Previous Track Record

A strong team has been assembled with the necessary elements for this project's success. This includes Talling's wide-ranging expertise in submarine flow process, Parsons' expertise in bathymetric measurement, flow monitoring and acoustic backscatter measurements, Sumner's expertise in analysing velocity data and sediment cores (including ongoing analysis of cores from Monterey Canyon), Cartigny's expertise in numerical modelling of flows (including those in Monterey Canyon), and Paull and Xu's strong track record in direct monitoring of flows in submarine canyons.

Dr. Peter Talling (PI: National Oceanography Centre) has collected innovative large-scale field data sets that challenge existing models for submarine flows, as summarised by a 67-page State-of-the-Science article published this year in Sedimentology [1]. He led the first study to map individual ancient flow deposits across a mountain belt [2], and has published as first-author in Nature on submarine sediment flows[3]. He has collaborated with Sumner on a novel program of laboratory experiments that show how small amounts of mud can cause turbulence collapse and flow transformation [4,5,6] and is involved in analytical [7] and finite element flow modelling as part of his ongoing (2011-2016) Royal Society Industry Fellowship. He is leading a £2.3M NERC consortium project on whether the landslide-tsunami risk to the UK will increase due to climate change. This unusually broad project includes analyses of tsunami and landslide deposits, modelling of future trends in seismicity and slope stability, analysis of hydrate bearing sediment, coupled landslide-tsunami modelling, modelling of tsunami interactions with UK coastal defences, and estimates of societal cost. He was an original proponent and shipboard member of IODP Leg 340 in 2012 offshore Montserrat and Martinique, which was the first to core volcanic landslides and he led the NERC site survey cruise (JC045/46) in 2010 that successfully collected the most detailed geophysical survey of submarine volcanic landslide deposits [8-10]. He will test a new ROV-based vibracorer offshore Montserrat in March 2013. Talling leads the Submarine Geohazards and Sedimentology Group at the UK National Oceanography Centre and has been PI for seven NERC awards, and a Co-Investigator for a further award. They have resulted in 39 international journal publications since 2006, with 15 ISI-ranked papers in 2012, and 13 manuscripts currently in review.

Prof. Dan Parsons (Co-I: University of Hull) recently took up a Chair in Process Sedimentology at Hull. Prior to this he completed a NERC Fellowship 2005-2009 investigating three-dimensionality in flow and bedform morphodynamics using a combination of field work, laboratory investigations, and numerical modelling. Parsons is an expert in acoustic-based (including ADCP) flow measurement techniques having successfully deployed these instruments in a range of experimental and field environments [11-14]. He holds a number of grants from NERC for field and laboratory based investigation of flow, sediment transport & morphodynamic processes (NE/E016022, NE/E001661, NE/G01051X/1) and this includes a project that involves novel field monitoring of submarine channel flow processes across the Black Sea shelf (NE/F020511/1), which was published in Geology in 2010. Parsons was the recipient of the *Gordon Warwick Award* from the British Society for Geomorphology in 2010 for 'scientific excellence within the field of geomorphology as evidenced by a set of publications by a researcher under the age of 35'. He was an invited/keynote speaker at Shallow Survey 2005, 2009 International Conference on Fluvial Sedimentology, 158th Meeting of the Acoustical Society of America in 2009, AGU 2010 and 2012, and Underwater Acoustic Measurements in 2007, 2009 and 2011

Dr. Esther Sumner (Co-I: University of Southampton) is currently based at MBARI (until mid 2015) using core and bathymetric datasets to study canyon shaping processes, which will provide ideal background information for this proposal. She has expertise in deploying acoustic techniques to measure dynamics of field scale submarine gravity currents, and processing these datasets to understand flow dynamics (as PDRA for NERC grant NE/F020511/1 whilst at Leeds (with Parsons)). She led the coring programme for the NERC funded cruise offshore Sumatra in 2009 [15], and was previously responsible for shipboard description of cores during a 30-day coring cruise offshore NW Africa and Iberia. Sumner has expertise in experimental modelling of submarine flow processes having led a programme of innovative experiments that demonstrate the profound influence of mud content on submarine flow rheology and deposit character [4-6]. Sumner has experience of collaborating with numerical modellers on both experimental and field-scale geophysical datasets [7].

Dr. Matthieu Cartigny (Co-I; National Oceanography Centre) has a strong background in physical and numerical studies of hydrodynamics, sediment transport, morphodynamics of turbidity currents. In previous work he used numerical models and sediment wave geometries found on canyon floors, including the Monterey Canyon, to reconstruct turbidity current properties [16]. His experimental work focussed on the morphodynamics of turbidity currents, where he links flow properties such as velocity and sediment concentration profiles to depositional characteristics [17]. In previous projects he has shown how different flow characteristics and submarine channel morphologies lead to different deposit architectures [17].

Prof. Charlie Paull (Project Partner – Monterey Bay Aquarium Research Institute, USA) is a Senior Scientist at MBARI and has pursued a broad variety of research topics that has resulted in over 180 peer-reviewed publications, often involving the development of innovative technology [18-22]. These include identifying the first cold seep communities, being the chief proponent and co-chief scientist for the first ODP Leg dedicated to gas hydrate research, serving as chief scientist for the MBARI Monterey Ocean Observing System (MOOS), which has developed and installed cable-connected deep-water sea floor scientific measurement infrastructures, and leading various sea floor exploration efforts using ROVs, AUVs, and submersibles. He recently chaired the US National Research Council's report "Realizing the Energy Potential of Methane Hydrate for the US".

Dr. Jingping Xu (Project Partner: USGS, USA) has led USGS projects studying turbidity currents in submarine canyons over the past 10 years. Collaboration between the USGS and MBARI in monitoring Monterey Canyon has provided by far the most complete data yet collected for marine turbidity currents. More recently, his work has expanded to study Hueneme Canyon, Mugu Canyon and other canyons along the US West Coast, and to canyons in Southwest Taiwan. He has published extensively on field turbidity currents [24-30], bedforms [29]; and sediment transport [24-30], including a 2012 paper in Geology with monitoring data from sites to be reoccupied in this study [30].

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Submarine turbidity currents: first synchronous quantification of flow and suspended sediment dynamics at the field-scale

RATIONALE: Submarine sediment density flows ("turbidity currents") are, volumetrically, the most important sediment-flow transport process on our planet [1]. Only subaerial river systems transport comparable volumes of sediment across such large areas. However, a single turbidity current lasting a few hours can transport ten times the combined annual sediment load from all of the world's rivers [1]. The most remarkable feature of submarine turbidity currents is that their sediment concentration and velocity profiles have only ever been measured three times, and never with a frequency greater than every 5 minutes [29-30]. Flow velocity and concentration are the two most fundamental parameters for understanding any sediment flow-process. This remarkable lack of key field observations contrasts strongly with rivers for which there are hundreds of thousands of sediment concentration and velocity measurements in locations worldwide, including synchronous measurements of both parameters. ***This project will document directly the key features of one of the most important sediment transport processes on Earth for the first time.***

Turbidity currents can run out for thousands of kilometres, dominating sediment supply to many parts of the deep ocean, and form the most extensive sediment accumulations on Earth (submarine fans). They have created thick sequences in the rock record, and subsurface sandbodies that now contain many of our largest oil and gas reserves [31]. Submarine flows carve canyons into the continental shelf, which are deeper than the Grand Canyon, through processes that are still poorly understood, and flows within these canyons play a key role in supplying organic carbon and nutrients to benthic ecosystems (that include important diversity hotspots) in the deep sea [33]. Contemporary flows through canyons and into the deep sea are also important because of the hazard they pose. Such flows can break networks of seafloor cables that now carry over 95% of the global data traffic that underpins our daily lives (including the internet and financial markets) [32,34].

Understanding of submarine turbidity currents is severely hampered by an almost complete lack of key measurements [1]. The only direct measurements of sediment concentration come from Xu et al. [29-30], who report data from Hueneme, Mugu and Monterey Canyons offshore California. Xu et al. demonstrate the feasibility of using Acoustic Doppler Current Profilers (ADCPs) to collect synchronous flow and concentration profiles, including from the exact location in Monterey Canyon used for this project (Figs 1 & 3) [30]. However, their data are of poor temporal resolution as they are only 30-second averages measured every 5 minutes. Their past work used single-frequency acoustic backscatter as a proxy for suspended sediment concentration, but backscatter depends on both concentration and grain size. We will therefore use multi-frequency ADCPs to better constrain the affects of grain size and thus fully quantify sediment concentrations.

Changes in frontal speed of submarine flows have been measured in just five locations, mainly through the timing of sequential cable breaks [28,34,35]. No flow has ever been monitored along its full path, which is of key importance because flows are thought to evolve considerably in character [1,2]. Dilute and slow moving flows in lakes and reservoirs have been monitored in greater detail [36]. However, such weak flows most likely differ in key regards from more powerful submarine flows, for instance in the development of higher concentration near-bed layers [1, 37]. Flow deposits have been studied extensively, but it is problematic to infer flow character unambiguously from deposits that only record the later-stage and near-bed (depositional) stages of flow. Laboratory and numerical models have provided valuable insights into flow dynamics [5,38-40], but there is a pressing need for models to be validated against full-scale monitoring data as many aspects of laboratory experiments will not scale-up, whilst the basis of the numerical models urgently needs adequate testing. To produce a fundamental step-change in our understanding of submarine flows, it is therefore necessary to monitor active flows directly to understand their sediment concentration profiles, determine how sediment concentration and velocity are related, and assess how they evolve in time and space. Until this is achieved, our understanding of these flows will remain severely limited

AIMS*: The over-arching aim of the NERC project is to produce a step-change in our understanding of submarine turbidity currents by (i) measuring their two key features (synchronous velocity and concentration profiles) in detail (every 2-to-30 s) for the first time, and (ii) documenting spatial changes in their flow dynamics from source-to-sink for the first time. We will answer specific questions that include: (1) Do turbidity currents contain distinct near-bed layers with elevated sediment concentration that damps turbulence, and what is the relative importance of dense or dilute layers for overall momentum transfer? (2) Do turbidity currents either accelerate and erode (ignite) or decelerate and deposit (dissipate), or can they exist in an equilibrium-state with near uniform velocity? (3) What is the quantitative relationship between mean flow velocity and sediment carrying capacity as flow evolves?*

This NERC project is to enable deployment of a cluster of novel instruments in Monterey Canyon offshore California for 18 months in 2014-16 (Table 1). These instruments are specially configured to record data on a common time base at high sampling rates as part of the state-of-the-art MOOS (Monterey Bay Ocean Observatory System) and promise to provide the first high frequency (15-30 sec) synchronous measurements of the velocity and sediment concentration profiles, together with data on water temperature and salinity associated with the passage of turbidity currents. The project will also include deploying a series of self-triggering event detectors (STEDs) placed along the flow path within the canyon to document spatial changes in frontal flow velocity, in order to test the hypothesis that these flows ignite or dissipate. The context for these datasets will be provided by allied work by our Project Partners MBARI and the USGS, who will document how these flow events are triggered, and their initial stages in the upper canyon. Project Partners MBARI are providing this NERC project with access to innovative tools (MOOS and STEDs) that MBARI have designed, built and field tested over the last decade; an in-kind contribution worth well over $10 Million.

Why do MBARI not deploy MOOS and STEDs? As an endowment funded charity, it is important to note that MBARI's mission is to develop new technology rather than to undertake blue-skies science. As the MOOS and STEDs are tried and tested technology that MBARI know to work well in the field, their remit now prevents them from deploying these systems to answer research questions of the type proposed here. ***Without this NERC funding, the MOOS and STEDs will not be deployed.*** However, MBARI will deploy newly developed sensors to monitor more powerful flows in the upper canyon (BEDs; benthic event detectors embedded in the flow that record their axes of rotation every few seconds and hence show their mode of transport in a flow, with their data retrieved via acoustic telemetry using a ROV) and provide novel ultra-high resolution AUV surveys showing changes in the canyon floor before and after events. MBARI will also provide rapid response access to research vessels and ROVs necessary for equipment deployment and servicing during this 18 month period, as MBARI is located at the head of the canyon (Fig. 1). It would not be possible to repeatedly mobilise NERC vessels and ROVs in this way. As part of the allied work in the upper canyon, MBARI and USGS will provide 3 lower-resolution (every 5 minute) single-frequency ADCPs in locations further up the canyon. MBARI and USGS thus provide in-kind support for the project through provision of further monitoring equipment in the upper canyon that is worth a further $1.5 Million. Moreover, MBARI and USGS bear the risk for the loss of all of their equipment. Importantly, this allied work, will provide the NERC project with key information on how flows that reach the MOOS site are initiated, and information on their earlier more powerful stages.

The NERC project outlined herein therefore bears a small fraction of the total cost and risk for this unique field experiment, which therefore combines novel and timely science with exceptional value for money. Such an opportunity for UK science to undertake a field experiment of this scale at a viable cost will occur very infrequently. *The scope of the entire source-to-sink experiment is such that neither NERC, MBARI, nor USGS could conduct this experiment alone, within budget or remit. Such international collaboration will become increasingly important for large-scale ocean monitoring, and this is something that will need to be recognised in this (and future) NERC grant applications.*

BACKGROUND AND FIELDSITE: Monterey Canyon is ***the best location worldwide*** to monitor submarine flows because: (1) There are very few locations worldwide where we know, with confidence, that several submarine flows will occur annually (Figs. 1b & 2) [18-to-30]. Preliminary work [30] shows that multiple events occur where MOOS will be deployed at 1850 m water depth, and can be monitored with moored ADCPs (Fig. 2). Background data, including flow monitoring and repeat AUV mapping of changes in canyon floor morphology, shows that flows occur in the upper part of Monterey Canyon several times every year [18-21, 23-30]. These sub-annual events are very powerful, as they

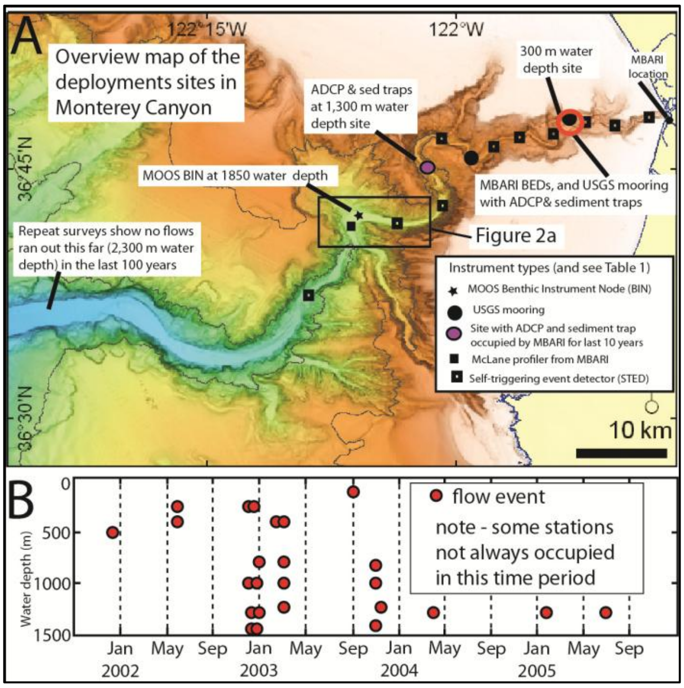


Figure 1*: (A) Monterey Canyon with location of proposed instrument deployments in 2014-16 (B) and frequency of flows [37; also see 35].*

move 45 kg concrete blocks with acoustic beacons [20], have mangled frames placed on the sea floor that weigh up to 1,360 kg [20], and from recent ADCP data can travel at speeds of at least 1.8 m/s [24,26]. (2) MBARI (Project Partner) is located in Moss Landing at the head of the canyon (Fig. 1). MBARI will provide regular access to research vessels and state-of-the-art equipment such as ROVs that are necessary to deploy, service or recover instruments placed on the sea floor during research outlined here. There is arguably no other location worldwide where such equipment and world-class expertise could be mobilised for the repeated ROV deployments needed for this type of project. (3) Unusually detailed preliminary monitoring, sediment sampling, and ultra high-resolution AUV mapping of the canyon axis [18,19] exists, providing all necessary background information needed for effective design of the proposed 2014-16 NERC project, and allied source-to-sink work.

Choice of MOOS location: Monterey Canyon is the most closely monitored submarine canyon in the world, with unusually detailed information over the last two decades on the run-out distance of flows (Figs 1 and 2; [18-30]). This past work is important because it allows the most suitable location for MOOS to be identified, thereby reducing risks substantially. This previous work has identified:

(1) Frequent events that did not damage equipment moorings (820 to 1860 m water depth): Downward pointing ADCPs at 820, 1020, 1300, 1450 & 1860 m water depth have all recorded numerous flows, including at the location where MOOS will be deployed in this project (Fig. 2b). Xu et al. [30] report 25 events in < 3 years (Fig. 1b), even though a limited range of locations were occupied for much of this time. ADCP's have successfully measured velocity profiles [24,29,30] showing maximum velocities of up to 2.8 m/s occurred 5 to 12 m above the sea floor, in flows that were 30 to 80 m thick, and lasted for up to 8 hours (Fig. 2b). Although they are the best data on vertical velocity structure yet collected for submarine flows, they omit the onset of flow and only crudely constrain temporal changes, as the measured velocities are only 5-minute averages made every hour [24,29,30]. The source for these flows is also unknown, as is their full run out distance.

(2) Powerful events in the upper (< 400 m depth) canyon: These sub-annual events are very powerful. In one experiment, 3 acoustic beacons encased in concrete 'monuments' were buried on the canyon floor initially at ~ 300 m water depths [18]. Relocation of monuments using an ROV showed at least 6 transport events over a 26 month period in 2007 and 2008 [13] which were sufficiently vigorous to move these monuments (weighing 45 kg) for a total of ~1.7 km down canyon [19]. Other events have moved and mangled frames placed on the canyon floor ~170 m that weigh up to 1,360 kg [20]. These observations cannot be explained by the types of current velocities documented by Xu et al. [24-26, 30] for flows using ADCPs that are located several 10's of m above the bed. The origin and character of these powerful near-bed events is currently contested [17,18].

(3) Movement of crescentic bedforms: Mapping of the canyon floor shows sub-annual events are associated with movement of spectacular fields of crescent shaped bedforms [18] that have amplitudes up to 2.5 m, and wavelengths of 20 to 80 m. These features are concave down-canyon and asymmetric with steep (15°) faces in a down-canyon direction. A master headscarp sometimes forms a local knickpoint below which an individual train of bedforms becomes progressively less distinct [18]. Tidal currents measured within the canyon are too weak to form these bedforms that, in places, are composted of gravel and boulders [18]. Precise ROV coring shows that this type of coarse sand only extends for ~ 6 m up the side of the canyon. This led Paull et al. [18] to suggest that the bedforms are slump scars formed as dense layers of liquefied sand come to a halt, although it has also been suggested that they were formed by repeated hydraulic jumps (cyclic steps) in dilute turbidity currents [17]. If they are slump scars, failure is occurring on sea floor gradients of just 1.8°. The crescentic beforms extend from the canyon head (11 m water depth) to water depths of 1900m.

The location of the MOOS at 1850 m water depth is chosen to avoid the more powerful flows in the upper canyon that would damage the equipment. Preliminary work shows that multiple events occur each year at 1850 m (Fig. 2c) [30], and can be monitored successfully using ADCPs of the type used in this project (Fig. 2b). ADCP measurements from moorings have also previously been successful at 820, 1020, 1300 and 1450 water depths [24,28,30], recording multiple events each year (Fig. 1b).

RESEARCH QUESTIONS: <u>Most simply we will obtain a set of novel and unique measurements that will allow us to document directly, for the first time, what turbidity currents actually are.</u> The following research questions will be addressed;

(Q1) What is the relationship between temporal changes in velocity and sediment concentration profiles? This two-way relationship is critical for understanding turbidity currents because they are driven by the excess density resulting from this suspended sediment. <u>Important feedbacks exist between flow velocity and concentration; changing flow speed affects the flow's sediment carrying capacity, which in turn affects the flow's velocity.</u> This project will provide the first high frequency (1 per 15 or 30 s) profiles of 3D (x-y-z) velocity and sediment concentration in a turbidity current. (a) *We will document the basic structure of flows, and allied work will document their triggers and initial stages in the upper canyon.* This will provide the first source to sink documentation of a turbidity current and allow us to constrain the fundamental dynamics of these flows that provide the foundation of all conceptual and numerical models. For example, do flows have an initial peak in velocity and then wane, or does velocity fluctuate due to processes such as breaching operating in the upper canyon? *(b) How do turbidity currents carry their sediment?* It has been proposed that remarkably low (0.05 % volume) sediment concentrations can damp turbulence, however, we know that turbidity currents transport vast volumes of sediment. One proposition is that flows are bipartite with a high-concentration laminar basal layer overlain by a more dilute turbulent flow [1]. We can test this hypothesis that reduced turbulence at the level of maximum velocity in a turbidity current is a barrier that prevents upward turbulent mixing of sediment, leading to a stepped concentration profile [42]. (c) Analysis of covariance of velocity and concentration profiles will elucidate how the amount of sediment suspended (the flow capacity) is related to changes in flow velocity. *(d) Using sediment traps and ROV-vibracores we will link these flow processes to their deposits*, which is the key to making better insights from the most common type of data that we have for these flows: their deposits in the geological record [1].

(Q2) How does flow speed vary along the flow path, and what controls these variations? Frontal flow velocity will be measured using transit times between a series of novel self triggering event detectors (STED's), and ADCPs at four separate locations along the flow path (Fig. 1; Table 1). *This project will therefore provide the first full-scale field test of the established paradigm that submarine flows erode sediment to become denser, and therefore faster, leading to further erosion, producing a positive feedback termed ignition [39]. Conversely, once deposition begins, a rapid decline in flow speed and concentration ensues, a process termed dissipation [39,40].* A widely held view is that flows either ignite or dissipate, with a sharp threshold between the two types of behaviour [40,41]. This view underpins explanations for why submarine flows can be so large and powerful, and run out for such long distances. However, recent data from cable breaks [34,35] and analysis of individual flow deposits by the PI [1,2] suggest that turbidity currents may exist in a near-equilibrium state for remarkable distances, with almost uniform speeds and deposit thickness.

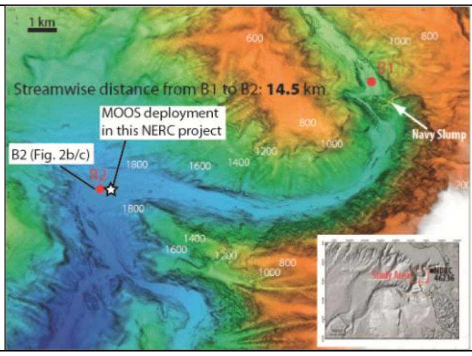
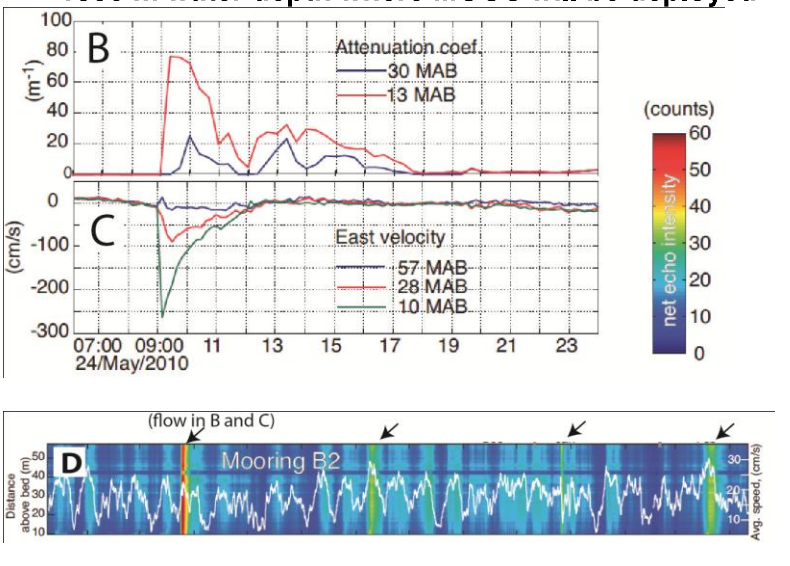


Fig. 2 (A) Map showing position of two ADCP moorings (B1 & B2) that successfully collected (B & C) backscatter and velocity data, including during a flow event on 05/24/10. (D) The B2 mooring recorded four events (arrowed) in this 13 month deployment. *From [30]*

ADCP (single frequency - 300 kHz) data from location at ~1850 m water depth where MOOS will be deployed



METHODOLOGY: Historically, we have lacked suitable tools and technologies to monitor submarine flows. ADCP's now provide the means to provide synchronous measurements of sediment concentration and velocity profiles within turbidity currents [29,30], whilst self-triggering event detectors can now document spatial changes in frontal flow speed [22].

a) Monterey Ocean Observing System (MOOS): MOOS was designed originally such that separate benthic instrument nodes (BINs), each comprising a set of instruments were attached to a central node [43]. As it is very expensive (£800k) to install the seafloor to surface cable mooring and cabling, the MOOS instruments will be used for this experiment without the seafloor to surface connection. MBARI's existing MOOS instrument cluster (a BIN) will be placed at 1850 m water depth (Fig. 1). The location at 1850 m water depth is chosen to avoid powerful flows in the upper canyon that would damage the equipment (see above). Preliminary work shows that multiple events occur each year at 1850 m (Fig. 2c) [30], and can be monitored successfully using ADCPs (Fig. 2b). ADCP measurements from moorings have also previously been successful at 820, 1020, 1300 and 1450 water depths [24,28,30], recording multiple events each year (Fig. 1b). The BIN will comprise **(i)** upward looking 300, 600 and 1200 kHz RDI Workhorse Sentinel ADCPs that record profiles of three-dimensional velocity and acoustic backscatter at 1-2m vertical intervals, with a range of 40-120 m. Measurements are recorded every 2s (1200 kHz), 15s (600 kHz) and 30s (300 kHz). **(ii)** a downward pointing Nortek Aquadopp ADCP located 1.5 m above the sea floor that measures point velocity every 15 s, **(iii)** SBE 16+ V2 CTD sensor that has a sampling period of 2 s, **(iv)** Seapoint backscatter and WETLabs sensors that measures point turbidity every 2 s. MOOS software records data from each instrument on a common time base using precise clocks to assure synchronization, which is critical at these high sampling rates. For this experiment, power will be provided to the BIN through large (~600 kg) battery packs. While this approach does not exercise some of the capabilities for which the MOOS system was originally engineered, it carries less risk and is a more economical way to obtain the high sampling rate data required for delivering the scientific aims.

A MOOS observatory (involving a mooring with a surface to seafloor fibre optic connection) was previously deployed at a water depth of 3,400 m [21]. However, no flow events occurred this far out and repeated mapping of a whale carcass shows that weak flows have not run out to 2,800 m water depth over the last 10 years [21] (Fig. 1). MOOS was subsequently moved to 1,850 m water depth for 6 months. MOOS operated fully, until failure of its acoustic release (not used in this project) meant that deployment was cut short. Instrument frames associated with this deployment at 1,850 m were not damaged during a further two year period. Nor were ADCP moorings damaged during a subsequent 13 month deployment by the USGS, although they recorded multiple flows (Fig. 2) [30]. These experiences indicate that the site at 1850 m experiences flows regularly, but that these flows are not powerful enough to damage the MOOS. Based on this experience, the 1850 m site offers an excellent choice for MOOS location. A mooring with two sediment traps (at 10 and 70 m above the seafloor) will be deployed adjacent to the BIN. This will provide a record of the materials transported in the water column. A McLane profiler will also be deployed near to the BIN. The McLane profiler travels up and down a taut mooring wire at 15 m/min, to collect a profile of temperature, salinity, dissolved oxygen, turbidity and velocity over the lower 500 m of the water column once per hour [43].

MBARI's primary mission is to develop new technology (see letter of support). As the MOOS technology is extensively tested and works well, MBARI given their remit cannot justify further significant funding for deploying MOOS in 2014/16 the research proposed herein involves no further development of MOOS technology. Deployment via this NERC project will therefore leverage over $10 M in funding and investment and will be the first scientific deployment of MOOS for submarine flow monitoring. This saves the NERC the extensive lead-time and costly investments that are involved in the development of such specialized scientific systems.

b) STEDs *(Self Triggering Event Detectors)* are relatively inexpensive (£5k) devices that record the time of flow event arrival [22]. There are no other cheaper alternatives that can be used, which can withstand powerful flows, and which provide this key information on changes in frontal flow velocity. STEDs comprise a 1 m high frame placed on the sea floor with a vane that orientates a pressure pad at right angles to an oncoming flow [22]. Once the pad experiences flow in excess of a predetermined trigger value a science package is released, floats to the surface, and relays data via satellite. STEDs have been deployed successfully on multiple (> 12) occasions in Monterey Canyon over the last 5 years [22], where they show that flows typically coincide with times of large seas. The threshold for release (fully tested in MBARI 1,500,000 litre test tank) is set so as to not be triggered by tidal daily flows, and will be set to trigger at >1.85 m/s +/- 0.10 m/s.

Allied Work: Our project partners will also deploy other new tools in the uppermost canyon in order to understand triggering and initial stages of these flow events, which is needed to provide the context for the detailed monitoring further down the canyon. MBARI has previously deployed "acoustic monuments" (45kg blocks of concrete encasing an acoustic beacon) that have already been successfully deployed in the upper canyon where they have documented occurrence of sub-annual events [18]. A next generation of acoustic monuments now exist which are called BEDs *(Benthic Event Detectors*). In addition to the acoustic beacons, BEDs also contain motion detectors developed at MBARI to show whether boulder sized objects placed in the canyon move by rolling, sliding or tumbling, and hence provide key insight into the nature of near bed flow, as well as the duration of the event. BEDs do this by recording their axis of rotation and acceleration. The detectors are mounted with a sphere that provides protection against powerful near bed layers.

Initial motion triggers rapid measurements (Hz sample frequency for up to a few hours). To avoid the necessity of recovering the instrument, the BEDs are designed to transmit data when buried through the sediments to an ROV. Initial tests indicate this is effective at ranges of >100 m even when buried under several meters of sediment. An array of 10 BEDs will be deployed throughout the canyon. Project partners USGS and MBARI will deploy three further moorings with downward looking ADCP's at 300, 1100 and 1300 m water depths, and sediment traps at 1300 m (Fig. 1).

PROPOSED PROGRAM OF WORK: NERC funding will (1) allow deployment of a MOOS BIN at 1850 m, (2) provide 10 STEDs to document velocity along the flow path, (3) constrain flow concentrations from ADCP backscatter data, and (4) support a part-time technical position needed to help prepare the equipment for deployment and synthesise and archive field data.

Table 1: *Equipment to be deployed in this NERC project, and allied work by MBARI and USGS.*

Instrument Name	Owned	Measures	Location	When deployed
This NERC-funded Project				
300kHz ADCP 600 kHz ADCP 1200 kHz ADCP	MBARI HULL HULL	Velocity every 2s, 15s and 30s at 1, 1.5 & 2m intervals for the 300, 600 & 1200 kHz ADCPs; upward pointing;	Set of sensors on the MOOS BIN. Deployed at 1800 m	Three 5.5-month periods (Oct 2014 to Feb 2015; April 2015 to Aug 2015; Oct 2015 to Feb 2016)
600 kHz ADCP	MBARI	Velocity every 15s; downward pointing (1.5 m above bed)		
CTD	MBARI	Conductivity, salinity, and temperature; Sampling period 2s		
Turbidity meter	MBARI	Turbidity (concentration) every 2s		
Sediment traps	MBARI	Two sediment traps located on mooring next to MOOS at 1800m		Oct 2014
STEDs (10x)	NERC	Time when flow arrives (assuming > 1.8 m/s) 10 STEDs spaced every 7.5 km along flow path		Deployed Oct –Nov 2014
Deployments in allied work by MBARI				
10 x Benthic Event Detectors	MBARI	Axis of rotation and acceleration	From 300 m to 600 m	Deployed from Oct 2014 until Feb 2016.
McLane Profiler	MBARI	temperature, salinity, turbidity and velocity over the lower 500 m of the water column every hour	Located next to MOOS BIN at 1800 m	Deployed Oct –Nov 2014
300 kHz ADCP and Sediment traps	MBARI	Downward looking ADCP and sediment traps on mooring	1300 m site revisited over last 10 years	Nov 2014
ROV-vibracorer Sediment cores	MBARI	> 400 cores already available at water depths down to 2300 m. Further cores will be taken at the MOOS BINs during this project, at times when MOOS BINs recovered.		
Repeated multibeam bathymetric surveys	by California State University Marine Laboratory (via a surface vessel; down to water depths of 250 m) and by MBARI (via an AUV; at the 300 m and 1800 m water depth sites)			
Deployments in allied work by USGS				
RDI 300 kHz ADCP	USGS	Downward pointing from 70m; 5 min average speed every hour	Located at 300 and 1100m	Deployed from Oct 2014 until Feb 2016.
Sediment traps	USGS	Each mooring has two sediment traps and turbidity meters		
Turbidity meter	USGS			
Temperature	USGS	Temperature sensor		

Work Block 1: Collection of field data will run for 18 months from fall 2014, across winter seasons of 2014/15 and 2015/16 in which flows are most common (Fig. 1b and 2). The MOOS BIN is to be deployed using MBARI vessels and ROVs for three 5.5-month periods (Figs. 1 and 2). Between these deployments, it will be recovered using MBARI's ROVs, serviced, and its data downloaded. The MOOS BIN comprises upward and downward pointing ADCPs, CTD, and four turbidity sensors all recording in a common time base. The MOOS BIN will be placed at the end of a straight stretch of canyon at 1850 m water depth to capture flow that is not affected strongly by the upstream bend (Fig. 1). A battery pack will be located 100 m downstream from the BIN to minimise interference with flow structure at the BIN. This site has been previously mapped by AUV & ROV observations.

A network of sensors will be deployed in autumn 2014 using MBARI ROVs and vessels at ~300 m water depth in the upper canyon where crescentic bedforms are active. This will include 10 BEDs. A USGS mooring consisting of ADCP, two sediment traps, and turbidity and temperature sensors will be deployed in the same area (Figs. 1; Table 1). Repeat AUV mapping of this location will be conducted (Table 1). A second USGS mooring (Table 1) with current meters and downward looking ADCP will be placed at ~1,100 water depths (Fig. 1). A mooring has been maintained in 1,300 m water depth by MBARI for most of the last decade and will be re-occupied during the 2014/16 period with sediment traps and ADCP (Fig. 1; Table 1). This provides 3 moorings with downward looking ADCPs, in addition to upward and downward looking ADCPs on the MOOS BIN.

A total of 10 self-triggering event detectors (STEDs) will capture changes in frontal velocity along the whole flow path, to determine the run out, and to better constrain where flows originate (Fig. 1). This will be important for linking information from the MOOS instrumentation of more powerful events in the upper canyon. STEDS will be spaced regularly (~7.5 km) down the canyon, such that STEDs extend from the start of the canyon to ~1950 m. All instruments that can be relocated will be recovered at the end of the experiment as required legally for work in Monterey Canyon.

Work Block 2: **Calibrating ADCP backscatter to better constrain sediment concentration:** ADCP's on the MOOS BIN will provide the first ever 2 m-spaced, vertical, three dimensional velocity profiles through submarine particulate density flows with high (< 30 s) sampling frequencies. The ADCP records from the USGS and MBARI long-term monitoring sites will also provide flow field information at a further three locations higher up the canyon. The record of acoustic backscatter intensity from each of the ADCPs can be used to constrain the concentration of sediment in dilute (< ~5%) flow [14,44]. Acoustic backscatter intensities within an ensonified volume are a function of spreading, attenuation and absorption losses (the sonar equation). The former is a function of distance from source, while the later depend on the concentration of backscatters within the water column. Provided that grain size distribution within the sampled volume is constant and Raleigh scattering criteria are met for the ensonified volume considered, then suspended sediment concentration has a direct relation to acoustic backscattering volume strength. As backscatter response of a given grain size varies as a function the frequency of the acoustic pulse and to control for the probability that grain size distributions during flow evolution will not be constant, we will deploy ADCPs with three different frequencies at the MOOS BIN (300 ,600 and 1200 kHz) [Table 1]. This, combined with information on grain size over time from the sediment traps, will assist in the acoustic inversion modelling and the determination of suspended sediment from acoustic backscatter. The use of three frequencies will allow us to examine the interrelated trends of the responses of each of the systems and thus allow a first order evaluation of the trends in grain size over time. We will first calibrate ADCP backscatter response for these three frequencies in controlled experiments at the NaREC (www.narec.co.uk) experimental dock facility in Blyth, UK, which has length, width and depth dimensions of 60 x 25 x 8 m. We will gravity inject well mixed sediment samples, of various concentrations (1%-10% by volume) into a central area of the facility ensonified by the ADCPs. These samples will include sediment already recovered from the base of Monterey Canyon and we will therefore match the grain size distributions from the canyon in the controlled tests. The ADCP responses will be recorded during sediment injection and will be calibrated using direct samples of sediment suspensions and pump sampling. This extends ongoing work led by Parsons conducted at NaREC as part of a recent NERC grant that has used scattering volume strength derived from acoustic backscatter to compute suspended sediment concentration [14]. We will obtain parameters for algorithms that will extract sediment concentrations from ADCP backscatter already developed in research led by Parsons, which allow quantification of suspended sediment concentration from the ADCP backscatter data collected in the canyon, and a first-order estimate of grain size variability during flow evolution.

Work Block 3: Field data processing and analysis. Archiving of the complex field data set, and logistical organisation of field data collection, will be overseen by a part-time (33% over 3 years) position at MBARI, for which we seek funding. 3-years of PDRA time (split between NOC and Hull) is needed to for analysis and synthesis of a substantial field data set. The PDRA will lead analysis of 4 sets of ADCP (3 upward and 1 downward pointing), CTD, and turbidity data from the MOOS BIN, together with temperature and salinity data from the nearby McLane Profiler (Fig. 1). The PDRA will analyse sediment samples from traps on the mooring at 1,850 m at NOC Southampton using a Laser-particle analyser. The PDRA will assist in the integration of data from BEDs, resurveying of bathymetry and monuments, and ADCP and sediment trap data from the 300 and 1,300 m sites (Table 1). They will work with Xu to integrate results from the three USGS moorings (Table 1) into this combined field data set. The PDRA's contribution whilst at Hull will be to lead the NaREC tests to calibrate backscatter response, extract data on sediment concentrations (and assess its uncertainties) from ADCP backscatter data collected in the canyon, in collaboration with Parsons. They will play a key role in synthesising, plotting and drafting figures that summarise the key aspects of the data for each monitored flow event. This will determine how STEDs constrain changes in frontal flow velocity (Question 2), what grading in ROV vibracores and sediment traps is associated with changes in velocity and concentration measured at the MOOS BIN (Question 1). The 3-year PDRA will spend 9 months hosted at MBARI, and 9 months at Hull to calibrate the ADCP backscatter data, followed by 18 months at NOC (see Fig. 3).

PROJECT MANAGEMENT: Talling will lead the NERC project, and collaborate closely with Paull, Xu and their colleagues at the MBARI and USGS through three project meetings at MBARI (Fig. 2), together with regular video conferencing. Parsons will lead calibration of ADCP backscatter data. Talling is responsible for integration of the work block results, supported by the PDRA. Data from MOOS will be archived at BODC and in the shore side data system (SSDS) at MBARI (see ODM Plan). Project results will be disseminated through two open workshops at MBARI and AGU, Talling's 2011-16 Royal Society Industry Fellowship hosted by the submarine cable sector, the UK-

TAPS Consortium of oil and gas companies, and conference presentations. Cartigny and Sumner will lead dissemination of data to numerical modellers, and the two open-workshops for modellers.

REDUCTION OF RISK: Previous work has shown that multiple events occur each year (Fig. 1b) [18-30], including at the proposed location for MOOS BIN at 1850 m (Fig. 2) [30]. This is by far the most detailed information available on flow frequency, power, and run-out distances for any submarine canyon worldwide, and substantially reduces risks that the MOOS BIN is damaged, or fails to experience flows during an 18 month period. Both the MOOS and STEDs have been extensively tested in the proposed field area, and have been shown to work well (e.g. 15 previous successful trials of the STEDs, or previous 6-month deployments of MOOS). Previous work by Parsons, Xu and others has shown how ADCP backscatter can place constraints on sediment concentration, and exploiting this technique is now timely for turbidity currents. ADCP data will be collected from four separate sites along the canyon minimising risk from failure of ADCPs at a single location, and some ADCP datasets already exist from less detailed preliminary work [30]. The allied work by MBARI and USGS will not be repeated or delayed, and it is needed to provide the context for this NERC project. There are very few (if any) other places worldwide where project partners such as MBARI and USGS can provide repeated access to ship and ROV time, and the world-class skills needed to operate them. NERC has borne none of the cost for developing the instruments ($10M in the case of MOOS), nor is it bearing the risk of losing the equipment. Turbidity currents are the volumetrically most important sediment transport process on the planet, yet we have never synchronously documented their sediment concentration and velocity in detail within the oceans, nor how their flow velocity changes along the flow path. This is a once in a generation opportunity, which will rarely (if ever) be repeated. The shiptime costs within NERC Standard Grants are commonly in excess of the amount sought here (£200k from NERC), although those costs are not typically listed explicitly in the case for support.

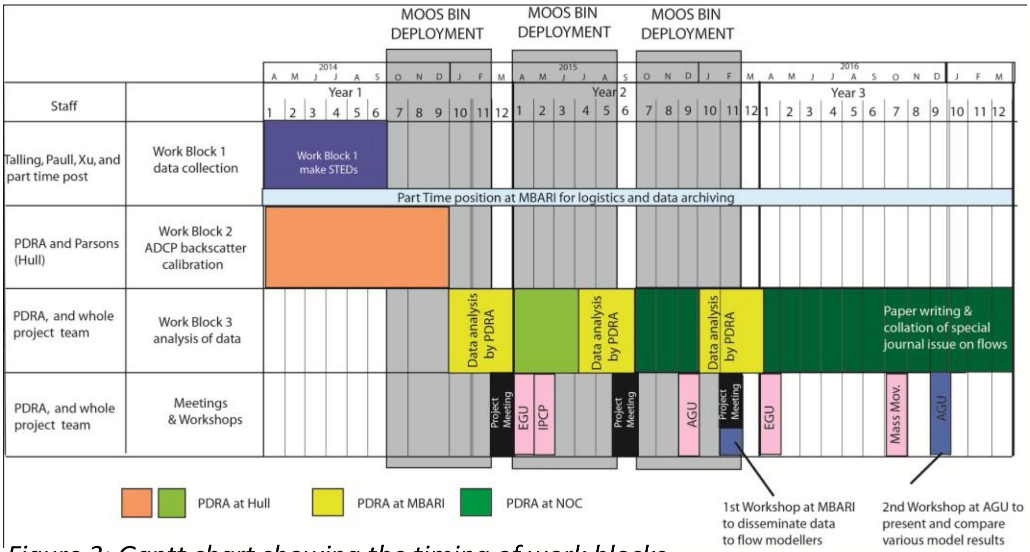


Figure 3: Gantt chart showing the timing of work blocks.

INTERACTION WITH NUMERICAL MODELLERS: This project will collect an outstanding data-set for comparison to numerical models of submarine sediment flows that can be exploited by future work. However, we do not include a component of modelling work explicitly within this proposal following advice from NERC. We agree that it is best to design this modelling after the source-to-sink dataset has been collected by NERC-MBARI-USGS, and the basic character of these flows is better constrained. We will include modellers within a project advisory group (e.g. Hogg at Bristol), and we will disseminate project results to the wider modelling community through two workshops.

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Outline Data Management Plan

Data centre	Dataset Description	release date to centre	Reuse scernarios
BODC	MOOS ADCP velocity time-series data	9 months after data recovered from MOOS	Numerical and experimental flow modellers
BODC	MOOS ADCP sediment concentration time-series data	End of project after calibration of backscatter data by WB2	Numerical and experimental flow modellers
BODC	STED triggering times series	3 months after end of STED deployment	Numerical and experimental flow modellers
BODC	MOOS CTD sensor data	9 months after data recovered from MOOS	Numerical and experimental flow modellers
BODC	MOOS turbidity meter data	9 months after data recovered from MOOS	Numerical and experimental flow modellers
BODC	Sediment grain size profile from traps	9 months after traps recovered	Numerical and experimental flow modellers

Notes

1. The complete dataset that includes both NERC funded data, and the data collected by allied work funded by MBARI and USGS will be archived in the shore side data system (SSDS) at MBARI specifically developed for delivering data from community based projects via the web [45]. This SSDS already includes encompasses the large amount of previous data collected by MBARI in Monterey Canyon, and it will be important to include the NERC funded data within the SSDS.

2. It is important that colleagues (such as flow modellers) that reuse the field data also understand the uncertainties in observational parameters, such as sediment concentration derived from ADCP backscatter. These uncertainties will need to be detailed in a metadata document attached to the raw data at BODC.

3. The project will provide an open-access international journal publication with the key integrated field observations for comparison to numerical and experimental modelling. This journal paper would include selected additional data in online supplementary material, for wider dissemination. An appendix to the paper will then advertise the location and format of the full field data held at BODC.

4. The existence and format and of the BODC dataset will also be advertised to flow modellers at the two open workshops within the project, and through conference presentations, and via a dedicated project website linked to the archived data at BODC/MBARI.