded together, including the most critical site surveys. Independent funding should be only for site surveys, associated science, and those parts of the program that are not essential to the overall success of the project.

Although core and cutting sampling are important to the SEIZE program, the deep drilling should be considered primarily as a method of access to the seismogenic zone, allowing a wide range of measurements and long-term recording. The borehole is an observatory. Many of the scientific objectives can be achieved only through a comprehensive and well prepared downhole measurement

and recording program. The most important sampling, measurement, and recording programs are outlined below; they include: (1) geophysical and geological site characterization studies, (2) measurements on core and cuttings, (3) analysis of fluid and gas samples, (4) downhole measurements, (5) fault zone long-term monitoring.

⁽¹⁾ The Seismogenic Zone Experiment (SEIZE) Workshop, Waikoloa, Hawaii, June 3-6, 1997 (<http://www.soest.hawaii.edu/margins/SEIZE.html>); The International Conference on Cooperative Ocean Riser Drilling (CONCORD), Tokyo, Japan, 22-24, 1997 (<http://www.jamstec.go.jp/jamstec/OD21/CONCORD/state.html>); Costa Rica - Nicaragua Seismogenic workshop report CriNiSEIZE; Scientific Drilling into the San Andreas Fault at Parkfield, CA: Project Overview and Operational Plan (<http://pangea.Stanford.EDU/FZD/>).

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Numerous other people contributed as replacements for DPG members unable to attend some meetings, as outside contributors at meetings, and by providing important information. These included: H. Kinoshita, S. Hickman, K. Suyehiro, S. Lallemant, M. Yamano, M. Ando, and S. Takegawa and others from JAMSTEC engineering and technical staff.

The Detailed Planning Group met three times: (1) San Francisco California, U.S.A., December 5-6, 1998; (2) JAMSTEC offices, Tokyo, Japan, 17-20 March, 1999; (3) at the Pacific Geoscience Centre, Geol. Survey Canada, Victoria Canada, 24-25 May, 1999. Initial general input from the scientific community was solicited as letters of intent. The members of the DPG were selected in part from these letters of intent.

A. MANDATE OF THE SEIZE DETAILED PLANNING GROUP (SEIZE)

The mandate of the SEIZE DPG was to advise the JOIDES Scientific Committee and other planning groups on:

1. Scientific objectives of subduction seismogenic zone drilling.
2. Drilling, sampling, downhole measurements and downhole recording that are required to meet the objectives.
3. Site requirements for such a drilling program; targets for (a) general requirements, (b) Japan area for initial drilling.
4. Site surveys and associated scientific studies needed for proposed sites, including science and safety issues.
5. Drilling technologies, facilities, downhole measurements, sampling, and long-term monitoring that will be required.
6. To solicit and encourage subduction thrust drilling (riser and non-riser) and measurement proposals, site surveys, and associated seismogenic zone studies.

B. SCIENTIFIC OBJECTIVES

The primary scientific objectives for subduction thrust seismogenic zone drilling resulting from DPG discussions are:

1. *What are the controls of the great earthquake cycle?*

Three factors may control the development with time toward the earthquake rupture, and the rupture process, (a) buildup of shear stress, (b) buildup of pore pressure that reduces the normal stress and thus frictional strength, (c) chemical and physical changes that may strengthen (or weaken) the fault zone and inhibit (or stimulate and activate) rupture. Measuring and understanding these parameters and monitoring changes with time may allow time dependent hazard assessment.

2. *What controls the updip and downdip limits of great earthquake rupture?*

The updip seaward few 10's of km of subduction thrusts are commonly found to be aseismic. Subduction thrusts also are aseismic below a downdip limit that occurs at depths ranging from 10

to 40 km. The accurate definition of these limits is important for estimating the ground shaking expected at land sites from great earthquakes. Some factors that may control these limits are, (a) temperature-induced mineralogical phase changes such as dehydration of stable sliding clays, and higher temperature metamorphism, (b) temperature-induced changes in deformation mechanisms controlling the brittle to ductile transition, (c) time-dependent changes in consolidation and fluid pressure increase with depth, (d) downdip changes in gross lithologic and mechanical properties of the fault zone, such as reaching the landward limit of accreted sediments or encountering serpentized forearc mantle.

3. Why does the fault strength appear to be very low?

There are clear indications of very low shear stress on subduction thrust faults and no thermal anomaly has been detected over the seismogenic zone as would be expected with significant shear heating. These characteristics are similar to those of the San Andreas fault. The subduction thrust faults are thus inferred to be very weak relative to Coloumb friction behaviour, in spite of generating great earthquakes.

4. What is the nature of "asperities"?

Asperities are areas of subduction thrust faults that have experienced large slip in great earthquakes. Adjacent areas that had smaller slip in a great earthquake may have some motion in non-seismic creep. Asperities are often inferred to be stronger than adjacent areas, but it has been difficult to establish what physical characteristics would make them stronger. It also is not certain that these areas of greater slip in one earthquake always have greater earthquake slip.

5. What causes tsunami earthquakes?

There appears to be large variations in the rate of slip in subduction thrust slip events, i.e., fast slip rates that generate strong earthquake waves, moderate slip rates that can generate large tsunamis, and slow slip that is detected only geodetically. Especially important is the nature of "tsunami earthquakes". Why do some large slip events have most stress release in the seismic motion of great earthquakes, whereas others have slower slip that generates only moderate earthquakes but large tsunamis?

6. What controls the décollement depth on subduction thrust faults, and how is the décollement depth connected to seismogenesis?

The subduction thrust fault vertical location varies from directly at the top of the oceanic crust to over 1000 m higher within thick incoming sediment sections. In some areas the decollement depth changes with time and with landward distance, such as the step down from within the incoming sediment section to near the top of the oceanic crust observed in areas of the Nankai margin. Composition variations such as clay rich layers, pore pressure, consolidation, and mineralogy phase changes have been suggested as controls.

C. THE OD21 RISER DRILL SHIP CAPABILITIES

A scientific riser drill ship is planned to be constructed and operated by Japan with the scientific program and operating costs to be shared internationally. Industry needs for deep water drilling technologies are helping to drive the project. The ship sea trials are planned for 2003 and initial drilling at the end of 2004 or in 2005. The capabilities were discussed by the DPG with OD21 engineers in some detail. A short summary is given here. Numerous technical challenges are being addressed. For example, a coring bit is being designed in collaboration with ODP to withstand temperatures up to 250 C. The coring facilities are to be the mainly the same as for the present JOIDES Resolution, and include a pressurized core recovery system. The proposed targets include coring for biological studies and drilling into the mantle, as well as subduction zone targets. Shorter pilot holes are expected at each deep drilling site to evaluate the formation and drilling conditions. The time to drill the maximum 7 km below the seafloor is very approximately 3 years. Holes of 3-5 km should take less than a year and it may be possible to achieve prime initial objectives with these depths.

OD21 Water Depth and Penetration Capability

The planned riser drill ship has an initial capability of 2,500 m water depth (i.e., riser length), to be extended in later phases, and a 10,000 m drill string. The drill string length is not a serious limitation since a 7,500 m hole would require very long drilling times and difficult drilling conditions, so may be avoided in initial phases of OD21 if the main objectives can be achieved with less drill penetration. However, the 2,500 m water depth limit does severely limit the possible sites

for seismogenic zone drilling. For most subduction zones, this water depth is on the middle continental slope where the sub-bottom depth to the subduction thrust is over 5 km and temperatures are quite high. Areas must be sought where the drill penetration required is a minimum. Accurate estimates of the depth to the decollement (seismogenic zone) are needed prior to drilling, mainly from detailed multichannel seismic reflection data.

Hazards for drilling

The main expected subduction zone deep drilling hazards are, (a) unconsolidated sediments, faulting and associated geological problems, (b) formation overpressure, (c) high downhole temperatures, (d) severe weather, especially typhoons and hurricanes, (e) strong ocean currents, such as the Kuroshiro ocean current off S.W. Japan, (f) gas hydrates and gas/water flow.

Borehole instability due to faulting and unstable sediments, and formation overpressure due to water, hydrocarbons, and gas hydrates should be much less of a problem for the OD21 drill ship than for the JOIDES Resolution. OD21 will be able to circulate heavy drilling mud, balancing the formation overpressures and conditioning the borehole wall for improved hole stability. However, in order to balance the expected high formation pressure in the deep portions of the hole with heavy mud and not fracture the upper formation, it will be necessary to case at least the upper portions of the holes. It may be necessary to case most of the hole. The riser system also allows the critical well control (blowout prevention) needed to drill where there is the potential for hydrocarbons.

High downhole temperatures are a feature of most sites where the subduction thrust is at a depth within the drilling limit (i.e., subducting young crust, see below). For a region subducting young oceanic crust such as Nankai Trough, the formation temperatures at a 5 km subbottom decollement are about 150C +/-50C. The hole may be cooled by drilling circulation which reduces the temperature problem for drill bits and downhole assemblies. However, with cold drilling fluid there is the potential to thermally fracture the formation. The hole also may be cool enough to operate logging tools having a moderate temperature limit, if cooling circulation is for a long period and measurements are done quickly before significant thermal recovery. A much more serious temperature limitation is for long-term downhole recording. It may be necessary to limit recording electronics to near the top of the hole, with connection to high temperature-limit sensors located at

greater depth. Detailed heat flow probe measurements and thermal proxy data such as BSR depth, detailed thermal modelling, and pilot hole temperatures are essential to accurately predict the temperature of the formation to be drilled.

Typhoons and hurricanes (defined by wind speeds greater than 17.2 m/s) are a serious hazard for long duration drilling in the Pacific and Atlantic. There are 4-5 per year off SW Japan in summer to autumn. They have diameter 100-2000 km. The maximum recorded wind speed was 70 m/s (in 1979). Drilling off SW Japan is not recommended in July-October although routines for temporarily abandoning the hole will be developed. Coping with typhoons requires: clear and firm criteria for determining when to evacuate; enough warning for orderly evacuation (condition and plug hole, retrieve downhole pipe and equipment, and prepare ship); initial estimates are that the minimum lost time would be 1 week.

Strong ocean currents are a hazard in several areas, including off SW Japan Nankai Trough. The Kuroshiro current can reach speeds of up to 3-5 knots (1.5-2.6 m/s) and covers much of the 2,500 m water depth sites in this area. The OD21 riser drill ship initial design is to operate in maximum current 1.5 kts and wind speed 30 m/s, and current of 2.5 kts at wind speed 23 m/s, so there may be times that the ship cannot operate continuously at the centre of the Kuroshiro current. The riser, rather than station keeping is the limiting factor. Excessive side force could cause damage or loss of the riser. Further studies are in progress to deal with strong currents.

D. SELECTION OF SEISMOGENIC ZONE DRILL SITES

The choice of sites for SEIZE drilling involves, (a) suitability of sites for achieving the scientific objectives, (b) physical capabilities of the OD21 drill ship, (c) practical drill hole depths and drilling durations, (d) availability of detailed site surveys and other information needed for drilling, and needed to complement the borehole scientific results. The DPG mainly examined sites in the Japan area, but the analyses are applicable to sites elsewhere around the world.

Scientific Requirements for Site Selection

The DPG did not review in detail the available site survey and previous studies for the Japan region or other possible sites globally. However, some of the important site needs are listed here:

1. A subduction zone where the tectonics, structure, thermal regime, and earthquakes are very well studied and well known (see site characterization requirements below). Previous shallow drilling of the subduction thrust and on the continental slope in the area of the proposed deep site would be essential. The regions should be structurally simple with an inferred décollement that is fairly stable in position and depth with time.

2. Shallow plate dip and shallow trench such that the subduction thrust fault can be reached by OD21 drilling in a reasonable time, i.e., less than 5 km penetration. This appears to require sites where young oceanic plates are being subducted. It is recognized that young plates also usually means high thrust temperatures. In addition to the greater drilling time and greater potential for failure, deeper subduction thrusts can be less well characterized because of the decreased resolution of seismic and other signals with depth.

3. Accretionary prism sediments or other formation that it is expected to be readily penetrated by the OD21 drilling. A low temperature gradient (heat flow) is desirable, although it is recognized that shallow drilling penetration generally is associated with young hot plates.

4. The subduction thrust should be accessible to non-riser drilling seaward from the main deep riser site that penetrates the seismogenic zone. The 2,500 m water depth limit does not apply to non-riser drilling, but the practical maximum penetration for non-riser drilling is probably less than 2 km. At Nankai Trough (Site 808) penetration of 1,300 m through the décollement into basement was achieved. However, there have been considerable drilling difficulties previously by ODP for penetrations in accretionary prisms much greater than about 1 km.

Non-riser drilling of an out-of-sequence thrust fault, connected to the décollement and well imaged with defined reflection polarity, is very desirable.

5. A recent great earthquake within the seismogenic zone that has been well studied is needed to characterize the seismogenic zone. A map of slip displacement in the event is desirable. Shorter earthquake return times should mean a shorter time scale for the changes associated with the great earthquake cycle.

6. The subduction thrust should be well imaged by multichannel seismic data, especially in the area of the seismogenic zone to be drilled. It is critical to know the depth of the decollement, and its thickness and reflection polarity. Also the better the image of the surface of the seismogenic zone the more readily can the drilling data results and conclusions be extended laterally and to other regions.

7. The locked part of the seismogenic zone should be defined. This may be achieved by, (a) the updip and downdip limits of rupture of great earthquakes (seismic modelling, aftershock distribution, tsunami modelling), (b) the distribution of intermediate size and small earthquakes (especially with thrust mechanisms) that define which part of the thrust is seismic, (c) geodetic data (interseismic and coseismic), both on land and if possible on the seafloor, that define the locked zone. In some areas peninsulas allow land geodetic measurements sufficiently far seaward to define the seaward as well as landward limit of the locked zone.

Drill Site Water Depth, and Penetration to Seismogenic Zone

As noted above, the maximum water depth for the first phase of OD21 drilling is 2,500 m; this is an important technical limitation. Initial study indicates that around Japan, only at a few sites with sufficiently shallow water can the seismogenic zone be reached with reasonable drill penetration. Subduction zone water depths are mainly controlled by the age of the subducting oceanic lithosphere. This is seen by the great depth of the Japan Trench which subducts old oceanic crust compared to the much shallower Nankai Trough which subducts approximately 15 Ma oceanic crust. Cascadia which subducts 5-8 Ma crust has an even shallower water depth. To a first order, thermal expansion in young high temperature lithosphere reduces the density, and isostasy results in shallow seafloor depths. Unfortunately, young lithosphere (and shallow depths) is also usually associated with high heat flow and high temperatures. Costa Rica is an atypical exception; the subducting crust is young but the heat flow is low probably because of hydrothermal heat loss from the underthrusting crust. High formation temperatures are an important drilling and measurement problem, and are especially serious for long-term recording instrumentation. Local variations in the topography of the subducting oceanic crust also are important to the required drilling depth. Areas of subducting aseismic ridges (thickened oceanic crust) or of subducting seamounts may significantly

shallow the seismogenic zone, although these areas are geologically atypical. There may be a trade-off between much shallower drilling penetration and the desire to drill “typical” seismogenic zones. Although more study and survey is needed, it appears that the most feasible sites in the Japan area for initial seismogenic zone drilling are off SW Japan (Nankai Trough).

The SEIZE DPG did not examine potential drill sites in the Nankai Trough in detail. However, initial examination suggests the following limitations of water depth and penetration required to the subduction thrust fault,

Central-Western Nankai Trough is the area with the shallowest dip of the subduction thrust and thus the area where the seismogenic zone probably can be reached with the least penetration hole. Most of the Eastern Nankai Trough has a steeper thrust dip and thus the subduction thrust is at too great a depth. However, one area in the easternmost Nankai Trough may be reached at a shallower depth. This area needs further high quality multichannel seismic reflection to confirm the depth to the subduction thrust fault. The area is structurally complex but may have less influence from the Kuroshiro current that is an important drilling hazard for Nankai Trough.

The Central-Western Nankai Trough area of ODP Site 808, Leg 131, is in an embayment in the continental slope. As a consequence, where the water depth is 2,500 m in this immediate area, the depth to the subduction thrust is near the limit of the OD21 drilling capability. However, in an adjacent area just to the southwest the thrust is shallower due to the top of the oceanic crust rising over a seamount or aseismic ridge. This latter area has an atypical crustal and thrust structure so is not ideal, but the subduction thrust may be reached at only 3-5 km so the site warrants serious consideration.

For most drill sites with water depth less than 2,500 m, the borehole should penetrate the seismogenic portion of the subduction thrust. Such sites should be landward of the aseismic updip portion of the thrust; for the Nankai Trough the aseismic zone extends very approximately 30 km landward of the trench.

Site characterization requirements; site surveys and studies

Extensive site surveys and studies are needed prior to drilling, (a) for drilling information such as the drilling depth, formation type and conditions etc., and (b) for scientific integration with

the results of the drilling and downhole measurement and for extrapolation of the borehole data regionally.

1. *Seismic structure:*

The seismic structure must be well imaged in 3 dimensions (e.g., 3-D multichannel, OBS, seismic refraction, earthquake determined structure). Excellent seismic reflection images and accurate velocity information are needed to; (a) determine the drilling depths to the decollement, (b) to provide information on the sediment type and state that will be penetrated, (c) determine the structure of the decollement, e.g., the thickness and reflection impedance structure (note the regional variation in reflection polarity found in a 3-D seismic survey of the Barbados subduction zone), (d) determine the regional structure to allow extrapolation of the borehole results to regional patterns. Such surveys need to be well in advance of the drilling (about years 2000-02 for initial OD21 SEIZE drilling).

2. *Earthquakes:*

Great subduction thrust earthquakes in the area must be studied exhaustively, especially to provide information on the updip and downdip limits of rupture, and the spatial distribution of slip on the thrust. Smaller thrust events also may provide limits to the seismogenic zone. Events not on the thrust (Wadati-Benioff and in overlying crust) provide information on the state of stress in the subduction oceanic plate and in the overlying crust. The regional seismicity provides information on the tectonic regime. Recording with ocean bottom seismographs and seafloor cables are very desirable.

3. *Tsunamis:*

Tsunamis along with earthquake shaking are a very important hazard of great earthquakes. Tsunamis that have occurred in the area of the planned OD21 drilling should be carefully studied and modelled. Modelling of the observed wave heights and waveforms at regional tide gauge stations allows quantitative estimates of the seaward limit of the fault rupture, i.e., the seaward updip limit of the seismogenic zone. Analysis of tide gauge data also may constrain any major seafloor failures or slumping, especially associated with great earthquakes. The deformation regime at the toe of the accretionary sedimentary prism, and any inferred seafloor failures should be correlated with data from seafloor mapping.

4. Thermal data and deep temperatures:

Heat flow data and deep temperatures estimated from thermal models are essential for, (a) the conditions in the borehole for drilling, measurement and recording, (b) temperatures on the subduction thrust for interpreting thermal controls on the limits to the seismogenic zone, (c) to constrain regional tectonic models. Heat flow data comes from heat probe measurements, heat flow estimated from gas hydrate BSR depths, and from measurements in pilot drill holes. High quality (including insitu thermal conductivity) very detailed multipenetration heat probe surveys are needed in a profile across the margin in the area of the drill sites, as well as regional 2-D coverage. The seismic reflection surveys (see above) allow regional mapping of the heat flow through the depth to the gas hydrate BSR where it is present. Strong advective fluid flow heat transport such as up fault zones, will locally change the BSR depth. Thermal models used to extrapolate temperatures to depth require, (a) the thermal properties of the sediments with depth, especially thermal conductivity, (b) the radioactive heat generation (and other heat generation) with depth, and (c) estimates of any fluid flow advective heat transfer.

5. Tectonic regime:

The overall present tectonic regime and tectonic history must be well understood, including plate convergence rate and direction, incoming plate thermal regime, age of the incoming oceanic plate, incoming sediment section and history. These characteristics provide the input to the subduction system. Details of faulting and deformation in the accretionary sedimentary prism are also important. For example, fluids coming from thrusts that reach the surface (“out-of-sequence thrusts”) may tap the seismogenic zone.

6. Regional geophysics: magnetics, gravity etc.:

Detailed mapping of the structure of the incoming oceanic crust is needed. Magnetic and gravity data are important for interpretation of the age and structure of the incoming oceanic plate, and for the regional tectonic regime of the subduction zone.

7. Seafloor geology:

Much information on deeper structure and processes can be inferred from mapping and measurements on the seafloor. The data should include seafloor bathymetry, morphology, composition, lithology, surface faulting, fluid vents, and evidence for seafloor slumps and other

geological hazards. High resolution swath bathymetry and swath imagery (backscatter) can define structures such as faults that reach to or near to the seafloor, erosion and slope failure processes, and seafloor venting. Coring and dredge samples should be obtained over systematic profiles and grids. Core pore fluid chemistry provides important information on upward fluid and chemical transport; thrust faults may channel fluids up from the depth of the seismogenic zone to the surface. Pore fluid chemistry also can provide information on the approximate temperature at the fluid source. Piston coring also provides near-surface samples at the drill site; drilling usually does not sample the near-surface sediments well. Manned and unmanned (ROV) submersible studies of specific structures including areas of fluid expulsion, especially in the immediate area of proposed drill sites should provide important information.

8. *Geodesy (land and seafloor)*

Geodetic data provide important constraints on the great earthquake cycle. Such data and interpretative dislocation and other fault deformation models constrain the part of the subduction thrust fault that is locked at present and that is seismogenic. Modelling of the abrupt surface deformation (horizontal and vertical) at the time of great earthquakes constrains the rupture area. The pattern of slow, steady deformation in the interseismic period between great events, also constrains the part of the fault that is locked at present and may rupture in future great earthquakes. The most important geodetic data comes from GPS horizontal measurements, both from continuously operating sites, and from campaigns of re-measurement of geodetic benchmarks at intervals of a few years. Horizontal data also comes from repeated laser ranging between geodetic benchmarks. So far, GPS data determines vertical deformation less well, and interseismic vertical motions are best constrained by repeated precision levelling lines, repeated precision gravity measurements (especially high precision absolute gravimeters), and long-term tide gauge records. On most subduction zone margins, land GPS and other geodetic data can provide good constraint to the landward limit of the locked seismogenic zone, but provide little information on the seaward limit. Constraint for the seaward limit of the locked zone requires seafloor measurements. Initial measurements across the N. Cascadia subduction margin and trials off Japan have demonstrated that adequate accuracy is possible using precision acoustics to range from seafloor benchmarks to the sea surface, and GPS from the sea surface to land GPS sites. Such measurements would be very

valuable for margins to be drilled by OD21.

9. Exhumed ancient subduction zones

An important source of information on the deep structure and composition of subduction zones comes from eroded ancient subduction zones. Although some ephemeral characteristics such as pore fluid chemistry may be lost with the change from original insitu conditions, the main changes in sediment composition and structure should be preserved. Exhumed fluid inclusions in ancient veining may constrain previous fluid and previous pore pressure regimes. In some areas it may be possible to identify and study previously seismogenic parts of ancient subduction thrust faults.

The Nankai Trough

The Nankai Trough is one of the best studied and characterized subduction accretionary prisms in the world and thus meets most of the requirements well (see below). Although more survey and study are needed, the area is well known and the most important measurements and studies have been made, i.e., multichannel seismic reflection and OBS seismic structure information, detailed earthquake studies, detailed heat flow probe measurements and heat flow estimates from the depth to gas hydrate BSRs. It has had numerous detailed regional seafloor geological and geophysical surveys and studies. It also has had a series of previous DSDP/ODP drilling legs, and two proposed new drilling legs.

E. MEASUREMENTS ON CORE, CUTTINGS AND FLUIDS

Core and cuttings studies in a transect of holes across the updip limit of the seismogenic zone are required to determine the changes of subducted materials in response to progressive downdip changes in the environment of the thrust. The changes include the physical, chemical, and structural properties of the sediment matrix and of the pore fluids. Most of the required core measurements are now being done on samples recovered by JOIDES Resolution, but some additional measurements and analyses are needed for SEIZE objectives. Also, a sampling and measurement program must be set up for the cuttings recovered from the return drilling fluid circulation.

Important questions include: (a) What is the input sediment at the level of the decollement?

(b) How do the physical and chemical changes relate to changes in the environment; temperature, pressure, stress, hydrological regime etc.? (c) What are the relationships between episodic faulting, fluid flow and chemical changes at different depths along the subduction thrust fault? (d) What are the along strike changes in composition, physical and chemical state, and in environment, and how do they relate to the seismic behaviour?

Some of the important core and cuttings measurements with depth and landward are (with special attention to the decollement):

1. Detailed sediment lithology, with depth and landward
2. Sediment type and matrix composition (and underlying basement composition),
3. Sediment chemical and physical changes with depth and landward; compaction, diagenesis, alteration, pressure solution, mineralogy changes etc.
4. Sediment physical properties; sonic, elastic, index, thermal, electrical, magnetic, etc.,
5. Sediment pore fluid chemical composition and isotopic regime;
6. Sediment and pore fluid inorganic and organic chemistry, including gas hydrate recovered in a pressurized sampler,
7. Pore fluid gases in core and cuttings, and in return fluid circulation,
8. Structural fabric, faulting, fracturing, cataclasis, strain localization, and relations to fluid flow,
9. Geophysical fabrics; magnetic fabric, anisotropy, X-ray tomography, etc.
10. Mechanical and geotechnical deformation properties; dilatancy, frictional characteristics
11. Hydrogeological properties, especially permeability, and dependence on pore pressure etc.,
12. Dependence of many of the above parameters on insitu temperature, pressure, stress etc., as determined in the laboratory.

It is noted that the drilling mud selection and monitoring must consider chemical and physical contamination of the cuttings and core samples, especially the pore fluids.

F. DOWNHOLE MEASUREMENT AND RECORDING

Downhole measurements

A full suite of downhole measurements is critical to the scientific success of the SEIZE

project. These must be acquired using a combination of wireline logging, logging while drilling (LWD) and packer pore pressure and permeability tests in cemented and perforated casing, and in the open hole. The types of data needed are listed below, grouped into items that are essential to the scientific success of the project and those that would be useful but that are not as critical.

In this list, asterisks (*) denote measurements for which significant instrument technology development is required for use at very high temperatures (greater than about 250C). If high-temperature tools are known to exist, the temperature limitations of these tools and the known sources for these tools are given in parentheses. Downhole geophysical tools are being developed rapidly, and it is recommended that a review of the current status of high-temperature and other tool development in industry, government and university laboratories be carried out, to ensure that this list is current and to identify which new high-temperature tool development is warranted. It is noted that development of high-temperature tools is expensive. If possible, high temperature formations should be measured using rapid circulation cooling followed by short measurement durations such as to allow conventional logging and other measurement tools to operate.

1. *Wireline logs*

(temperature limit of present tools in brackets)

Essential Logs

- *Formation Micro Imager (FMI or FMS)
- Borehole Televiewer (250C)
- Density (260C)
- Natural Gamma (260C)
- *Porosity (200C)
- *Dipole Sonic log (directional Vp, Vs and full waveform)
conventional acoustic log (232C)
- *Resistivity (high-T)
- *Geochemical Logging
- Vertical Seismic Profiling (VSP) (250C)
- *Cement Bond Log (200C)
- Temperature (continuous 260C; memory 400C)

-Temperature, bottom-hole penetrating probes (100C for shallow sediments)

Some Additional Logs

-Magnetic Field (300C)

-*Magnetic Susceptibility

-*Nuclear Magnetic Resonance

-*Cross-hole seismics, resistivity, and hydrologic testing

-*Sidewall Coring

-*Gyroscopic Directional Survey (repeat logging for casing shear)

-*Ultrasonic Cement Imager (" " " ")

-Borehole Gravimeter, for formation densities (250C)

2. Logging-while-drilling

Logging-while-drilling (LWD) is especially important for SEIZE drilling because of the need to measure transient properties immediately after drill penetration. Moreover, it will be necessary to case much the hole, limiting conventional logging to short segments prior to installation of each casing string. LWD is being rapidly developed and the tools available are increasing and improving. The state of tool development and availability should be reviewed just prior to the SEIZE drilling. The tools should include at least the following:

-*Resistivity (150C)

-*Density Neutron (150C)

-*Sonic (150C)

-Natural gamma (150C)

-*Drilling Parameters/MWD (175C)

There may be substantial borehole cooling during drilling so tools may be used where the equilibrium formation is higher than the tool rating. However, tools may overheat if they become stuck in the hole.

Fluid sampling, permeability, pore pressure and stress

A number of tools and packer systems are available to determine the formation pore pressure, formation permeability, and to sample formation fluids. These include:

- Packers set at base of casing after each casing string installed, and over perforations in cemented casing (250C); for permeability, fluid pressure and stress
- Borehole Fluid Samplers (250C); for fluid sampling in conjunction with above packers if formation permeability is high
- *Modular Dynamics Tester (175C); for fluid sampling and permeability through casing perforations if formation permeability is low.
- Borehole flow and inferred permeability where flow rates are high: Temperature/Pressure/Spinner Flowmeter tools (250C); give vertical distribution of permeability if borehole flow rates are high.
- *Inflatable Packers deployed through the drill-pipe also may be used in the open-hole (150C)

Technology development (see * items above)

Seismogenic zone drilling, measurement and monitoring will bring special challenges in drilling, sampling and instrumentation. (a) A hole must be drilled to depths of up to 7 km in unstable and poorly indurated materials, where bottom-hole temperatures are expected to reach up to 250C. (b) Substantial amounts of core are needed in at least some intervals, either in the main hole or in inclined holes branched off the vertical borehole to cross the fault at multiple positions. (c) It should be possible to re-enter side branch drillholes for implanting or replacing borehole monitoring devices. (d) Sophisticated borehole geophysical logging operations, in-situ measurements and fluid/rock sampling at high temperatures are required. There is a strong likelihood that the drilling and sample recovery conditions within the fault will be extremely difficult, owing to high fluid pressures and poorly indurated gouge materials within the fault zone. (e) Some or all of these holes must be instrumented for continuous monitoring of seismicity, deformation, fluid pressure and a broad range of physical and chemical properties over long periods of time.

Areas in which technological research and development will be required for the SEIZE project, some of which are identified by asterisks (*) above include:

- Multiple whipstock and reentry from a single hole (especially for cross-hole surveys and hydrologic testing),
- Logging while drilling (LWD) at high temperatures
- High temperature geophysical logging tools, seismometers and packer systems,

- Long-term downhole monitoring (sensor design, cables, data telemetry, power sources, installation and repair procedures)
- Casing and completion at high temperatures and in poorly indurated/unstable materials.

G. LONG-TERM MONITORING (CORKS)

Downhole monitoring and recording

Borehole CORK-type downhole measurements and observatory systems are a critical part of the scientific program for SEIZE. These systems allow monitoring insitu pore pressure, temperature, and deformation during the earthquake cycle and provide reliable measures of undisturbed formation temperatures, especially if packers prevent fluid circulation in the borehole.

In conjunction with these measurements, seismic monitoring would provide invaluable information about the source processes of nearby microearthquakes. Monitoring of fluid chemistry, borehole flow and time varying electric and magnetic fields (e.g., streaming potential), together with periodic fluid sampling would provide insights into time-varying geochemical and hydrologic processes within the subduction zone, and changes with time of physical properties of the seismogenic zone.

The parameters that should be monitored in borehole CORK installations include:

1. Essential Measurements and Sampling

- *Strain/tilt
- Seismometry for earthquakes and controlled sources (250C);
- Temperature-depth
- *Fluid pressure at multiple horizons
- *In situ fluid chemistry

2. Other Measurements and Sampling

- *Fluid sampling with tracers/tags
- *Electromagnetic fields
- *Fluid conductivity
- *Flowrate (especially electromagnetic sensors)

Seafloor recording and monitoring

Borehole downhole monitoring should be augmented by a sea floor observatory (i.e., similar to the Italian GEOSTAR system) including ocean bottom seismometers as a minimum. Important parameters to be recorded include seismic data (with geophones and hydrophones) and sea floor deformation (geodetics).

H. MANAGEMENT OF SEIZE DRILLING AND MEASUREMENT PROGRAMS

The planning and scientific operations for longer duration OD21 programs will be very different from past ODP/DSDP experience based upon 2-month drilling legs. In ODP/DSDP the science objectives and science plan were distinct for each drilling leg, with the primary objectives defined by the proponents of successful drilling proposals. For OD21, much longer term planning is required and the objectives may be much broader. The SEIZE DPG recommends that an expert scientific team be set up for each major SEIZE program to develop detailed scientific and operational plans. The San Andreas Fault drilling proposal provides one model for such a team. The team is expected to develop detailed plans and to carry these plans through to the scientific program onboard the ship during drilling. The team should have subcommittees for each of the main scientific programs involved in the SEIZE drilling, including the required site surveys and associated scientific studies. The scientific team must work closely with the JAMSTEC drilling engineering and science groups who are responsible for design, construction and operation of the OD21 drill ship. An outline of the suggested scientific team needed for a SEIZE drilling and measurement program is given below.

SEIZE Management Team

The SEIZE management team may be made up of 4-5 subcommittees representing the different scientific components. For each subcommittee, 6 to 8 members are suggested (see below). For the subcommittees, it may be appropriate to have an initial competition for the best and most motivated participants based upon scientific and technical proposals. Previously received letters-of-intent for the SEIZE DPG should provide a partial list for soliciting proposals. These discipline

subcommittees then would prepare detailed science plans for their part of the program. A small oversight committee with representation from all of the subcommittees (i.e., chairmen of subcommittees) would provide overall scientific management of the SEIZE drilling project. For the initial phase of the SEIZE program it may be desirable to have one Japanese and one International co-chairman for each subcommittee.

A suggested SEIZE drilling subcommittee list and some of the scientific expertise needed to be represented are:

1. *Site Characterization*

- seismic structure (multichannel, refraction, OBS, earthquake determined structure)
- earthquakes (great and micro earthquakes; tectonics)
- potential fields, magnetics, gravity etc.
- thermal (heat flow probe data; BSR heat flow; heat generation; thermal properties; thermal modelling)
- seafloor (morphology, faults, fluid vents, coring and dredging)
- geodesy (land and seafloor)
- predictions of lithologic and structural character from ancient analogues

2. *Downhole Measurements*

- downhole logging
- accretionary prism hydrogeology (temperature, fluid sampling, packers etc.)
- seismic structure data; inhole experiments
- stress and strain measurements

3. *Sampling and Measurements on Core, Cuttings and Fluids*

- sedimentology; paleontology
- small scale structural geology
- formation fluid chemistry, inorganic and organic
- gas hydrate
- physical properties (velocity, electrical resistivity, density, porosity etc., geotechnical)
- magnetics
- biology

4. *Fault Zone and Sedimentary Prism Monitoring*

- pore fluid pressure, chemistry, temperature, CORK
- downhole recording of earthquakes
- stress and strain monitoring; tectonics, engineering geophysics
- electrical transients, velocity transients

(Note the need for high temperature instrumentation for long-term recording)

Data management

Careful and thorough data management and dissemination is essential to the success of the SEIZE drilling project. A data management subcommittee thus may be needed, although this function may be integrated into the overall OD21 data management.

SEIZE funding

Every effort should be made for the critical components of the project to be funded together, including the most important site surveys and studies. Independent funding should be only for site surveys, associated science, and parts of the program that are not essential to the overall success of the project.