Robots in the Wild: Challenges in Deploying Robust Autonomy for Robotic Exploration

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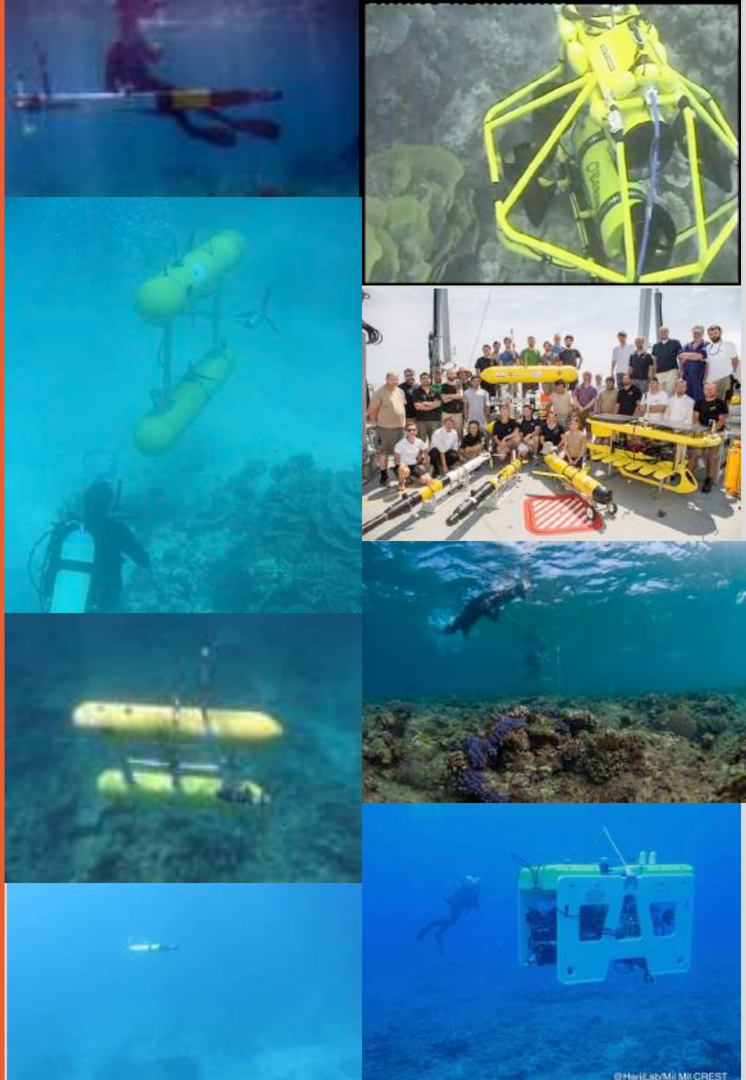
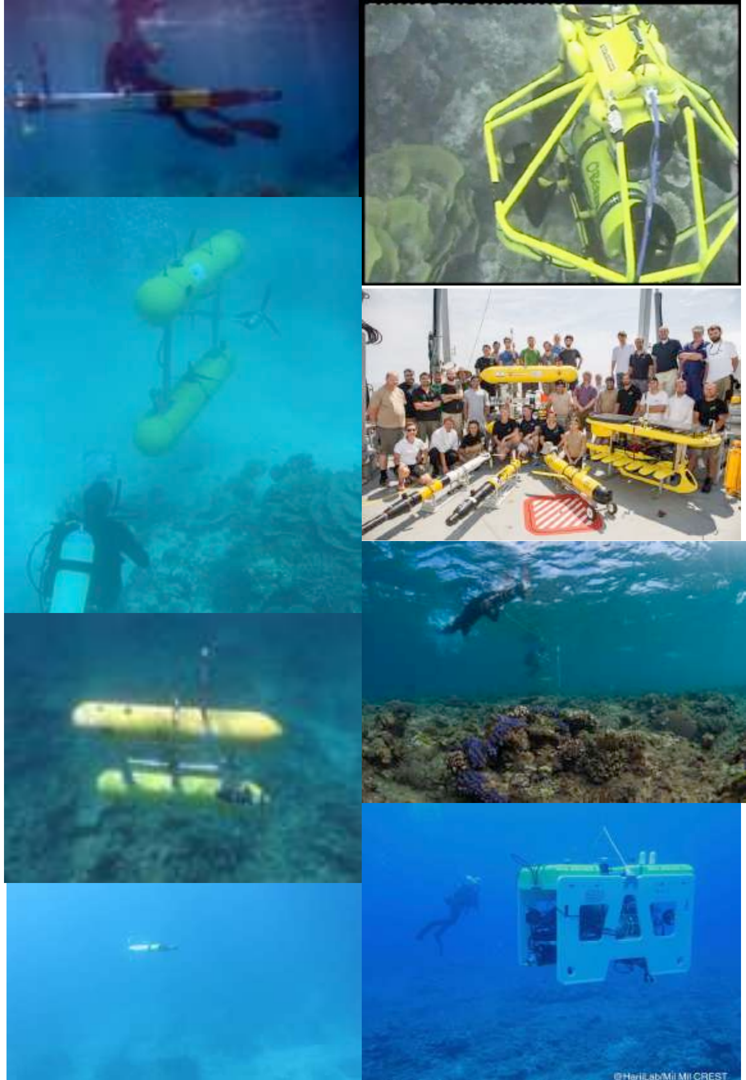


Marine robotics research at ACFR

- Main focus of research has been on
  - **Platforms and sensing:** vehicles, high-resolution stereo imaging, hyperspectral, lightfield imaging
  - **Navigation and mapping:** SLAM using both visual and acoustic data, visualization
  - **Planning and Control:** information based planning, low level control
  - **Data Analytics:** automated processing of large volumes of data, automatic registration of multi-year datasets, identification of direct change as well as distributions of organisms
  - **Applications:** Primary focus on survey to support ecology, archaeology and geoscience research
- Work with a large group of Australian and international collaborators



From Robotics to Science Outcomes

Platforms and Sensing

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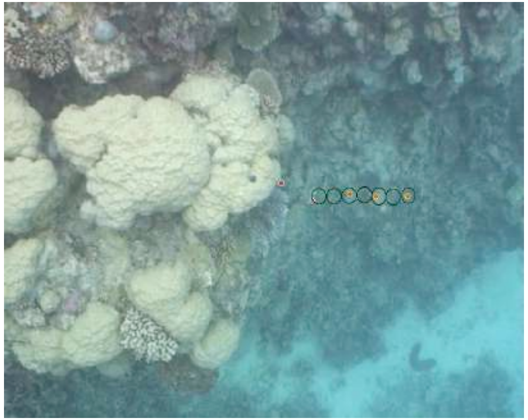
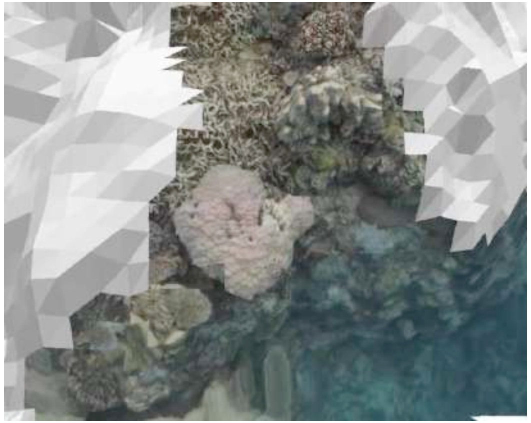
ROV Oberon on the Great Barrier Reef

- Our early work focused on the deployment of the ROV Oberon on the Great Barrier Reef
- The vehicle carried a 3CCD video camera and mechanically scanning sonar with an overlapping field of view
- Demonstrated how SLAM could be achieved by fusing this data to build 3D terrain models



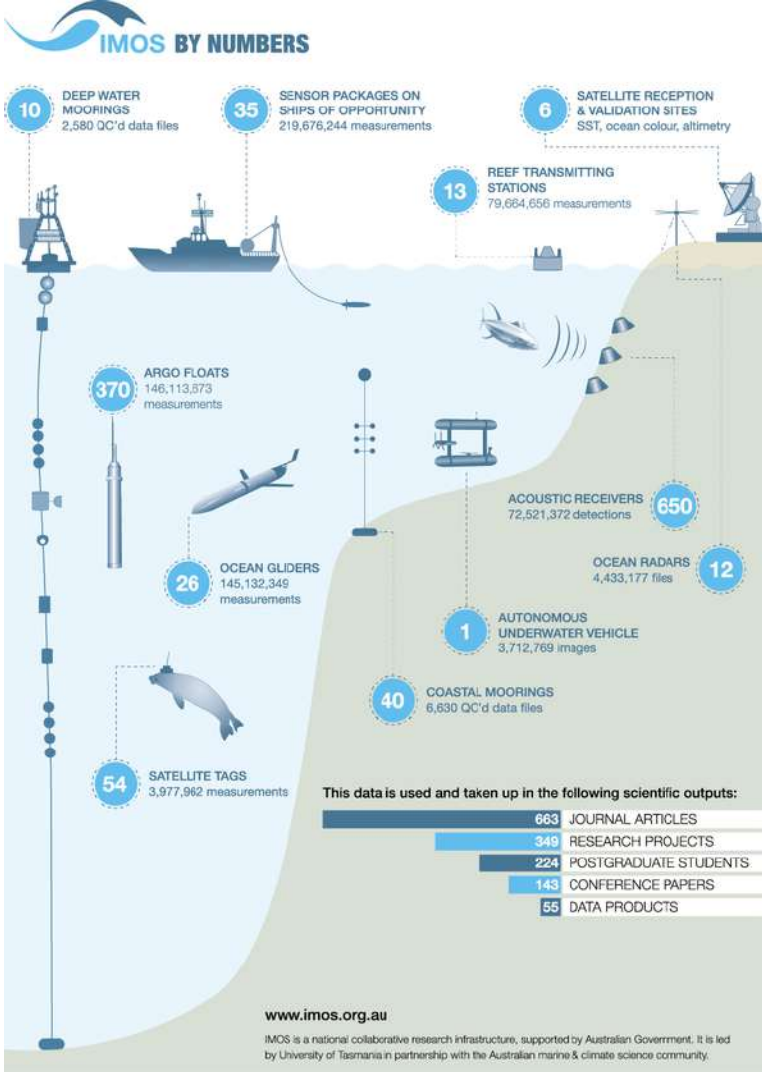


S.B. Williams and I.Mahon, '**Simultaneous Localisation and Mapping on the Great Barrier Reef**', *Proceedings of the IEEE International Conference on Robotics and Automation*, Vol. 2, pages 1771 - 1776, 2004

AUV SIRIUS

Integrated Marine Observing System

- NCRIS is a program designed to provide infrastructure to support national research priorities
- Marine Science designated as one of 8 priority programs
- A $180M program to provide infrastructure to support the marine sciences in Australia (2007-2018)
- Recently announced $1.9B investment in NCRIS over twelve years as part of Australian government's Innovation Agenda



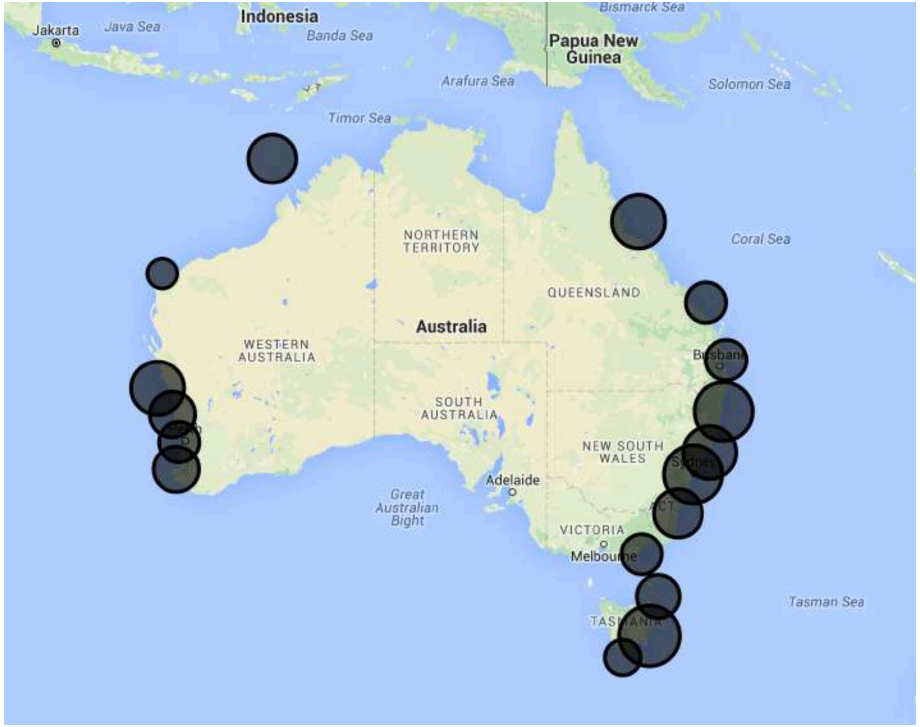
Key ecological features

- Identification of 31 Key Ecological Features (KEFs) nationally
- IMOS observations contributing to long term monitoring and establishment of a national representative system of marine reserves
- Selecting what variables to monitor and where is a key focus of the NERP Hub
- Significant relevance to Australian Government's program of marine bioregional planning

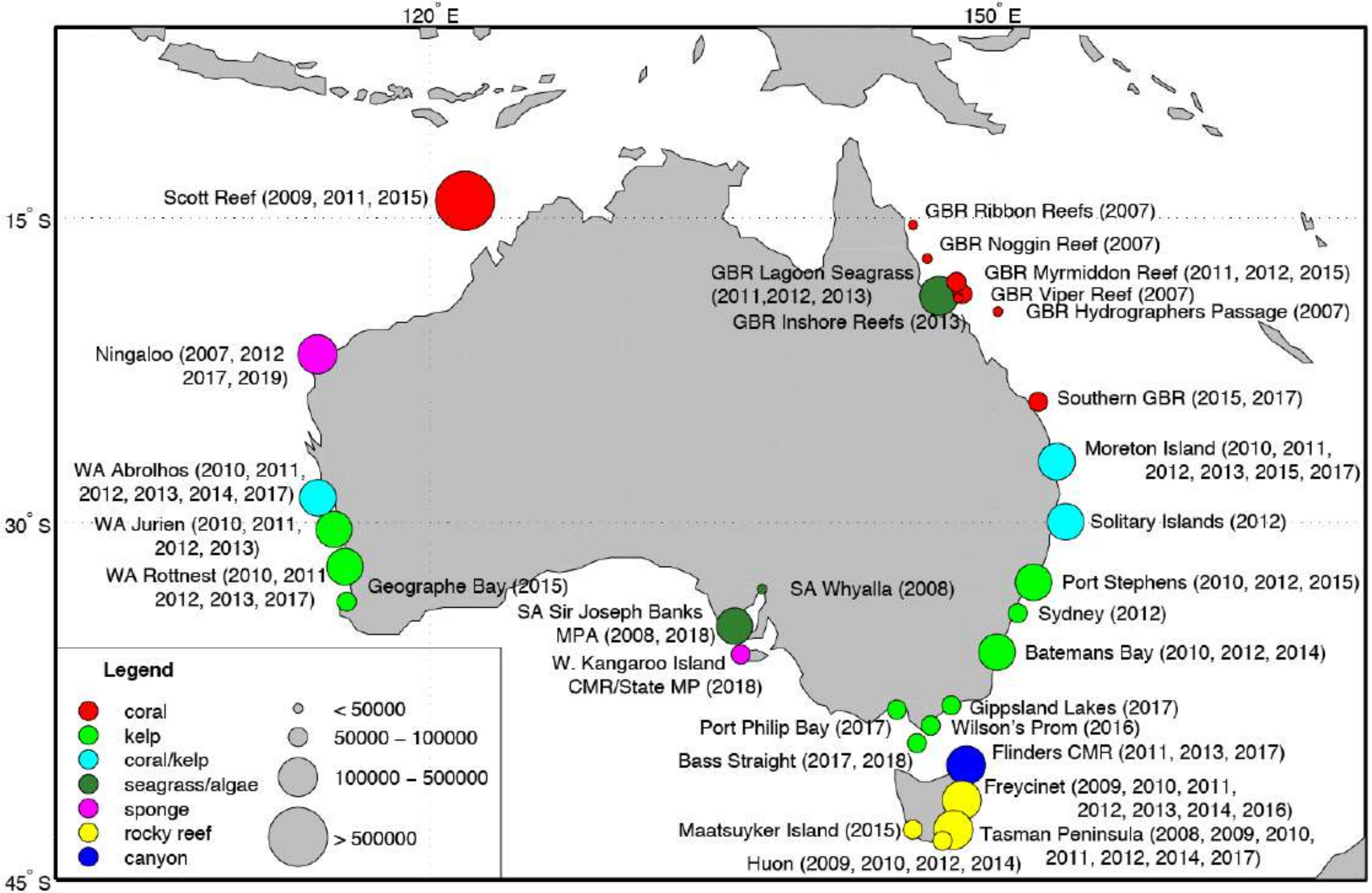
Figure 1.2: Key ecological features (KEFs) identified by DSEWPaC for which qualitative models were developed and analysed to identify ecological indicators for Australia's marine regions. KEFs are depicted in approximate spatial extent and form only. KEFs in each region are in a different monochromatic colour scheme, and numbers refer to KEF names listed in Table 1.1; KEF number 25 (Norfolk Ridge) is located in Commonwealth waters off-map to the east.

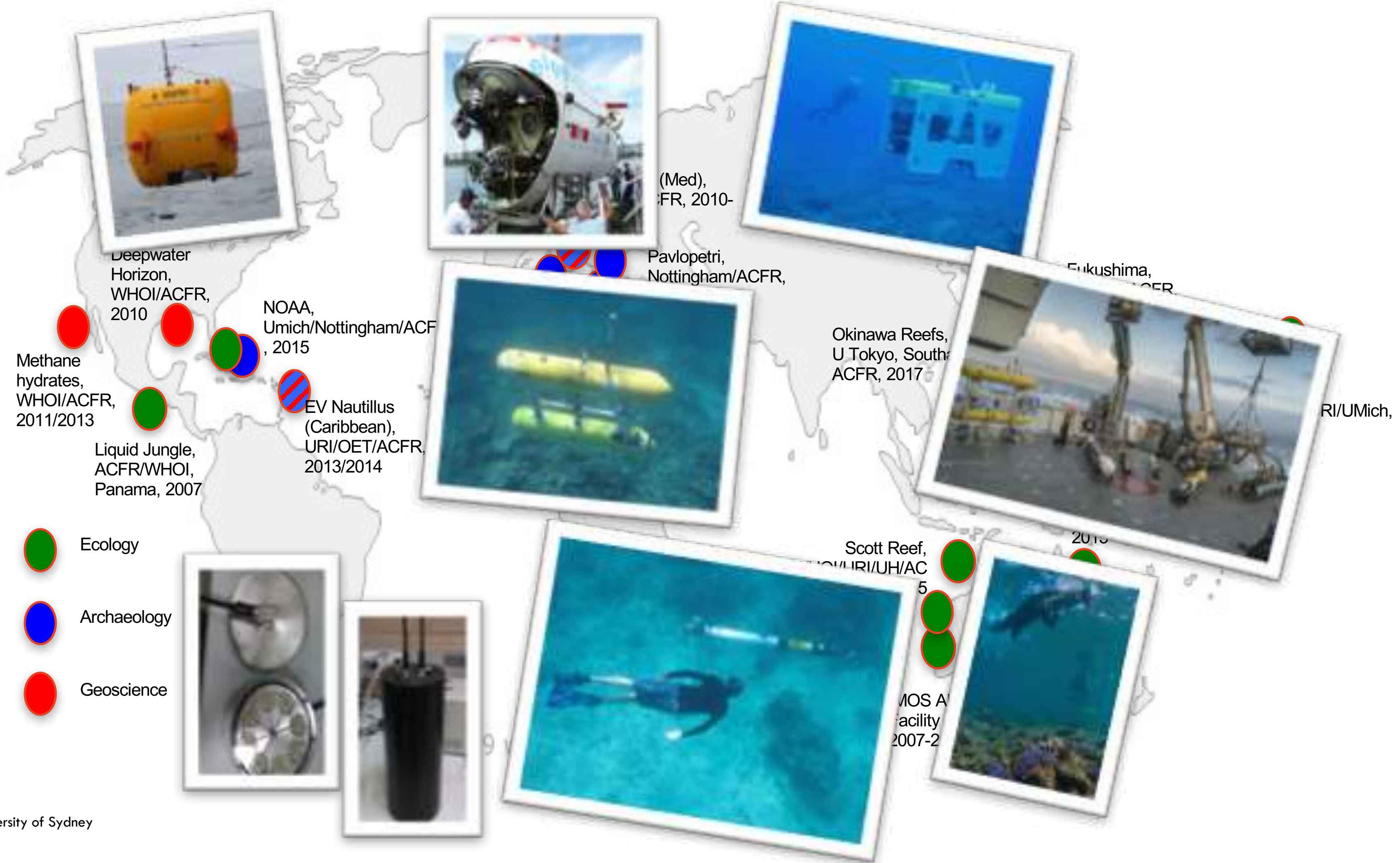
Integrated Benthic Monitoring Facility Objectives

- National perspective
  - Long term monitoring of deepwater (20 – 200 m) reefs
  - Monitoring of major habitat forming species around Australia
  - Interpreting dynamics of benthic reef systems in the context of biophysical coupling
  - Strong engagement with node science, particularly in temperate Australia along the East and West coasts
- Review of program in 2016 to clarify distinction between facility and user group



IMOS AUV Facility – Archive of 5M seafloor images available online




Deepwater Horizon, WHOI/ACFR, 2010
Methane hydrates, WHOI/ACFR, 2011/2013
Liquid Jungle, ACFR/WHOI, Panama, 2007
NOAA, Umich/Nottingham/ACF , 2015
EV Nautillus (Caribbean), URI/OET/ACFR, 2013/2014
(Med), FR, 2010-
Pavlopetri, Nottingham/ACFR,
Okinawa Reefs, U Tokyo, South ACFR, 2017
Fukushima,
RI/UMich,
Scott Reef,
Ecology
Archaeology
Geoscience

Navigation and Mapping

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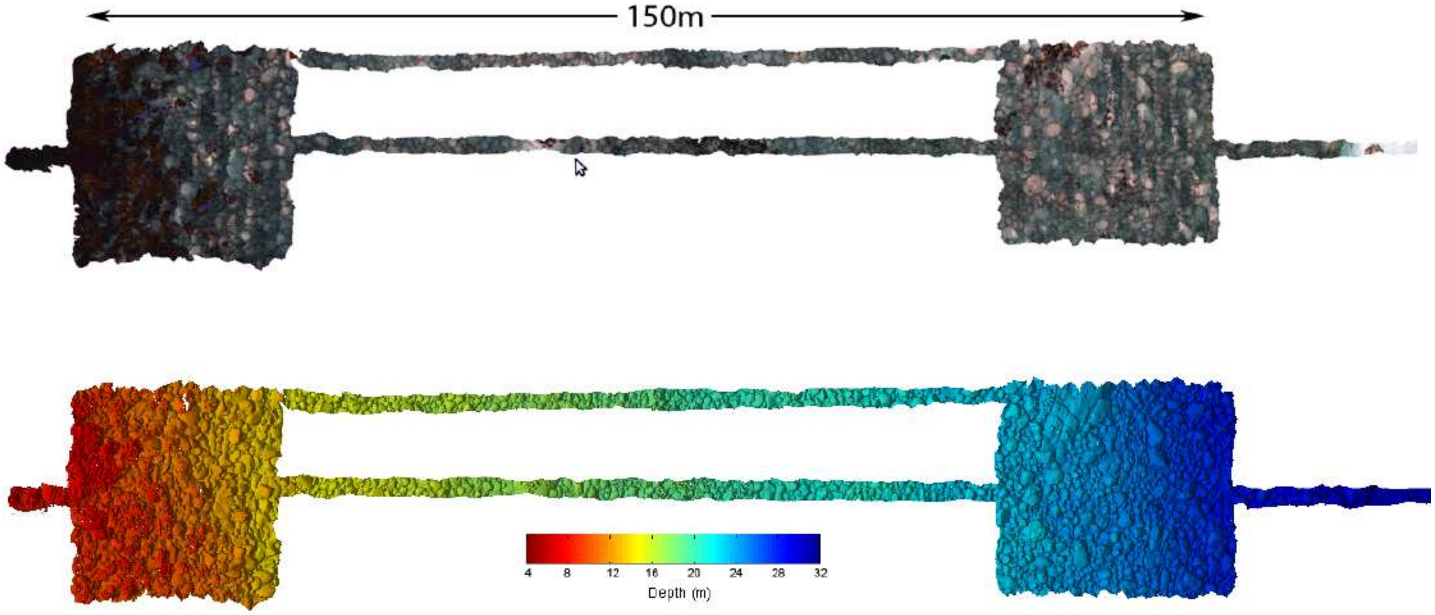
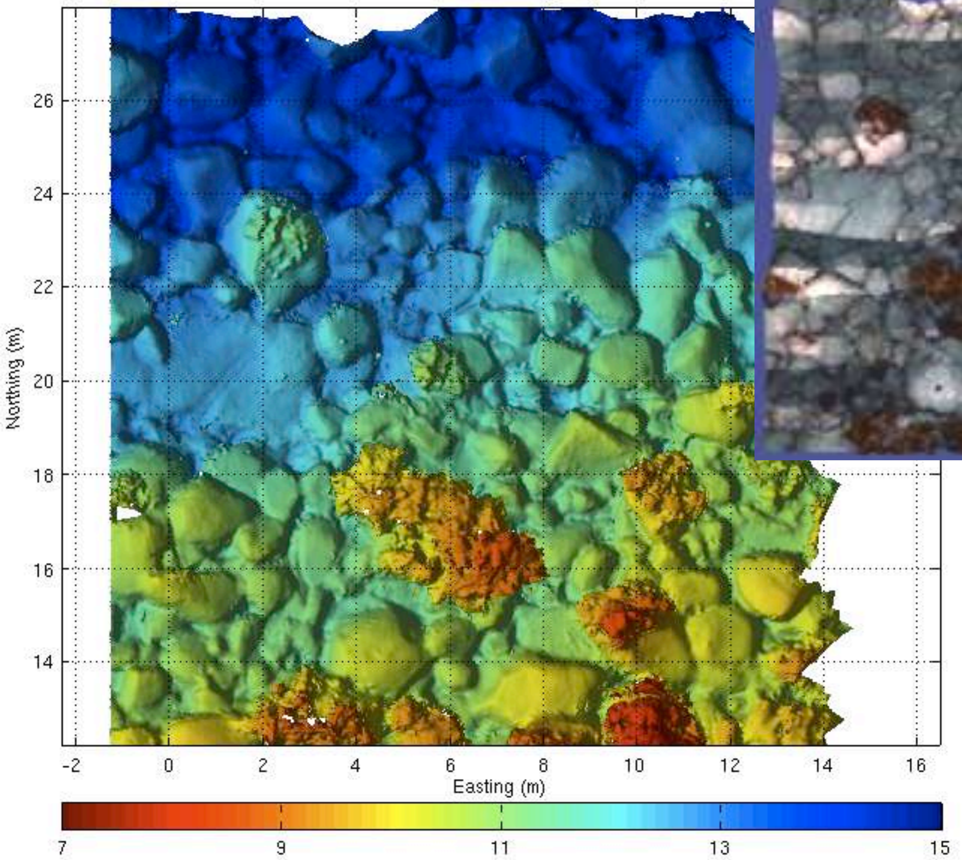
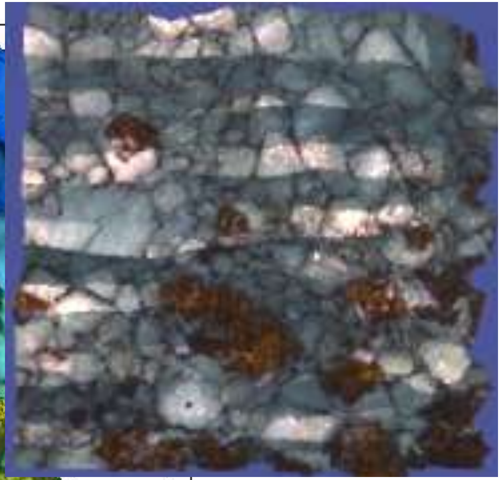
Bathymetry from Stereo

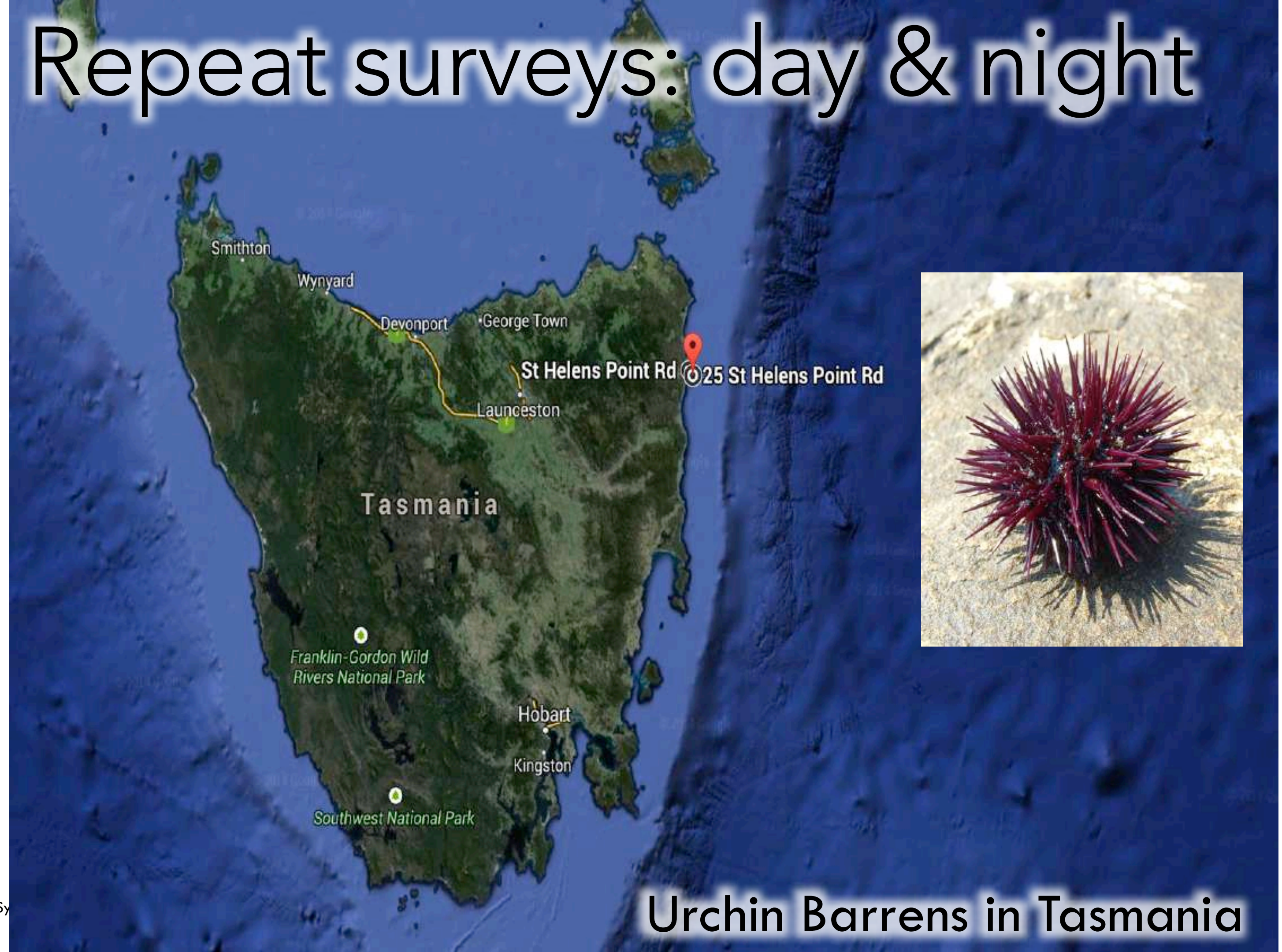


Bathymetry from Stereo

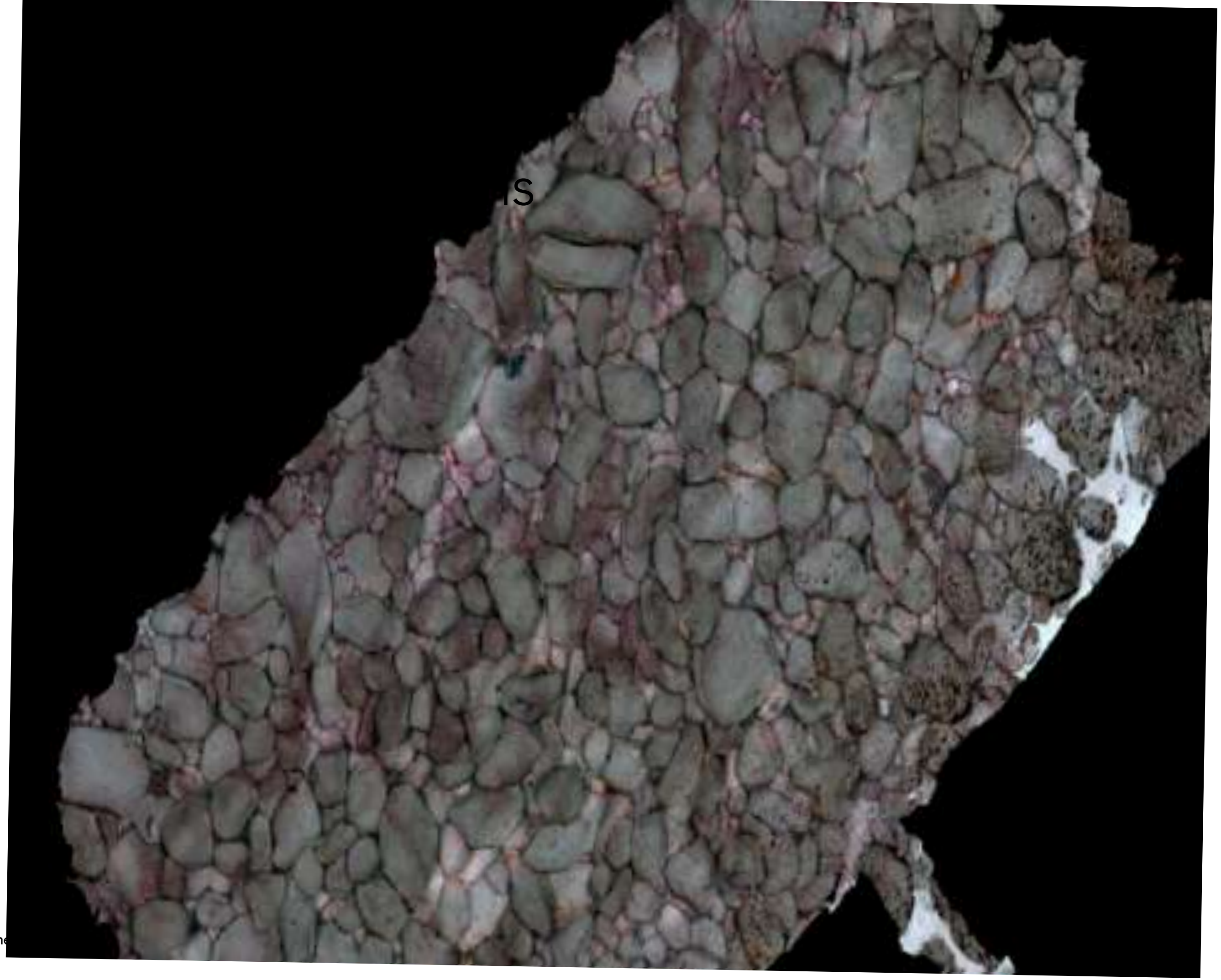




Repeat surveys: day & night

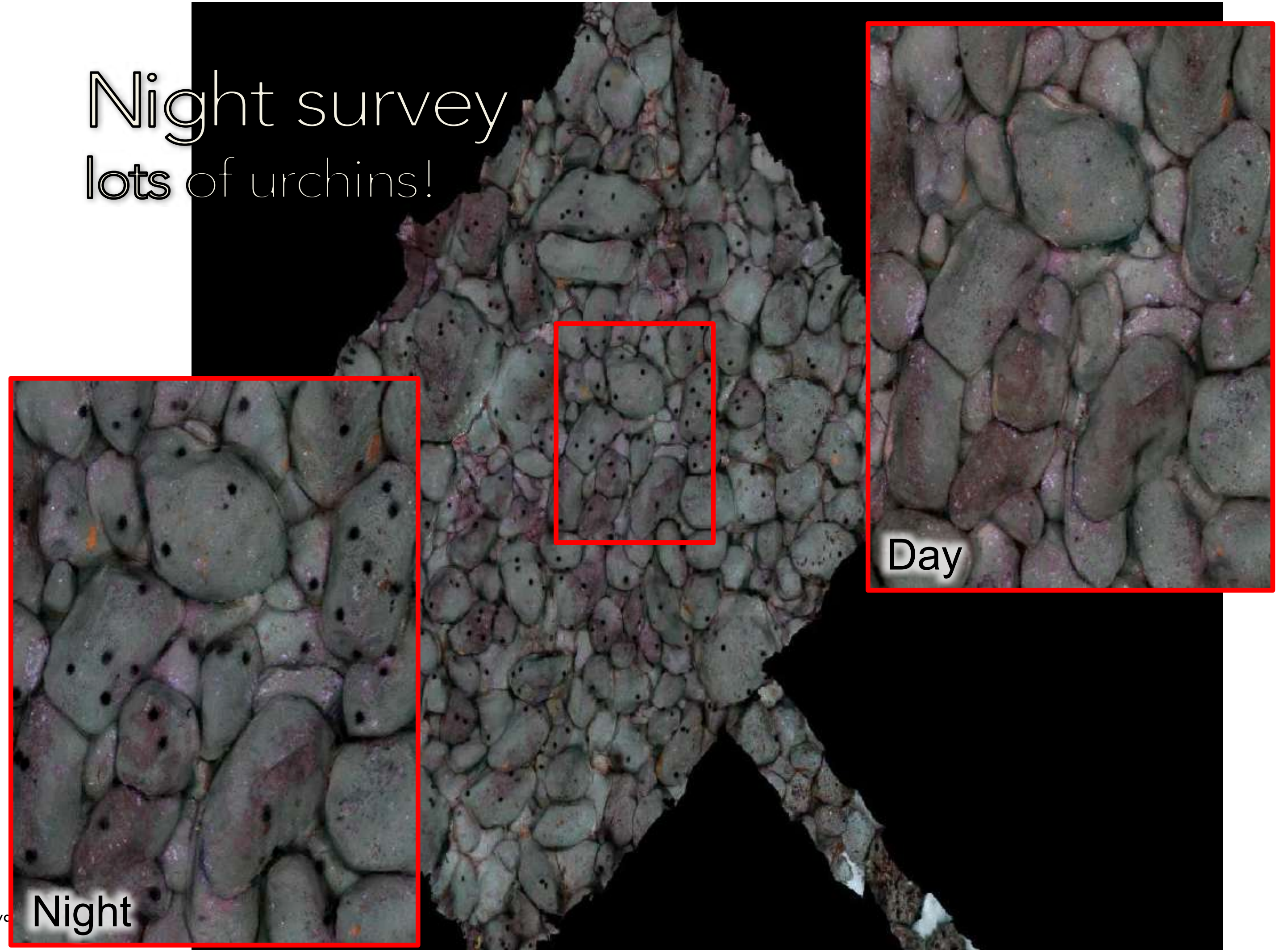


Urchin Barrens in Tasmania

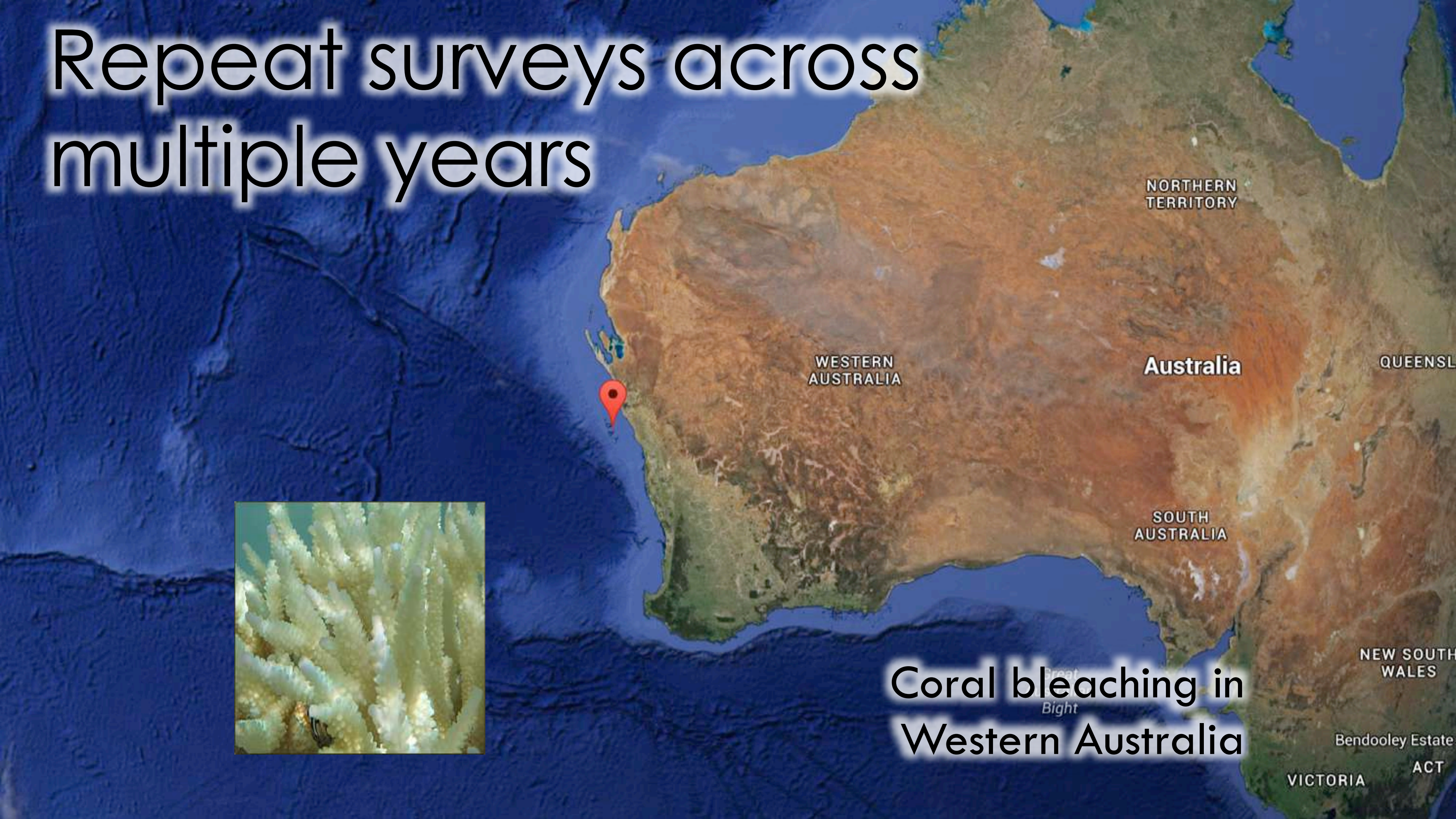


Night survey

lots of urchins!

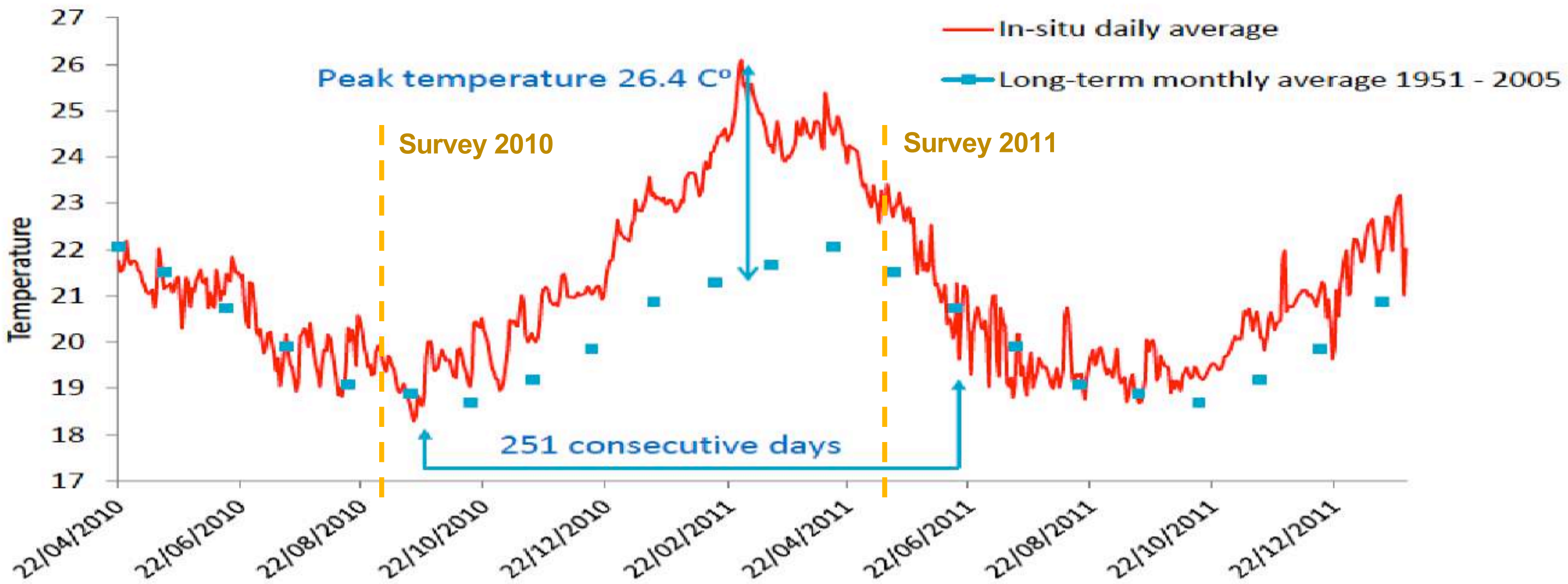


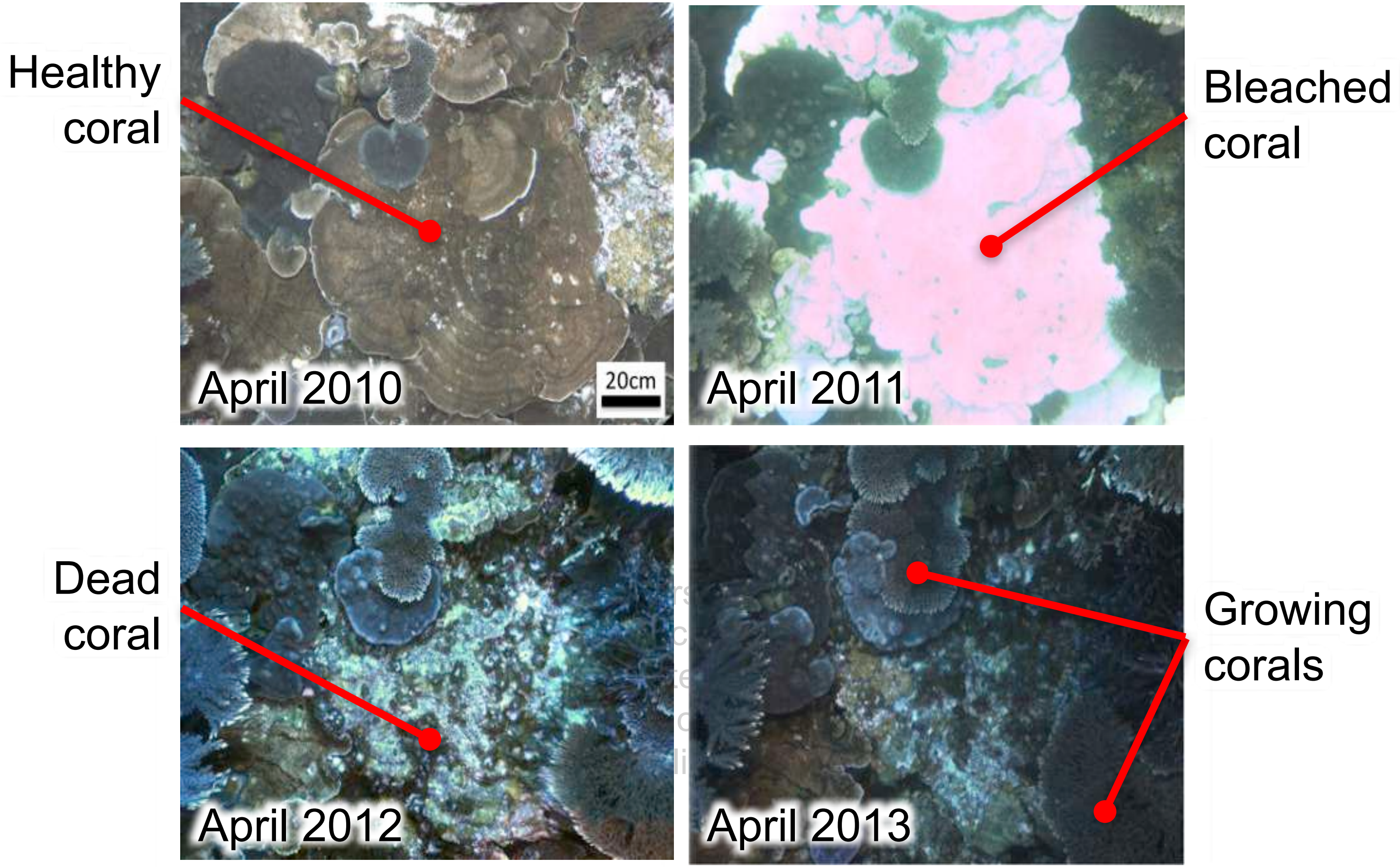
Repeat surveys across multiple years



Coral bleaching in Western Australia

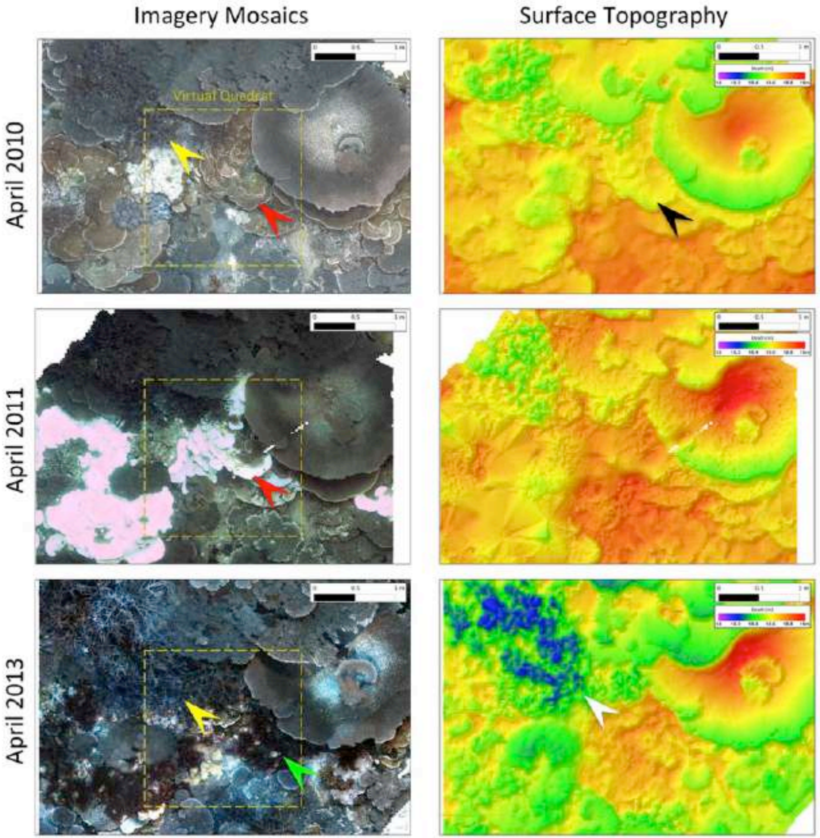
Western Australia – Heat Wave




Healthy coral
April 2010
20cm
April 2011
Bleached coral
Dead coral
April 2012
April 2013
Growing corals

Registering multi-year datasets

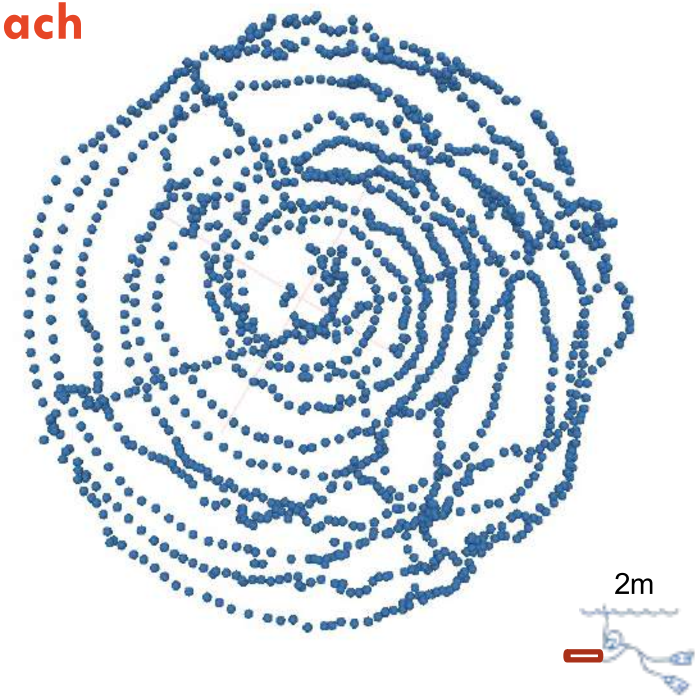
- Now examining detailed changes in structural complexity across plots
- Some areas show decreases in complexity due to mortality
- Others are increasing in complexity as branching corals begin to grow



Recovery of cyclone impacted reefs

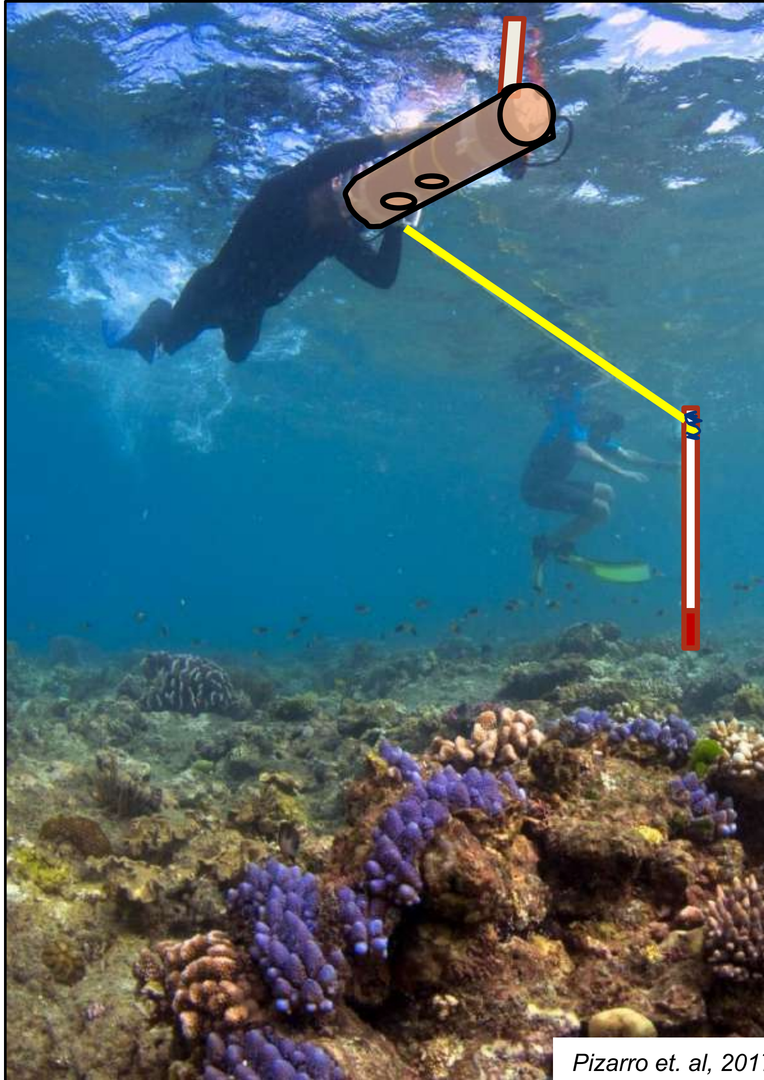
- Comprehensive surveys of reefs immediately following cyclone Ita in 2014, with some sites also surveyed prior to impact
- 7 days, 21 ‘reef records’
- Revisited these sites six months later and annual surveys to document recovery
- Lizard Island hit by another cyclone in 2015

Approach

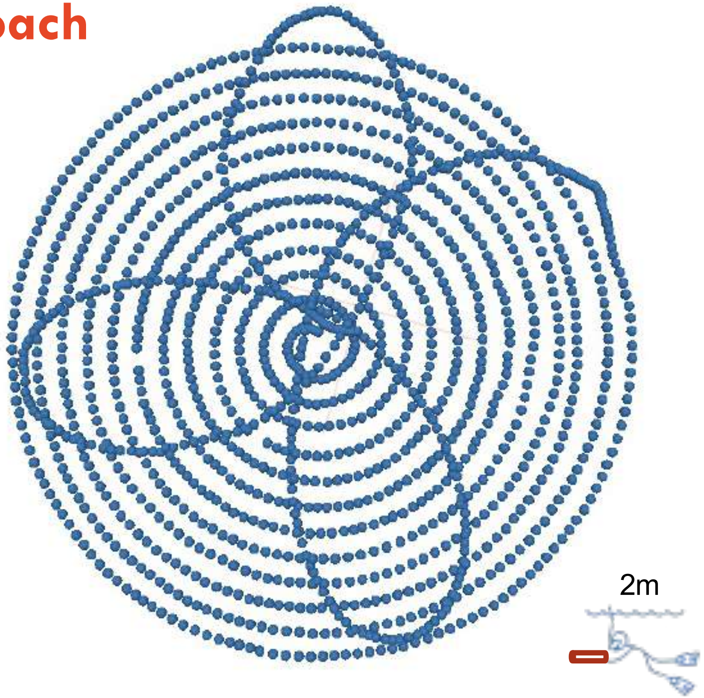


Habitat: Shallow water coral reef

Depth:	2m
Num of photos:	1,800
Image footprint:	2 m^2
Image overlap:	60 – 80%
Area coverage:	130 m^2
Time:	15 min



Approach



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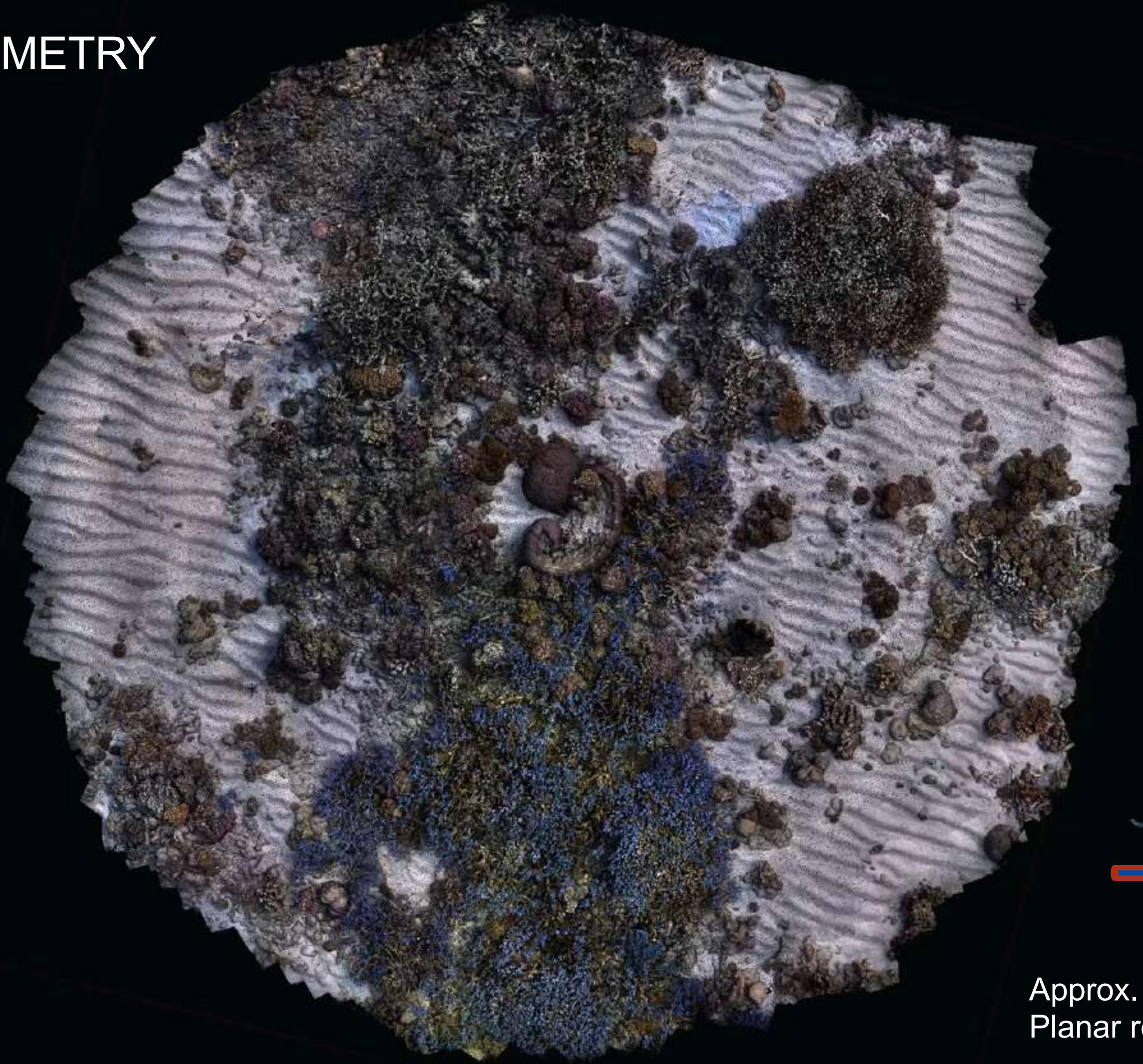
Time: 15 min

Pizarro et. al, 201

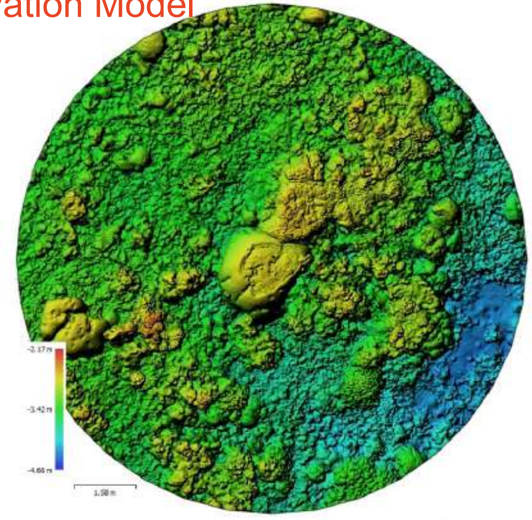
PHOTOGRAMMETRY



Approx. area = 130 m^2
Planar resolution = 4mm

Image Mosaic

Digital Elevation Model



The Universi

Reef Records: Spatial & Temporal Data Layers

Cyclone Ita

2014

T1 Apr

T2 Oct

Cyclone Nathan

2015

T3 May

T4 Dec

Severe Bleaching

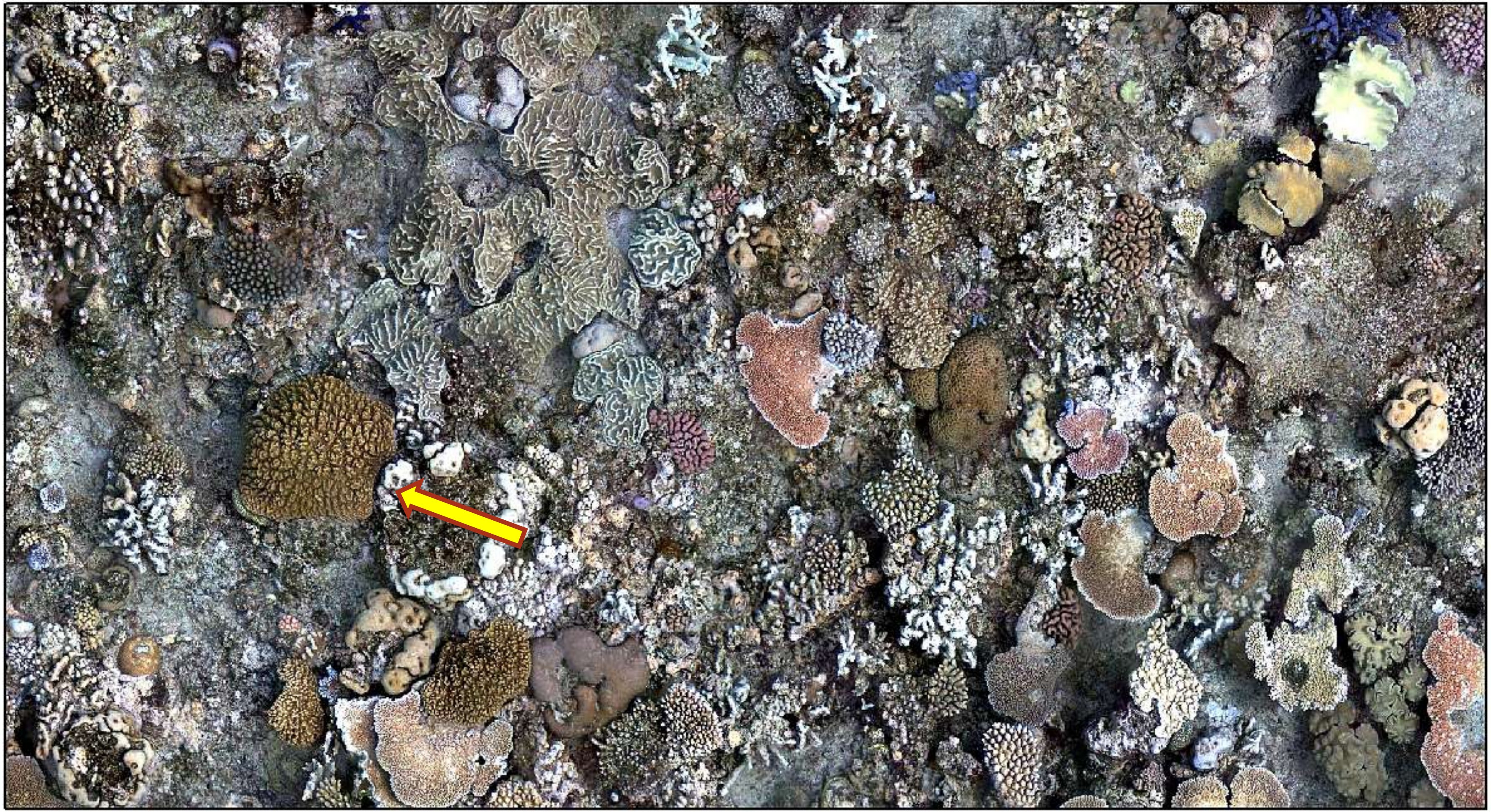
2016

T5 Nov

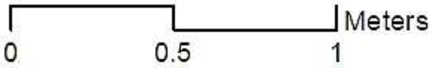
Mass Bleaching

2017

T6 Nov



2014

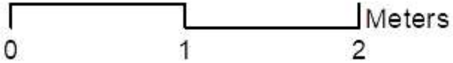


2015

2016

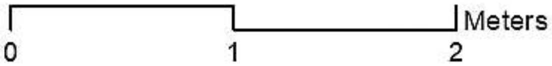
2014

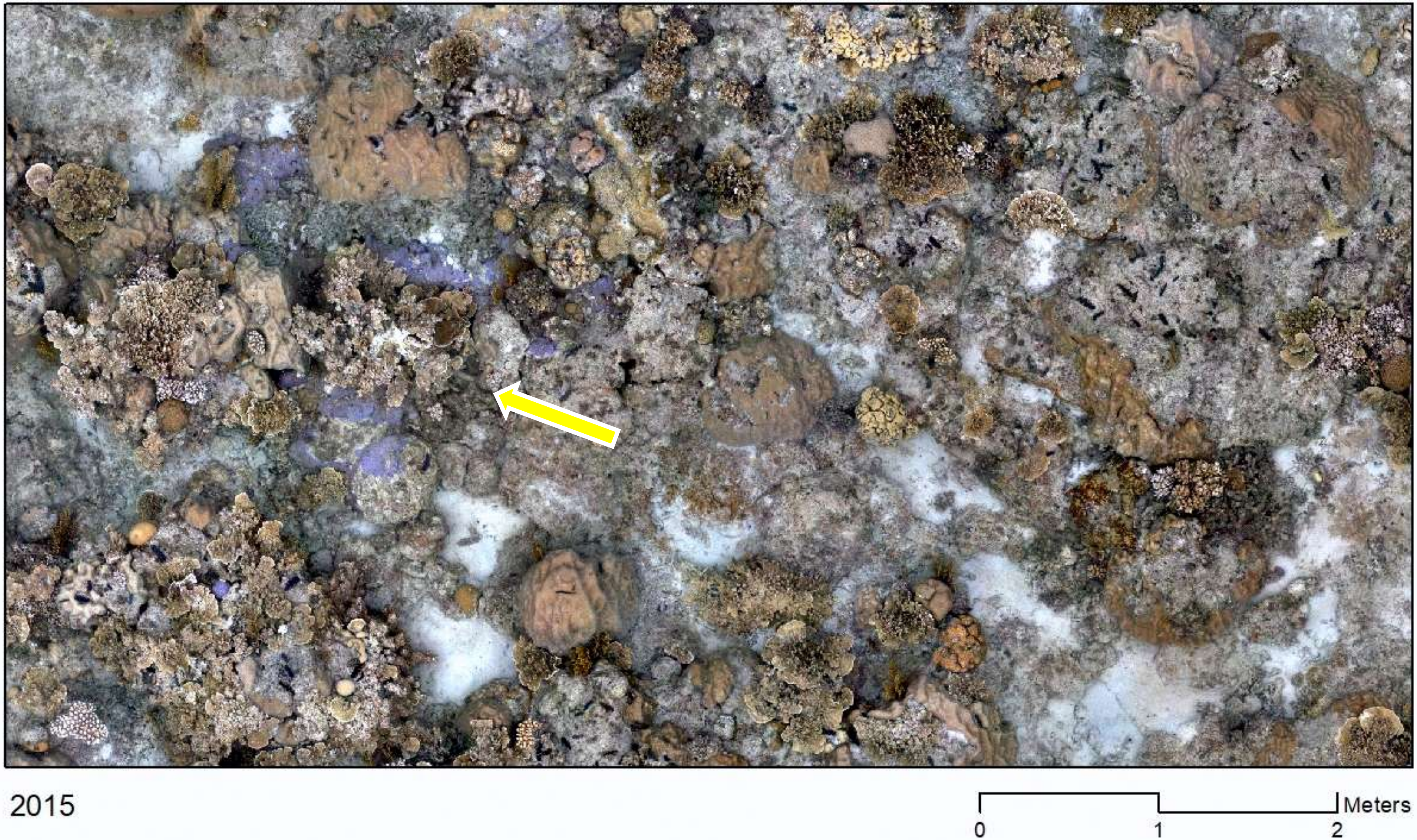
2015



2016

2014

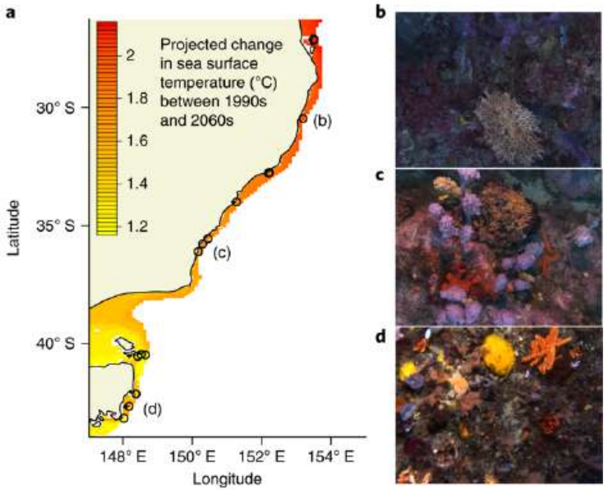



2015
0
1
2
Meters

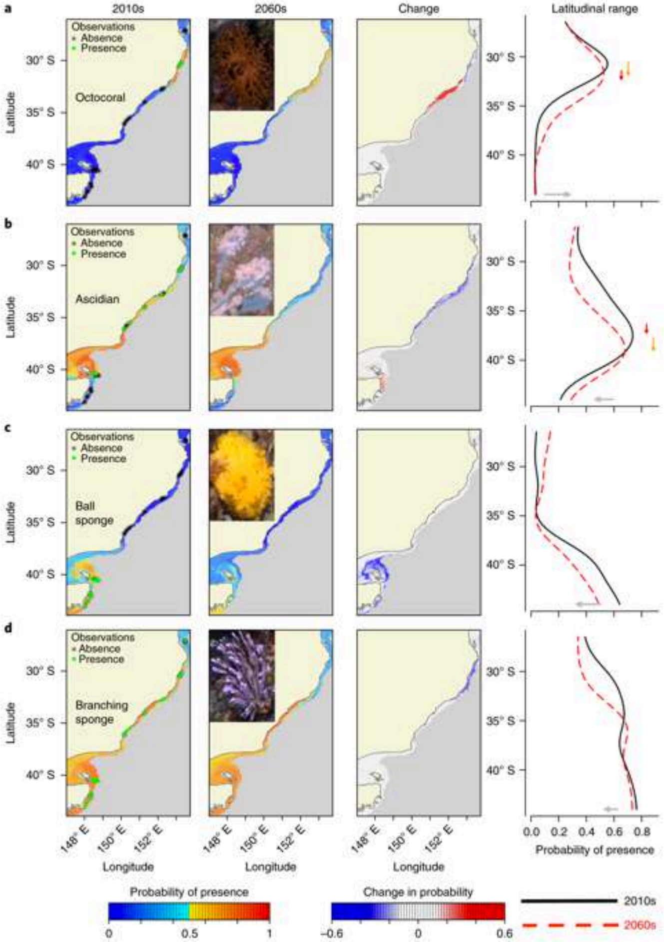
2017

Predicting Climate Change Impacts

- Effects of climate-driven ocean change on reef habitat-forming species are diverse
- Related change in community composition on *deep* reefs (30–90 m) across a latitudinal gradient (25–45°S) in southeastern Australia to high-resolution environmental and oceanographic data
- Predicted future changes using downscaled climate change projections for the 2060s
- Models show an overall tropicalization trend in these deep temperate reef communities



MP Marzloff, ECJ Oliver, NS Barrett, NJ Holbrook, L James, SJ Wotherspoon and CR Johnson, 'Differential vulnerability to climate change yields novel deep-reef communities', *Nature Climate Change*, Volume 8, pages873–878 (2018)



Planning and Control

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Coordinated Robotics

- Maui and Big Island, Hawaii in Jan/Feb 2018
  - Schmidt Ocean Institute, WHOI, MIT, URI, U Michigan
- Coordinate multiple vehicles across multi-day campaigns.
- Adapt models and selection of science opportunities as observations are made.
- Manage risk, while maximizing resource usage and opportunities.
- (Following slides courtesy of Brian Williams, MIT)

Logistics of Multivehicle Operations

Glider (WHOI)

Logitics (All)

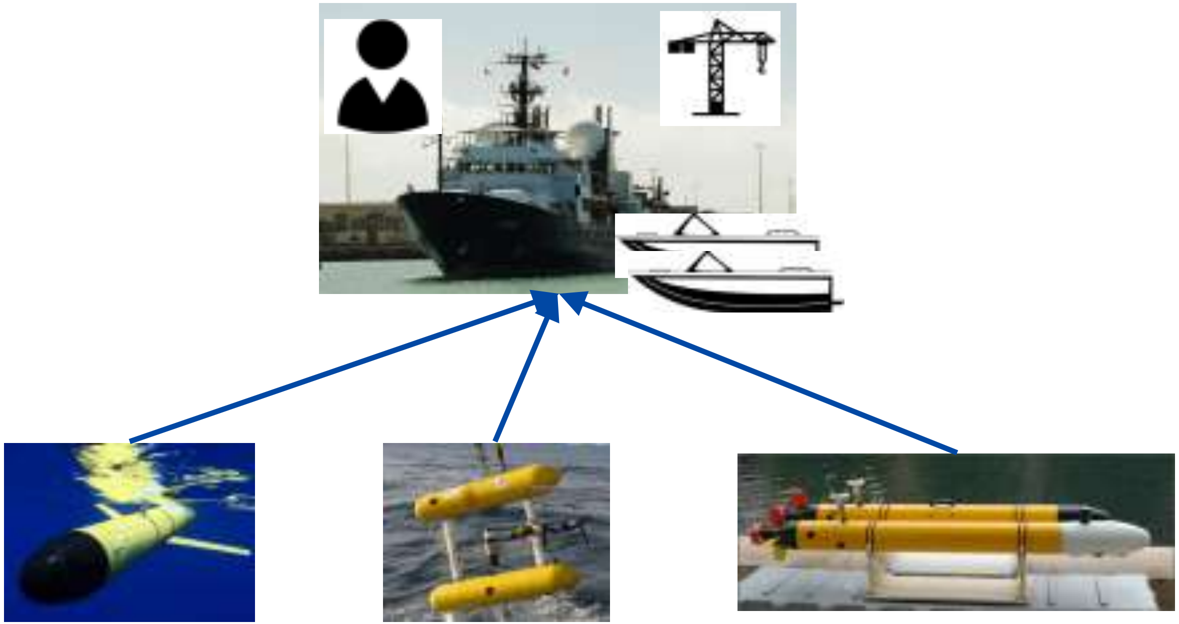
AUVs (Umich/Usyd)

Imaging Float (URI)

USV (USyd)

Everyday scenario: morning, Captain and Science team meet to elicit constraints and construct plan

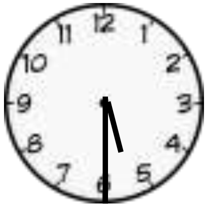
7 a.m.
Planning...



Slocum Glider

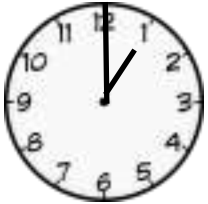
Sirius

Umich Iver

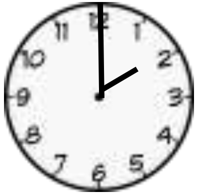


5:30 p.m.
Dinner

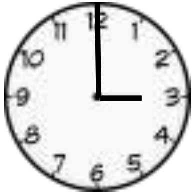
Everyday scenario: during the day, execution inevitably goes wrong...



1:00 p.m.
Execution..
.

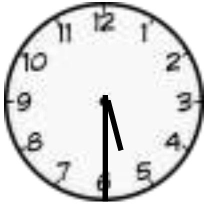


I lost
radio
signal...



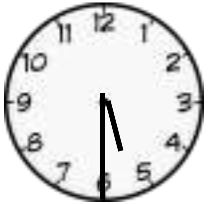
A whale is in
the ship's
way...

We're still
waiting...



5:30 p.m.
Dinner

Everyday scenario: towards the end of day, there are many negotiations between the teams...

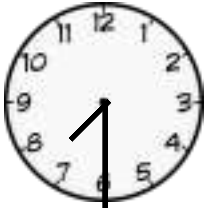


5:30 p.m.
Negotiation...

Can you shorten your mission from 90 minutes to 1 hour?

Can we push off the mission and recover your vehicle after dinner?

Can we use the emergency boat to recover the glider?



7:30 p.m.
Delay in missions

Risk Aware Planning Tools

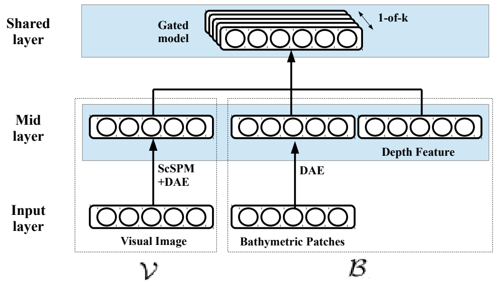
- Helps elicit each sub-team's options and preferences.
- Negotiate conflicting goals between teams, and suggests adjustments.
- Monitors mission and environment, and proactively alerts relevant team members, while considering delays in communication and taking action.

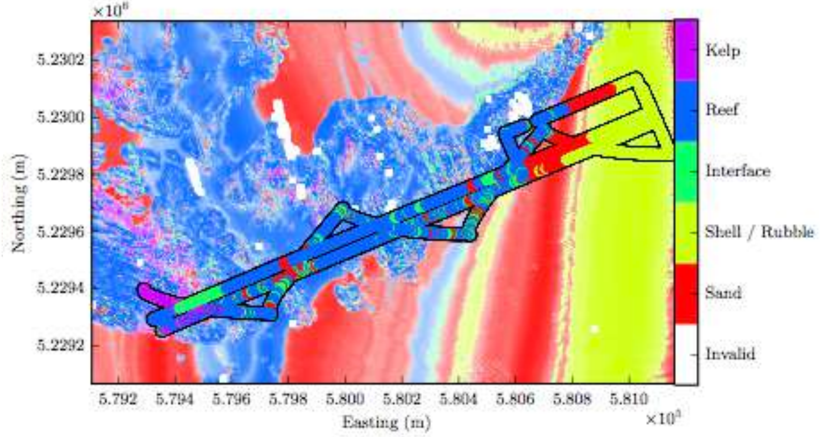
Inputting the problem in scheduler

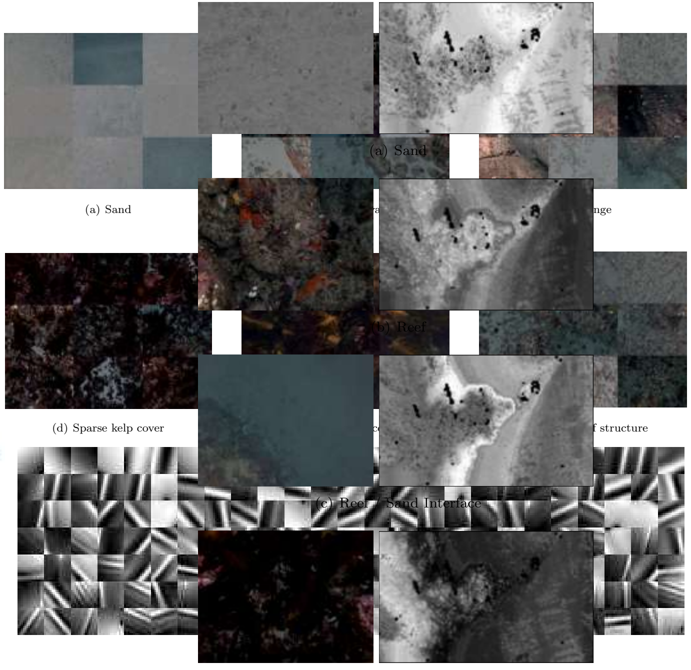
Feasible schedule in Gantt Chart

Probabilistic Habitat Modeling

- Multimodal learning and inference from visual and multibeam data
- Deep learning framework to learn joint relationships between multibeam and visual data

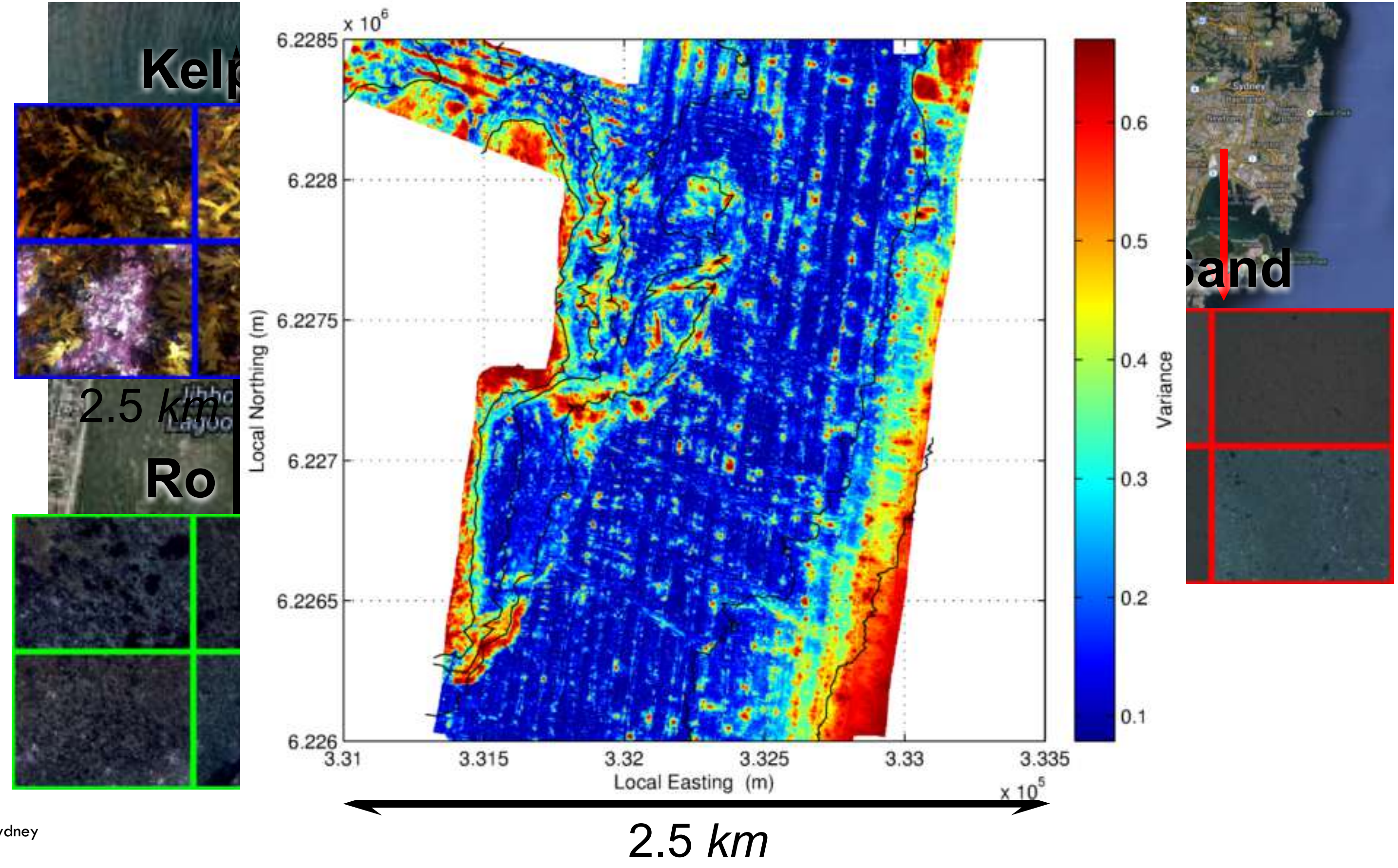






(d) Kelp

Bayesian Experimental Design

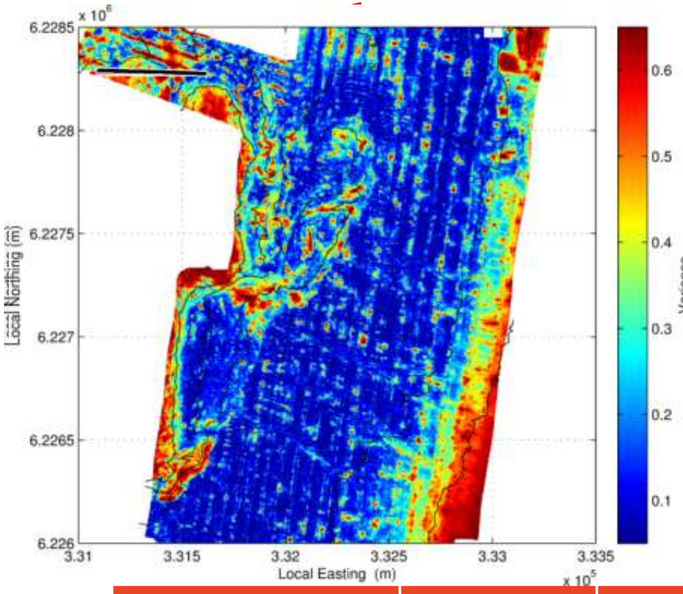


Bayesian Experimental Design

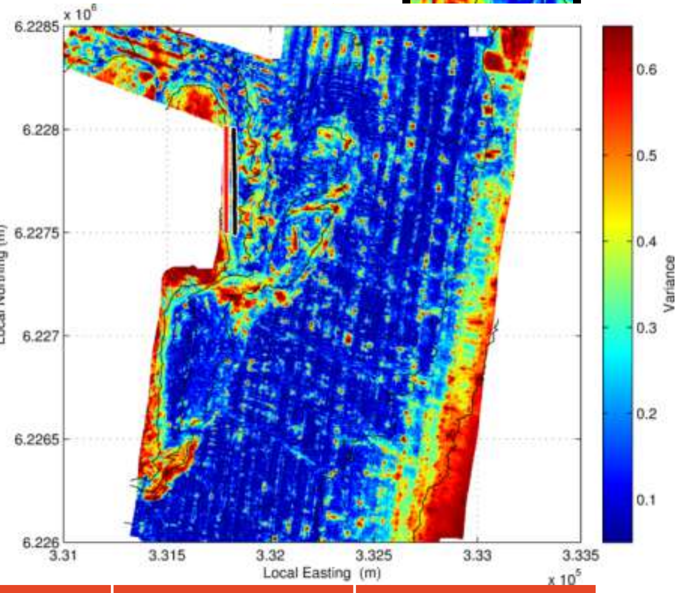
Planned Survey

Performed Survey

0.2541



0.2452



West-East	0.2541	0.2583	0.2601	0.3672
South-North	0.2452	0.2533	0.2488	0.2738

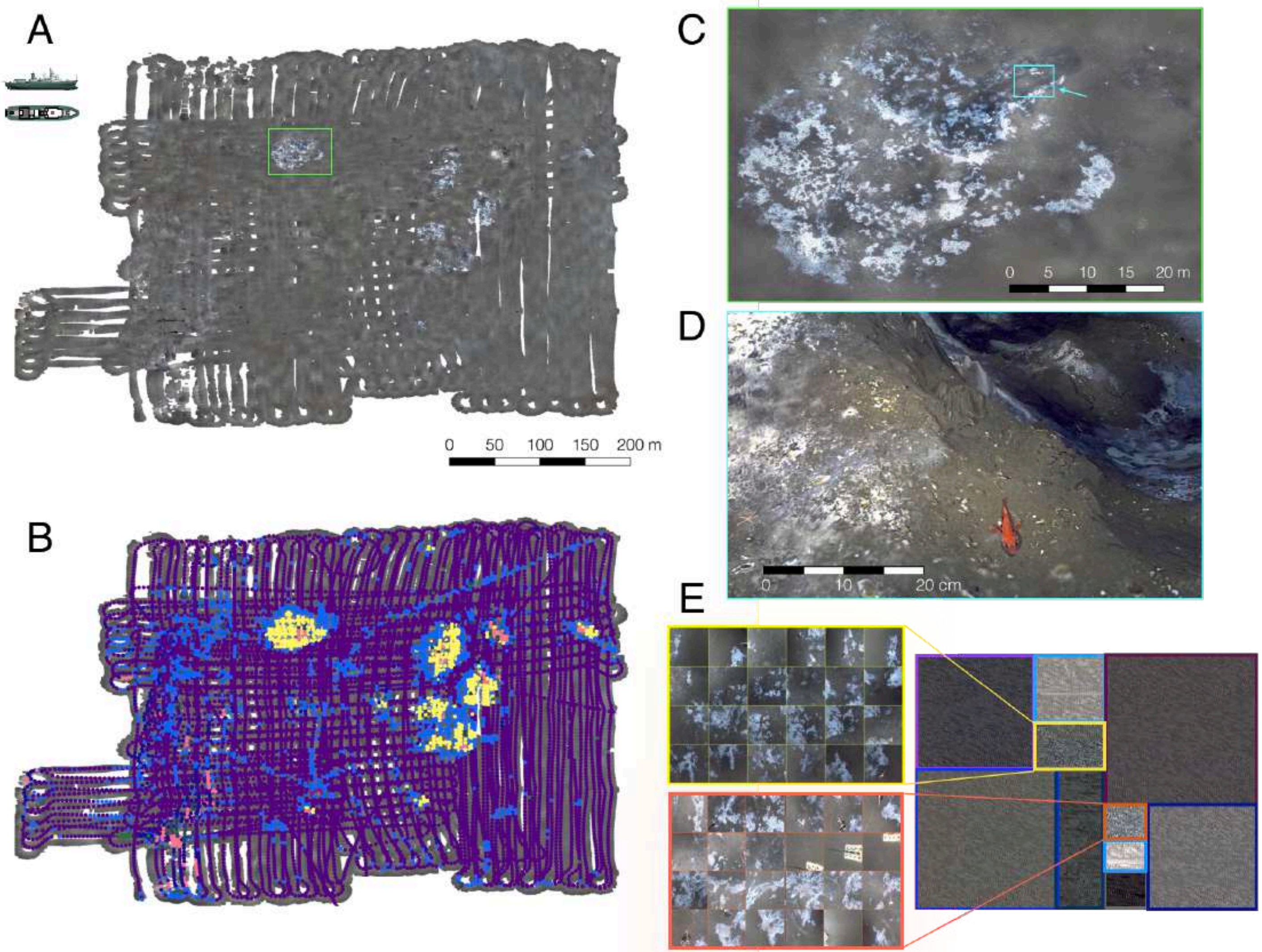
ADAPTIVE ROBOTICS AT BARKLEY CANYON AND HYDRATE RIDGE

- Schmidt Ocean Institute cruise with University of Southampton and University of Tokyo to Barkley Canyon and Hydrate Ridge
- Objective to close loop on data collection
- Processing of high resolution imagery in the field to inform low altitude imaging

SCHMIDT OCEAN INSTITUTE

UNIVERSITY OF Southampton

東京大学 THE UNIVERSITY OF TOKYO



SCHMIDT OCEAN INSTITUTE

UNIVERSITY OF Southampton

東京大学 THE UNIVERSITY OF TOKYO

The University of Sydney

Key Challenges with Planning

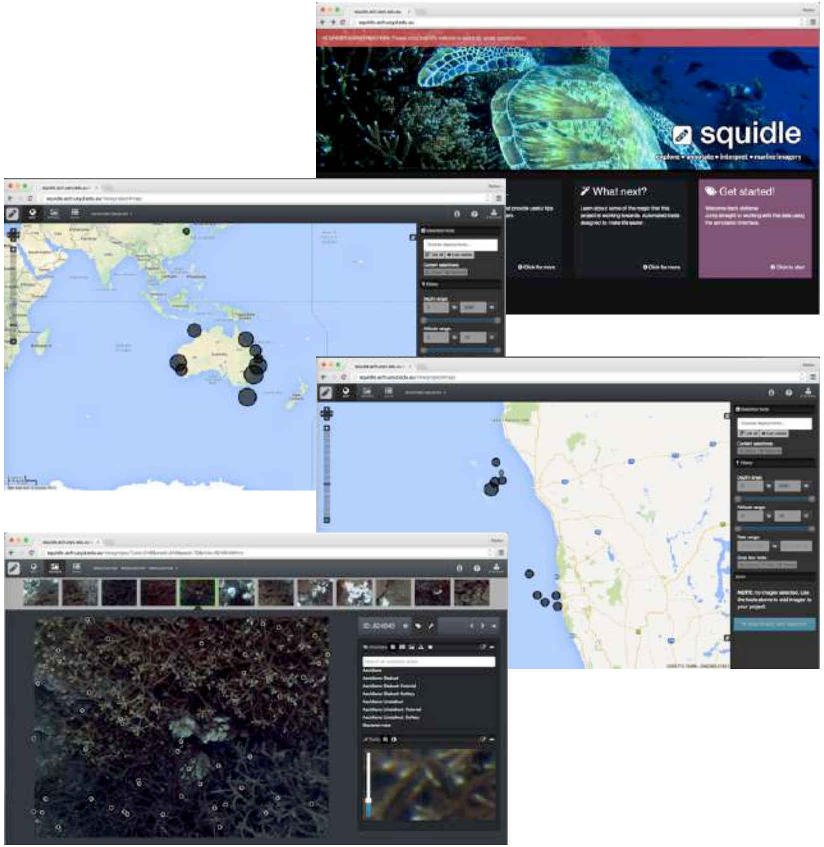
- High uncertainty in planning in the real world
  - Weather
  - Bathymetry
  - Currents
  - Vehicle Performance
  - Other vessels and unexpected events
- Often don't have access to an informative prior
  - Bathymetric data may be available but not always
  - Very little benthic imagery to help bootstrap planning process
- Difficulty in framing problem at a suitable level of abstraction
- Often faced with a poorly defined objective function
- Jointly planning over vehicle dives and ship locations is very high dimensional
- Lengthy process of setting up the planning problem relative to operational tempo

Data Analytics

Managing marine image data

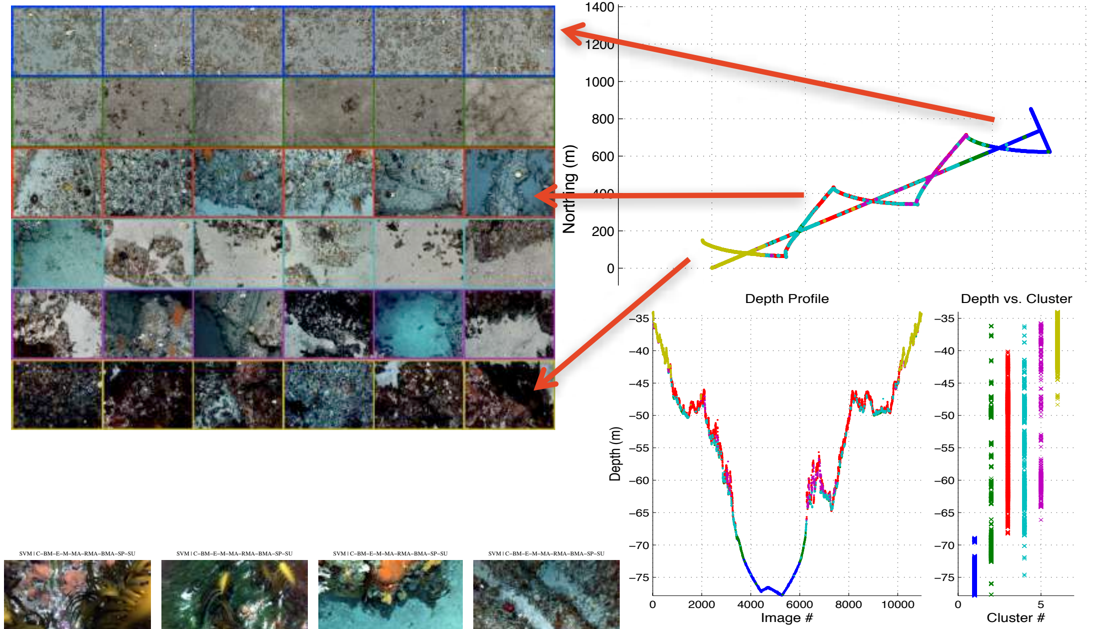
- Large, and growing, repository of online image data
  - Individual dives consist of 10-80k stereo pairs
- Detailed analysis conducted by end users is laborious
  - Require more efficient tools to manage datasets
- Identifying patterns in the data can help to guide analysis towards habitats or organisms of interest
  - Automated clustering and classification may help manage these datastreams

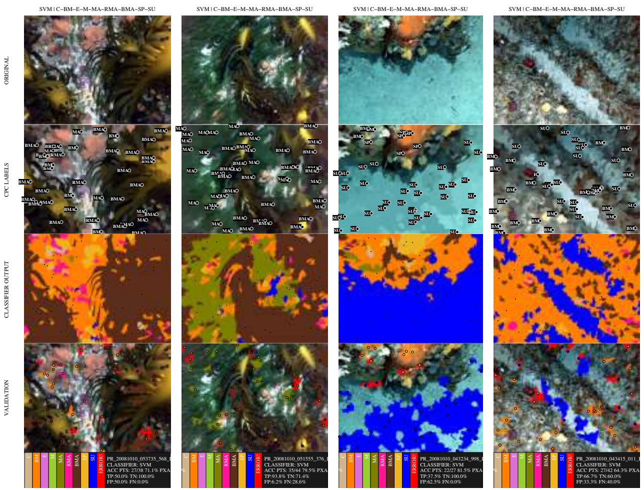
- Science Week outreach event provided access to public for citizen science
  - 10,000 users annotated 300,000 images over the course of two months

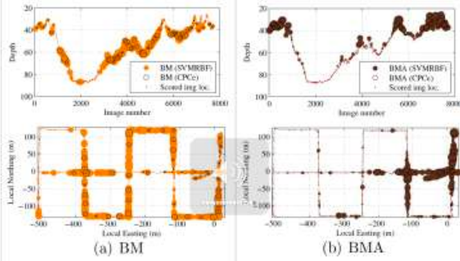


Machine Learning

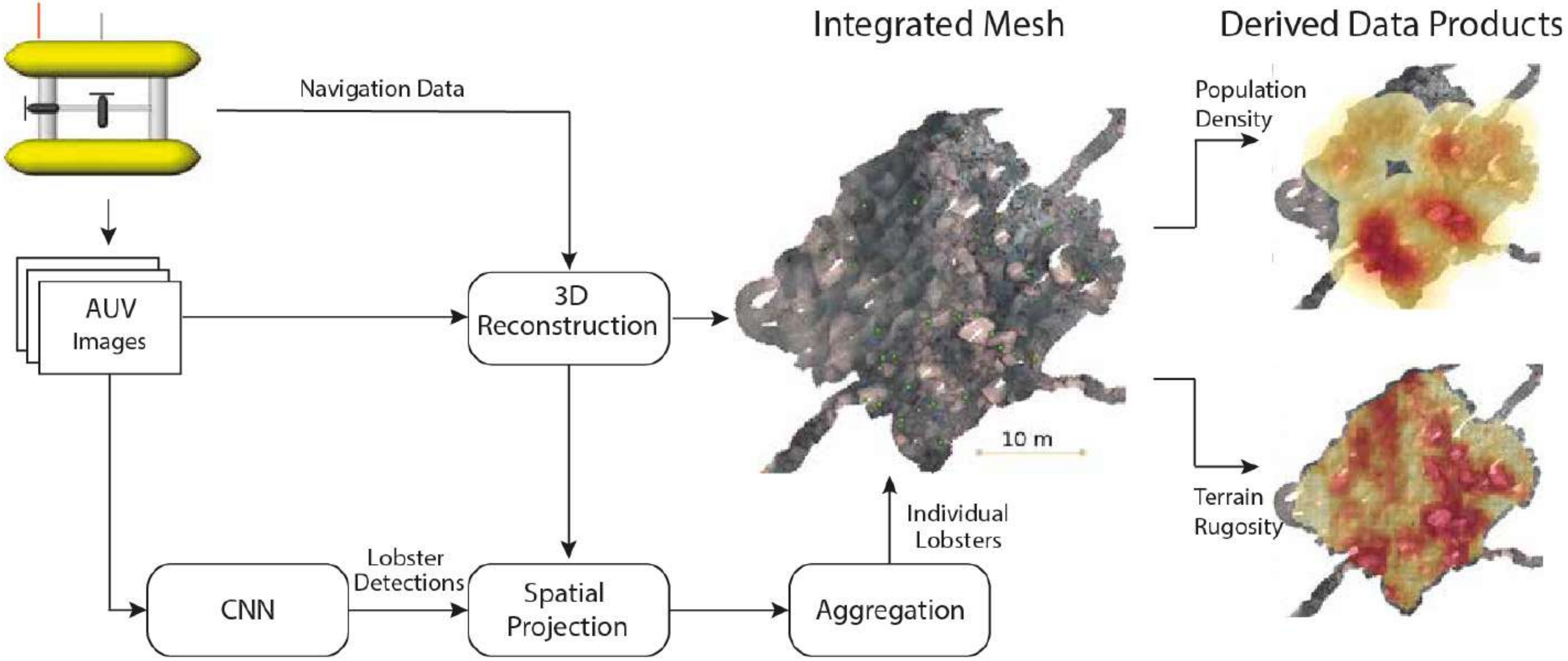
- Developing Machine Learning tools to help manage data
- Unsupervised Cluster
  - Similar to a dimensionality reduction algorithm
  - Cluster mixture/proportion descriptor for each dive
  - Compact way of describing whole campaigns
- Supervised Classification
  - Training algorithms to label whole images and pixels within images based on expert input



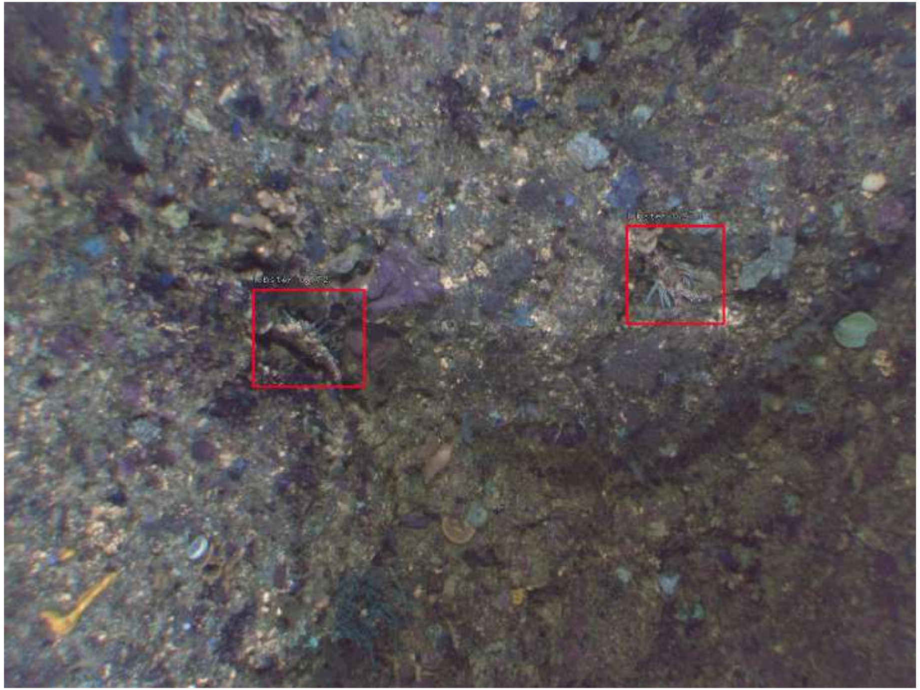




Automated Classifier for Lobsters

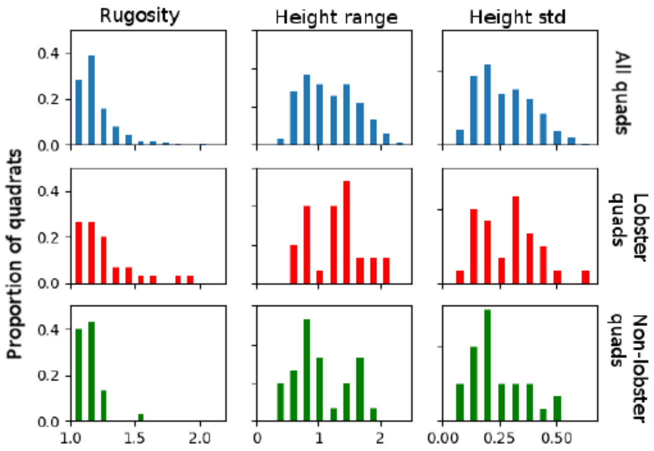


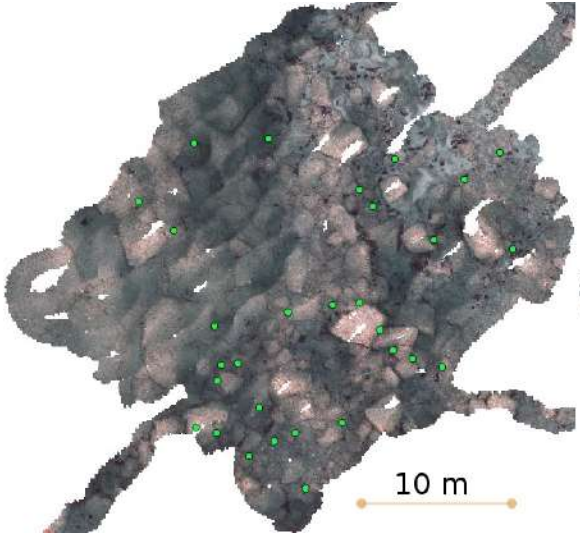
Automated Classifier for Lobsters



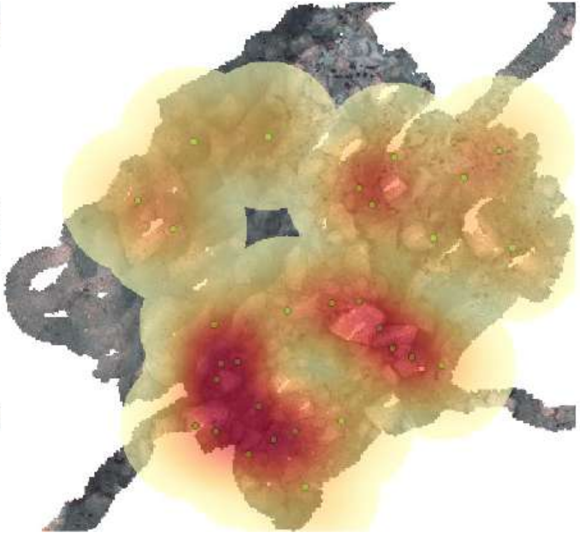
Automated Classifier for Lobsters

- Investigating correlation between lobster location and terrain structure (measured by rugosity)

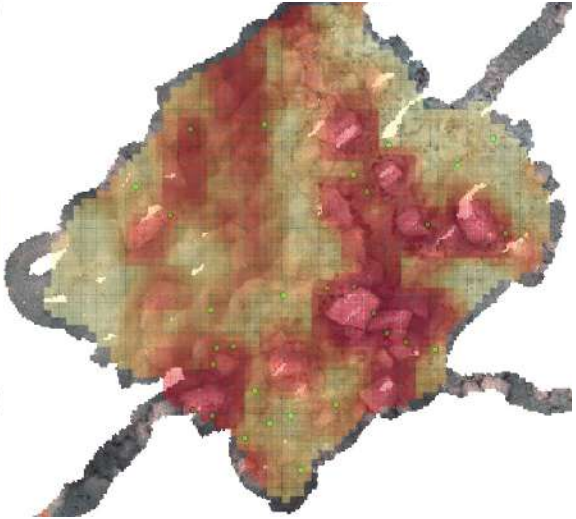




Detections



Lobster Heat Map



Rugosity Heat Map

Automated Classifier for Lobsters

True

False

Challenges with Data Analytics

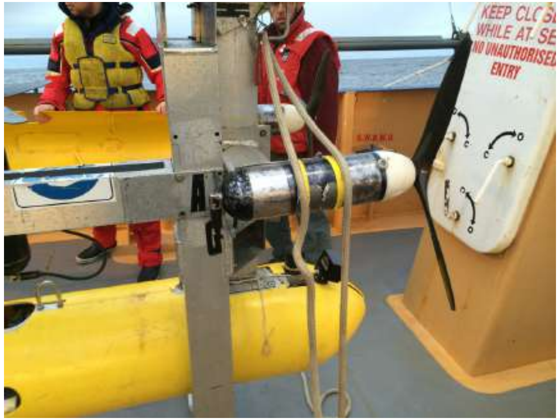
- Consistency in labels across environments
- Relatively small amount of labelled data available. Unbalanced across classes.
- Transfer learning across datasets, platforms, habitats
- Multimodal learning
- Low computational resources available on board (for online classification)
- Change detection in very unstructured, dynamic environments with significant challenges in lighting and registration

Most Significant Challenge:

Number of Deployments == Number of Recoveries

Tasmania – Safe Deployment and Recovery

Tasmania – Safe Deployment and Recovery

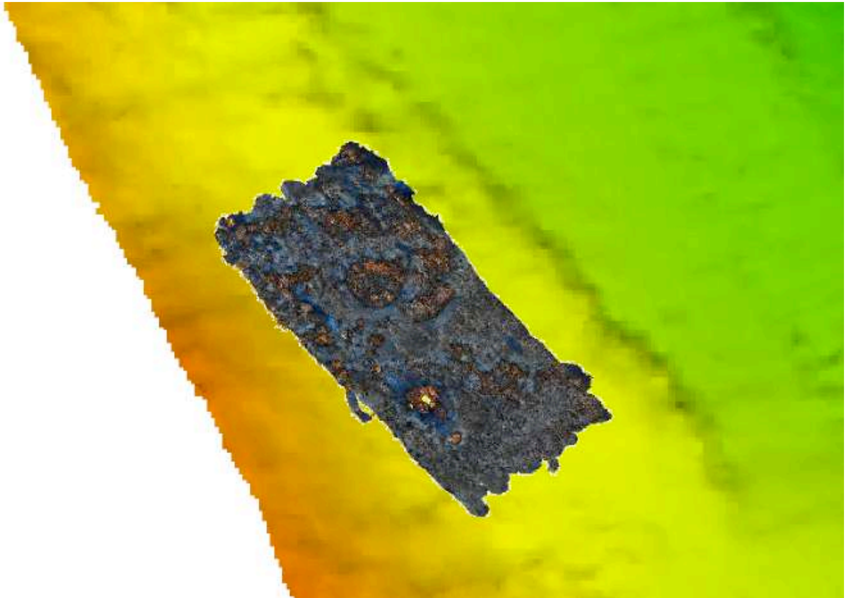


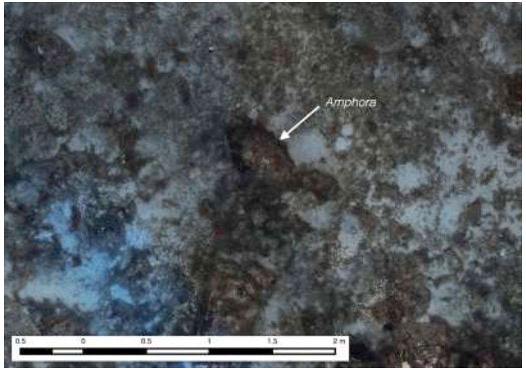
Antikythera 2014

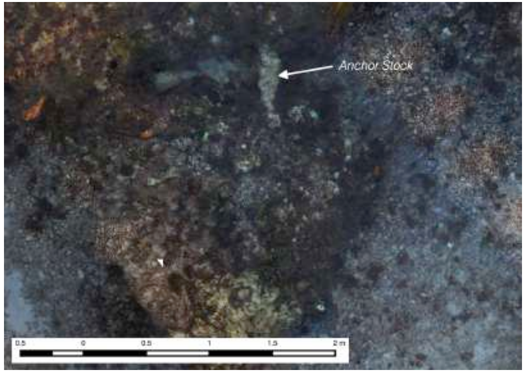
- Invited to participate in survey of first century BC wreck at Antikythera, Greece
- A team from HMC and WHOI relocated the wreck and conducted preliminary surveys in 2012 and 2013
- Plans were put in place to return with a dive team to begin further excavation
- Sponsors provided access to vessels
- Required a map of the site prior to intervention
  - Sonar bathymetric map produced in 2013
  - AUV based imaging mapping work conducted in 2014 and 2015

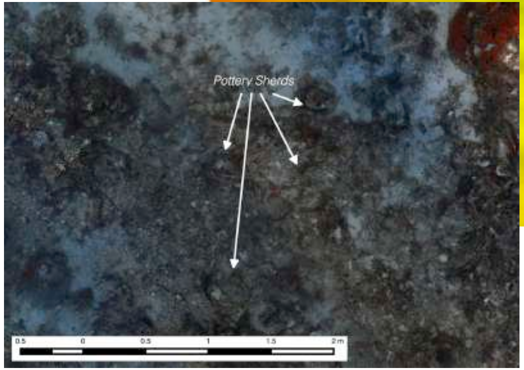
Antikythera 2014

- Georeferenced map overlaid on underlyin
  bathymetry
- Allows data be put into the context of the v
  site
- Models were used by divers to plan dives c
  record findings





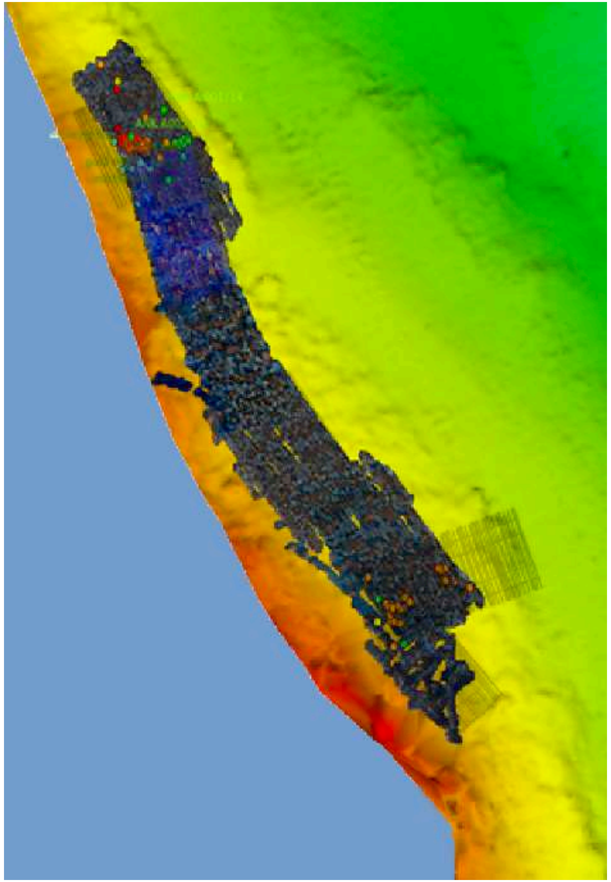




Antikythera 2014 excavation

The 2015 Field Season

- In 2015 we were invited to return to the Antikythera wreck site
- The objective was to cover the area between the main wreck site and a secondary wreck in the south
- One hypothesis was that this was one giant wreck site
- Preliminary analysis of the dives completed two weeks ago suggests that in fact it is two distinct wrecks



Can’t always trust the data…

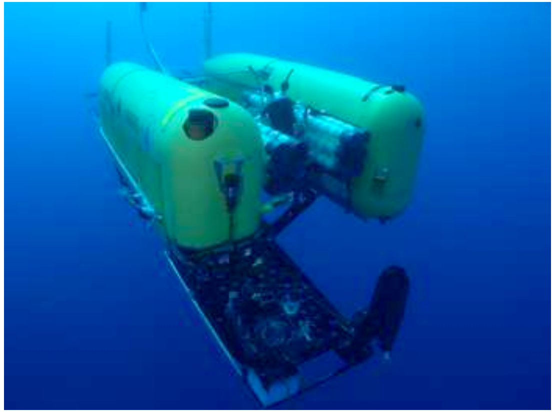
- Our first dive was planned using underlying bathymteric map
- Dive consisted of crossing legs designed to allow SLAM to find loop closures for the reciprocal, 1m spaced lines
- AUV started down first line, went over the edge of the cliff, turned to come back up the cliff and appeared to be stuck
- Abort sent but the vehicle remained at the base of the cliff in approximately 70m of water
- ROV deployed to investigate

Can't always trust the data…

That Lonely Day

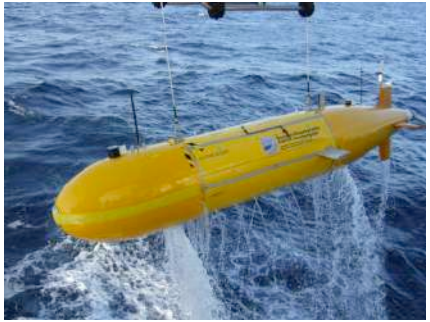
- Despite all the hard work, preparation, safety briefings, etc., sometimes things just go wrong
- At depth, failures can be unforgiving

ABE: Lost 03/10 off Chile



Nereus: Lost 05/14
N of NZ at 10km

ROV Kaiko: Lost 05/03 at 10km

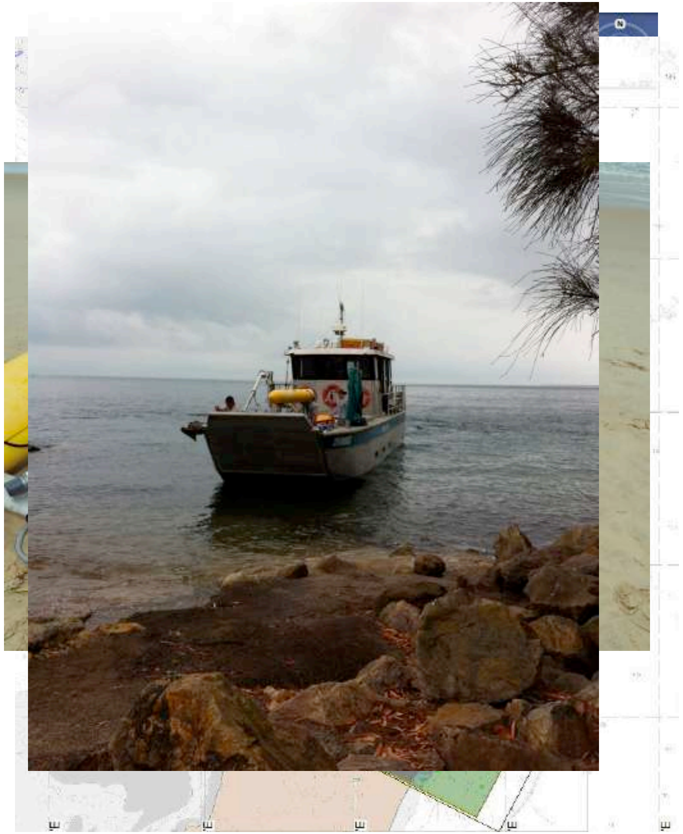


Autosub: Lost 02/05 at 100km
under Antarctic sea ice

ISIS ROV: Damaged 01/11
under ship

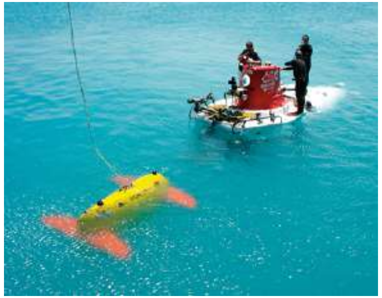
That Lonely Day

- Our AUV sank due to issues with trim during operations off SE Queensland in Nov. 2011
- Issues with vessel meant that tracking was halted to refuel, leaving the AUV untended for 4 hours
- On return acoustic tracking could not be re-established
- 3 days of search focused around area of loss as well as to the North and South but to no avail
- Received a call two weeks later alerting us to the fact that the vehicle had washed up on the Sunshine Coast 100km north of Moreton Island



Some Phenomenal Successes

- Despite all of these challenges, there have been some outstanding successes in the field
  - Discovery of hydrothermal spreading centres
  - A better understanding of life in our oceans support, Discovery of new forms of life and unknown ecosystems
  - Cost-effective, in-situ validation of satellite observations
  - Exploration of the deepest parts of our oceans
- It can be very rewarding – and a lot of fun

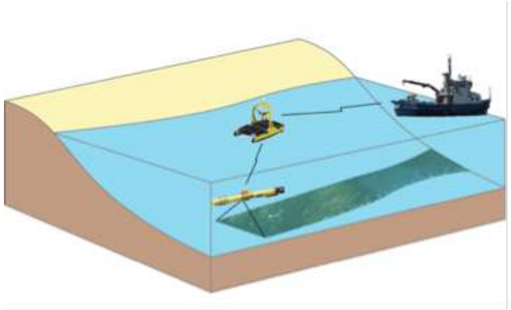


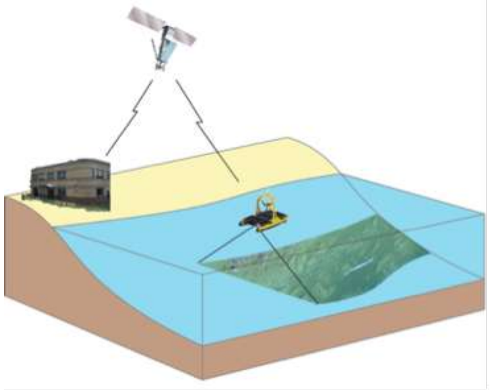
Key Challenges

- **Platforms and Sensing**
  - Vehicle operations ✅, ☐ ~
  - Operating in difficult environments (turbidity, low light, high altitude) ~
  - Coordinated deployments ✅
  - Cooperative deployments ~
  - Persistent operations ~
- **Navigation and Mapping**
  - Online navigation ✅
  - Post-dive visual SLAM ✅
  - Online SLAM ~
  - Automated registration ~
  - Multi-modal mapping ~
- **Planning and Control**
  - Low level control ✅
  - Manual dive planning ✅
  - Automated cruise planning ~
  - Online planning ~
- **Data Analytics**
  - Unsupervised analysis ✅
  - Deep Learning ~
  - Delivering information to stakeholders ~
  - Characterising change ~
- **Applications**
  - Responsive to stakeholder needs ✅
  - Understanding requirements ✅
  - Delivering raw data ✅
  - Transforming data to information and improved understanding of the environment ~

Future Challenges: Long Rang Autonomous Marine Teams

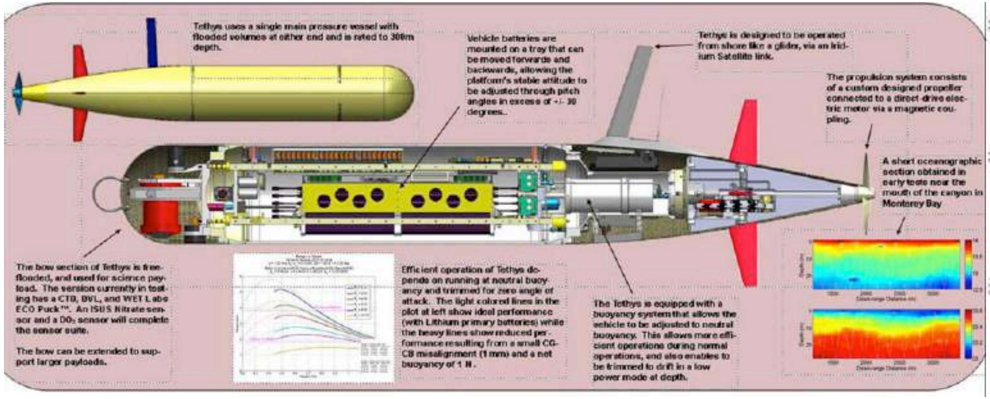
- Supervised autonomy for long range autonomous marine teams
  - Identify salient information within a vehicle's sensor data
  - Handle bandwidth constraints using information theoretic methods
  - Architecture for supervised autonomy that facilitates operator feedback
  - Integrated, operator-in-the-loop AUV system

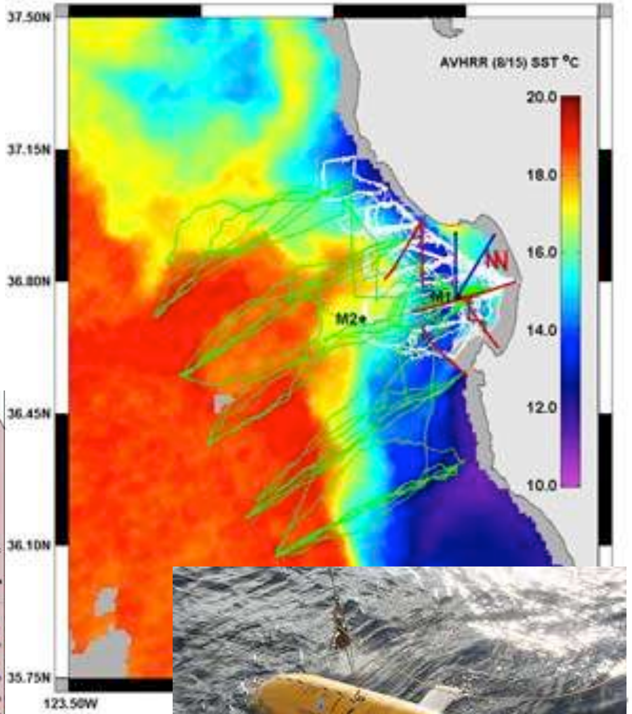




Long range AUVs

- A number of organisations are now developing long range AUVs
  - MBARI: Tethys vehicle (range: 1000km)
  - Southampton: Autosub long range (range: 6000km)

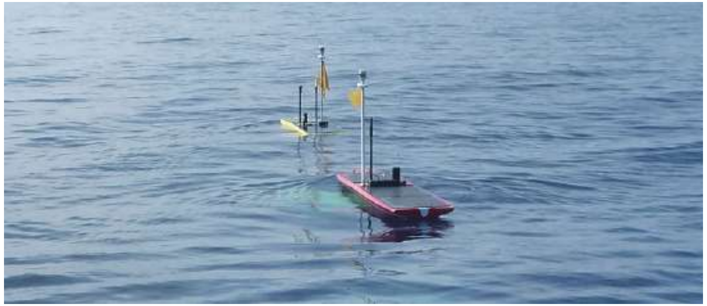


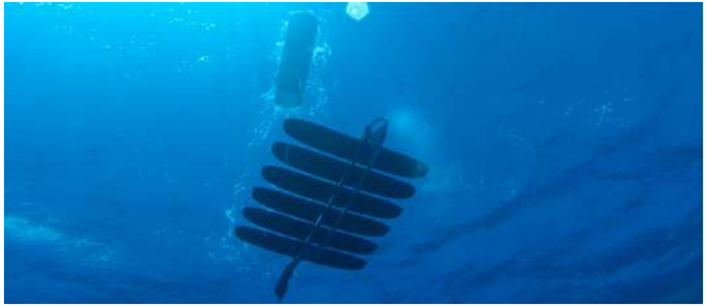


Images courtesy of MBARI and NOC

Long range USVs

- Wave glider uses wave energy for propulsion
- Wave glider Long range/duration capability (recently completed ~17000 km crossing of Pacific)
- Saildrone are deploying fleets of long range autonomous sailboats and have covered over 350,000 km of ocean transits





Images courtesy of Liquid Robotics and Saildrone

Conclusions and future work

- Marine robotic systems present novel tools for collecting rich, high resolution, geo-referenced data sets
- Managing the data and transforming it into data products continues to be a key challenge
- Engaging with the end user community in exploring the application of these technologies to a variety of application domains
- Exciting challenges and novel applications likely to drive developments in these areas

- Currently have PhD and Postdoc positions available in marine robotics (as well as in the areas of mining, agriculture, UAVs, etc.). Contact me if interested on stefan.williams@sydney.edu.au

Acknowledgements

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