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System Design of Hybrid-Driven Hadal Glider Serving in Full Ocean Depth

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GOOS

Outline

1. Background
2. Petrel-X^{PLUS} hadal glider
3. Sea trial in the Challenger Deep
4. Future vision and work

1 **Background**

2 Petrel-X PLUS hadal glider

3 Sea trial in the Challenger Deep

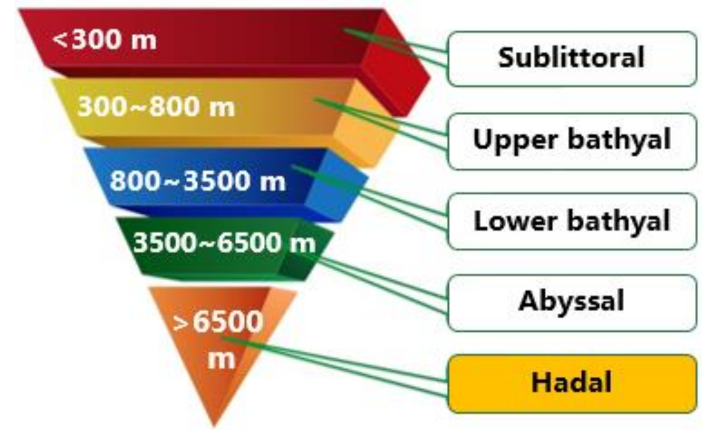
4 Future vision and work

1 Background

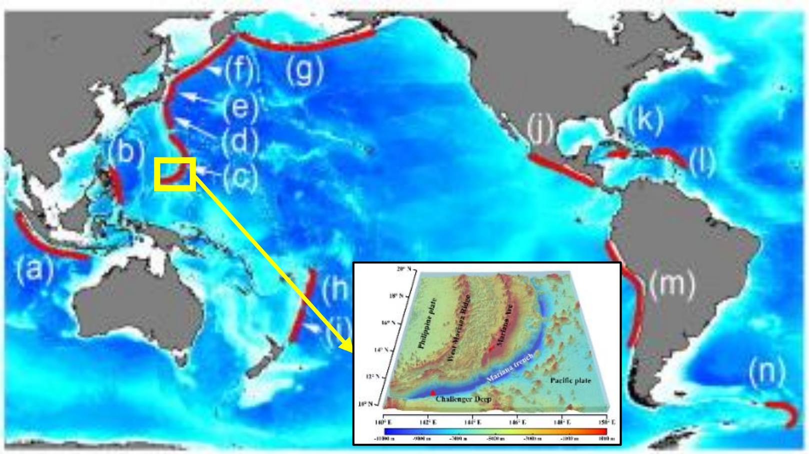
Hadal zone

- 6500m~11000m
- Only in few deep ocean trenches
- Less than 2% of the ocean area
- 45% of the depth range
- The fourth pole of the world
- The deepest and most mysterious ocean area

The five depth zones of the global oceans



According to the UNESCO



Major hadal trenches of the World

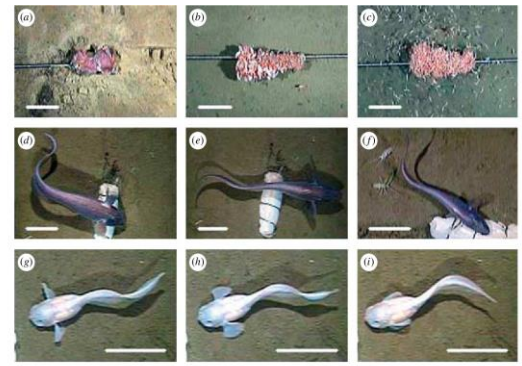
(b) Philippine Trench	-10 540 m;
(c) Marianas Trench	-10 989 m;
(f) Kurile-Kamchatka Trench	-10 542 m;
(h) Tonga Trench	-10 800 m;
(i) Kermadec Trench	-10 047 m.

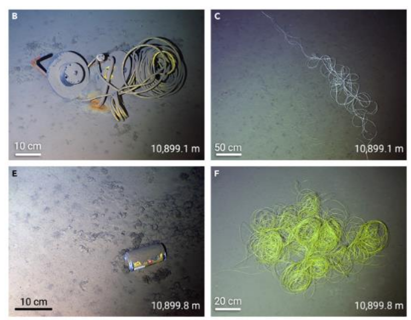
[1] Jamieson, A. J., et al. (2010). "Hadal trenches: the ecology of the deepest places on Earth." Trends in Ecology & evolution 25(3): 190-197.
[2] Briones, E. E., et al. (2009). "Global open oceans and deep seabed (GOODS) biogeographic classification." UNESCO, IOC **54**.

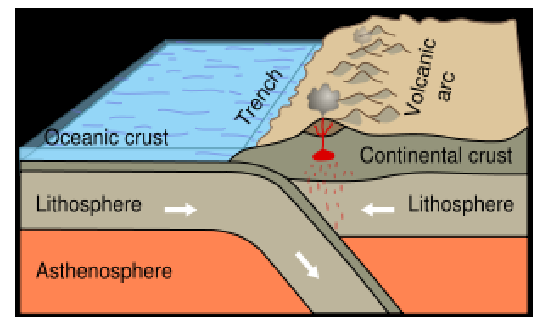
1 Background

Hadal science

- The physical and chemical properties, the transport mechanism of seawater **[3]**
- Microbial community and organic carbon transformation process **[4]**
- Energy and chemical cycle mechanism of ecological structure **[5]**
- Plate movement and seismicity **[6]**
- Influence of human activities on hadal ecology **[7]**
- …







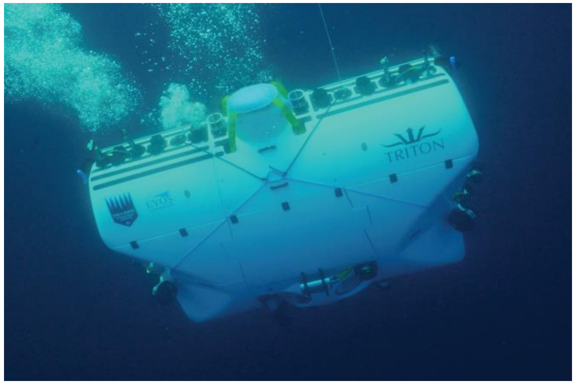
The large-depth submersible is the main way to obtain hadal research data and material.

[3] Kawagucci, S., et al., Hadal water biogeochemistry over the Izu-Ogasawara Trench observed with a full-depth CTD- CMS. Ocean Science, 2018. 14(4): 575–588.
[4] Glud, R.N., et al., High rates of microbial carbon turnover in sediments in the deepest oceanic trench on Earth. Nature Geoscience, 2013. 6(4): p. 284-288.
[5] Liu, R., et al., The hadal biosphere: Recent insights and new directions. Deep Sea Research Part II: Topical Studies in Oceanography, 2018. 155: p. 11-18.
[6] Oguri, K., et al., Hadal disturbance in the Japan Trench induced by the 2011 Tohoku–Oki Earthquake. Scientific Reports, 2013. 3: p. 1915.
[7] Jamieson, A.J., et al., Bioaccumulation of persistent organic pollutants in the deepest ocean fauna. Nature ecology & evolution, 2017. 1(3): p. 1-4.

1 Background

Large-depth submersible

Deepsea Challenger
HOV



Triton 36000/2
HOV

Rainbow fish
HOV

KAIKO
ROV

Nereus
HROV

Orpheus
AUV

1 Background

Large-depth submersible

Submersible	Deepsea Challenger	Triton 36000/2	KAIKO	Nereus
Type	HOV	HOV	ROV	HROV (ROV & AUV)
Design depth(m)	11 000	11 000	11 000	11 000
Sea trial depth (m)	10 898	10 928	10 911	10 902
Range (km)	32	59	12	40
Endurance (h)	9	16	—	—
Velocity (m/s)	1.5	1.5	1	2
L×W×H (m)	2.3×1.7×8.1	4.6×1.9×3.7	5.2×2.6×4.3	4.7×2.3×3.1
Weight (t)	11.8	11.7	10.9	2.8

Full-ocean-depth submersible is one of the important equipment for hadal observation.

1 Background

Hadal environment

Ultra high pressure

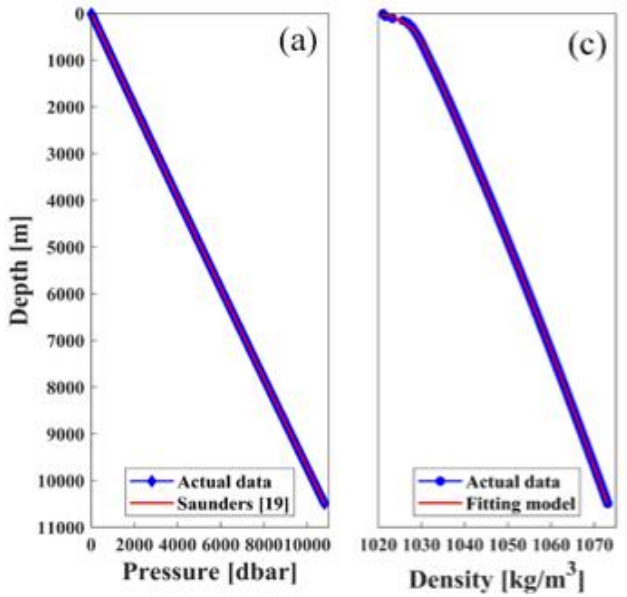
- Linear increase with depth
- The maximum is about 1.1×10^8 Pa (approximately 1.1 tonnes·cm^{-2})

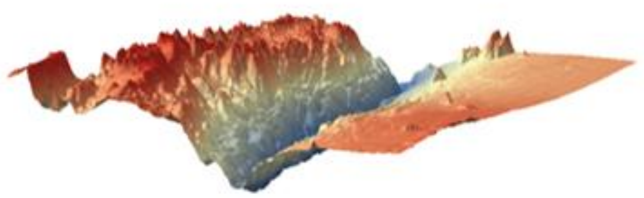
Great changeable density

- Nonlinear increase with depth
- The maximum increase in density is about 5.3%

Complex topography

- Located in the plate subduction
- Its cross section is asymmetrical V-shaped
- An average steepness of 5°~15°
- A maximum steepness of 45°





The unique and complex hadal environment has brought great technical challenges to the large-depth submersibles.

1 Background

Technical Challenges

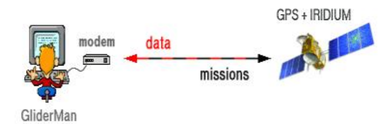
- The extreme pressure has caused the large-depth submersibles to be bulky and heavy, and the economic pressure for construction is great.
- The great changable density creates a big obstacle for continuous long-term observation
- The complex topography increases the difficulty of effective entry for large-depth submersibles.
- The use of armored cables limits the observation range of the submersible.

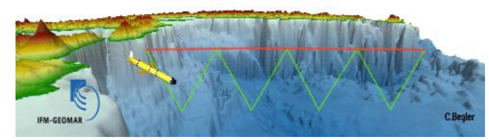
There is an urgent need for innovative technical solutions to realize the long-term and economic multidisciplinary monitoring of the hadal by large-depth submersibles.

1 Background

Underwater glider

- Small size and light weight
- Long range (>1000km)
- Strong endurance (Months)
- Low cost
- Multidisciplinary observation





	Slocum	Seaglider	Petrel-II	Deepglider
Appearance				
Depth (m)	1000	1000	1514	6003
Range (km)	7576	5528	3620	4587
Endurance (day)	418	292	141	280
L×D (m)	1.5×0.22	3×0.3	3.2×0.22	2.8×0.3
Weight (kg)	<70	52	68	79

Unconver hadal zone

At present, unmanned and multi profile technical means are needed to carry out continuous observation of the hadal zone.

1 Background

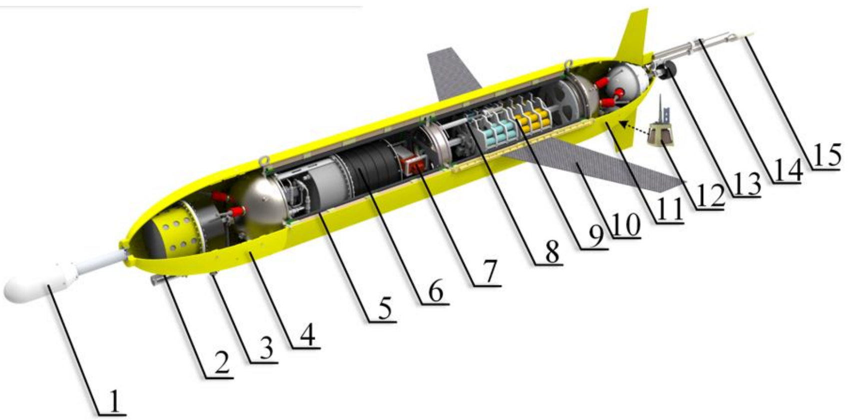
2 Petrel-X ^{PLUS} hadal glider

3 Sea trial in the Challenger Deep

4 Future vision and work

2 The Petrel-X^{PLUS} hadal glider

The petrel-X^{PLUS}



System configuration

1) Hydrophone, 2) Conductivity-Temperature-Depth(CTD), 3) Underwater camera, 4) Front fairing, 5) Multi-material combined pressure hull, 6) Buoyancy regulating module, 7) Controller, 8) Attitude regulating module, 9) Battery packs, 10) Wing, 11) Rear fairing, 12) Emergency jettison module, 13) Propeller 14) Beacon, 15) Antenna

Basic specifications

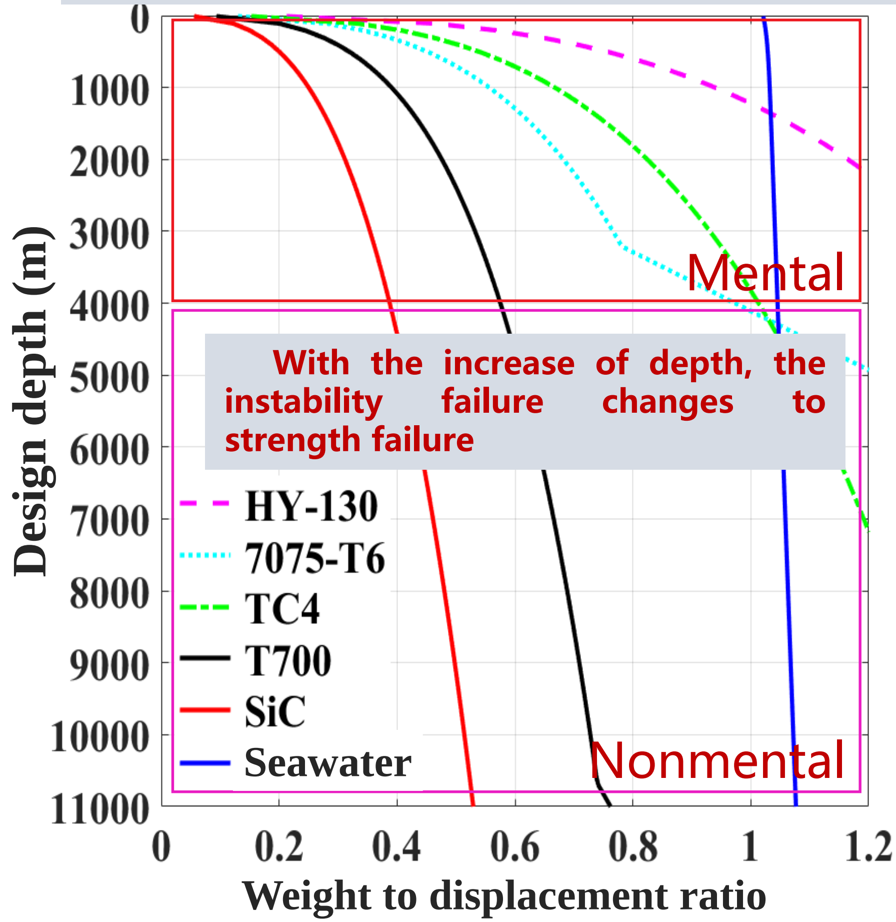
Description	value	Description	value
Diameter	390 mm	Volume change	Max 5L
Length	3180 mm	Battery	Lithium primary batteries
Wing span	1520 mm	Communi-cations	Iridium satellite, Wireless
Weight	230 kg	Navigation	GPS, altimeter, pressure sensor, compass
Depth rating	11000 m		
Range	≥2000 km	Scientific sensors	CTD, Hydrophone, Underwater camera
Duration	≥100 days		

2 The Petrel-X^{PLUS} hadal glider

Material		Density g/cm^3	Specific strength MPa (g/cm^3)$^{-1}$	Specific modulus GPa (g/cm^3)$^{-1}$
Mental	Aluminum alloy (7075-T6)	2.80	250	25
	Titanium alloy (TC4)	4.50	264	24
	Steel (HY130)	7.80	159	26
Non-mental	Carbon fiber composites (T700)	1.70	625 [1] 94 [2]	75 [1] 6 [2]
	Ceramic (SiC)	3.07	1107	130

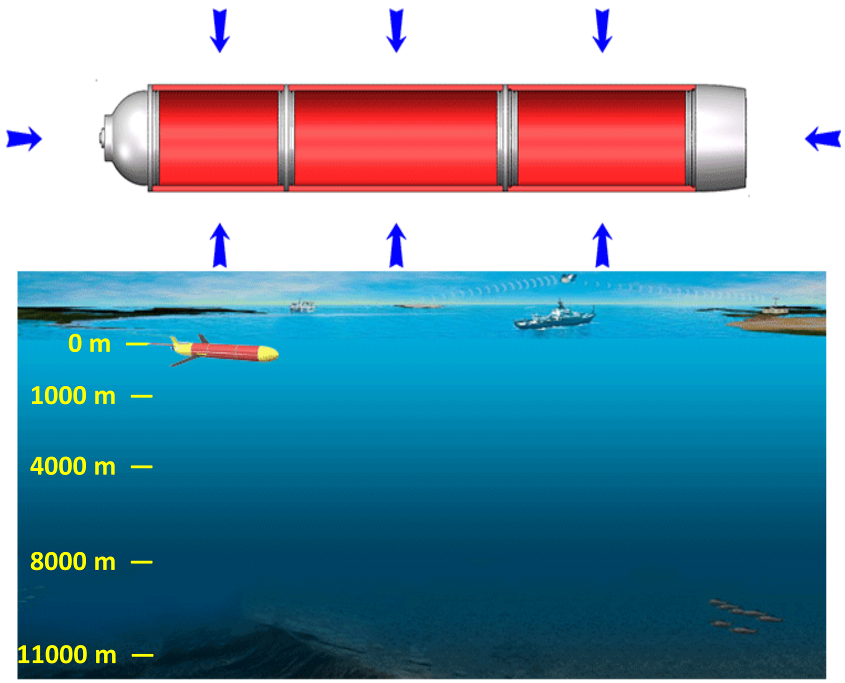
(Note: 1 Fiber direction; 2 vertical fiber direction)

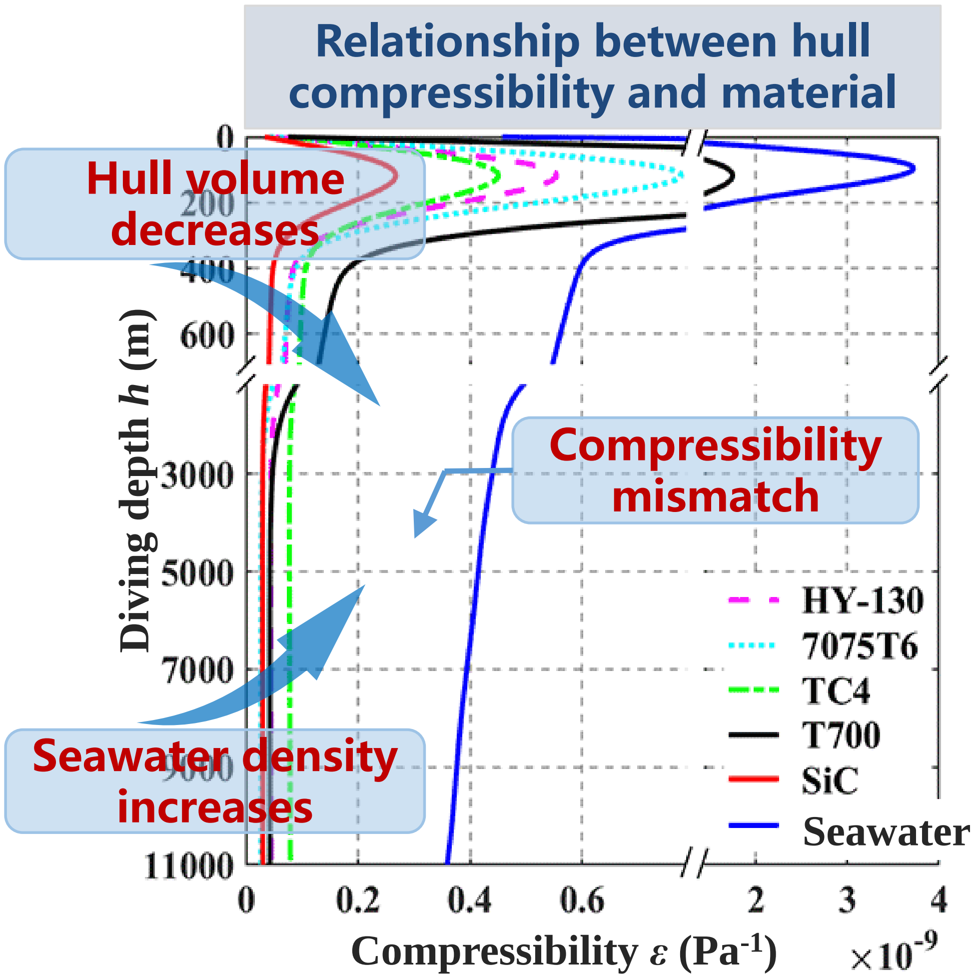
The relationship between the weight to displacement ratio of the hull and material



The performance of the hull material is the key to the pressure bearing capacity of the glider.

2 The Petrel-X^{PLUS} hadal glider

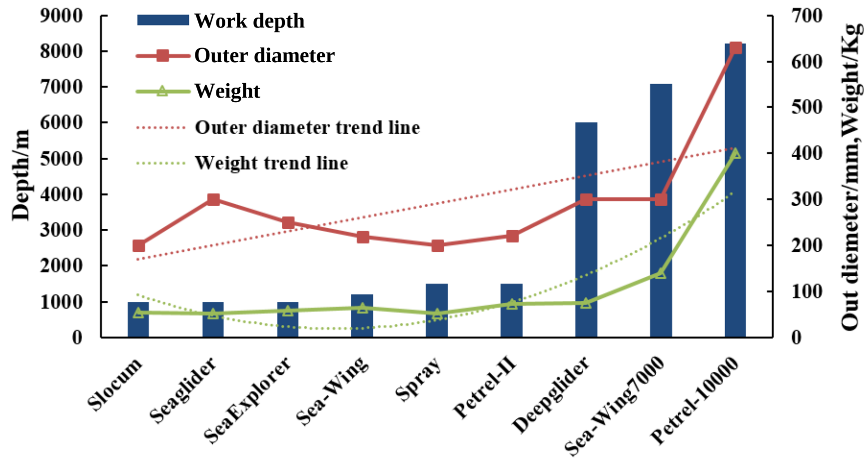




The compressibility of the pressure hull directly affects the dive depth, and improper matching will result in the inability to dive to the target depth .

2 The Petrel-X^PLUS hadal glider

Design requirements



The development trend of the size and weight of underwater gliders

- ☐ **Out diemeter**

  From **200mm**

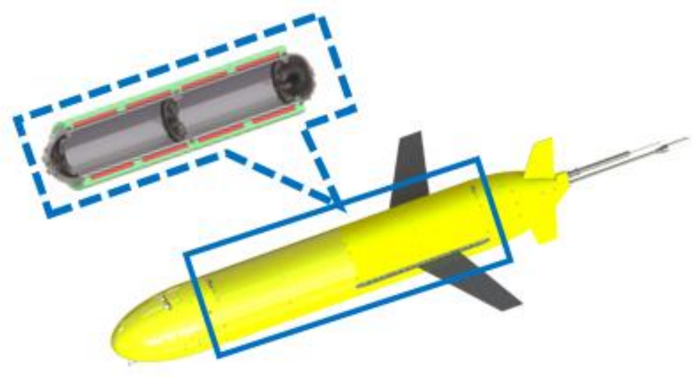
  to **300mm**

- ☐ **Weight**

  From **50kg class**

  to **100kg class**

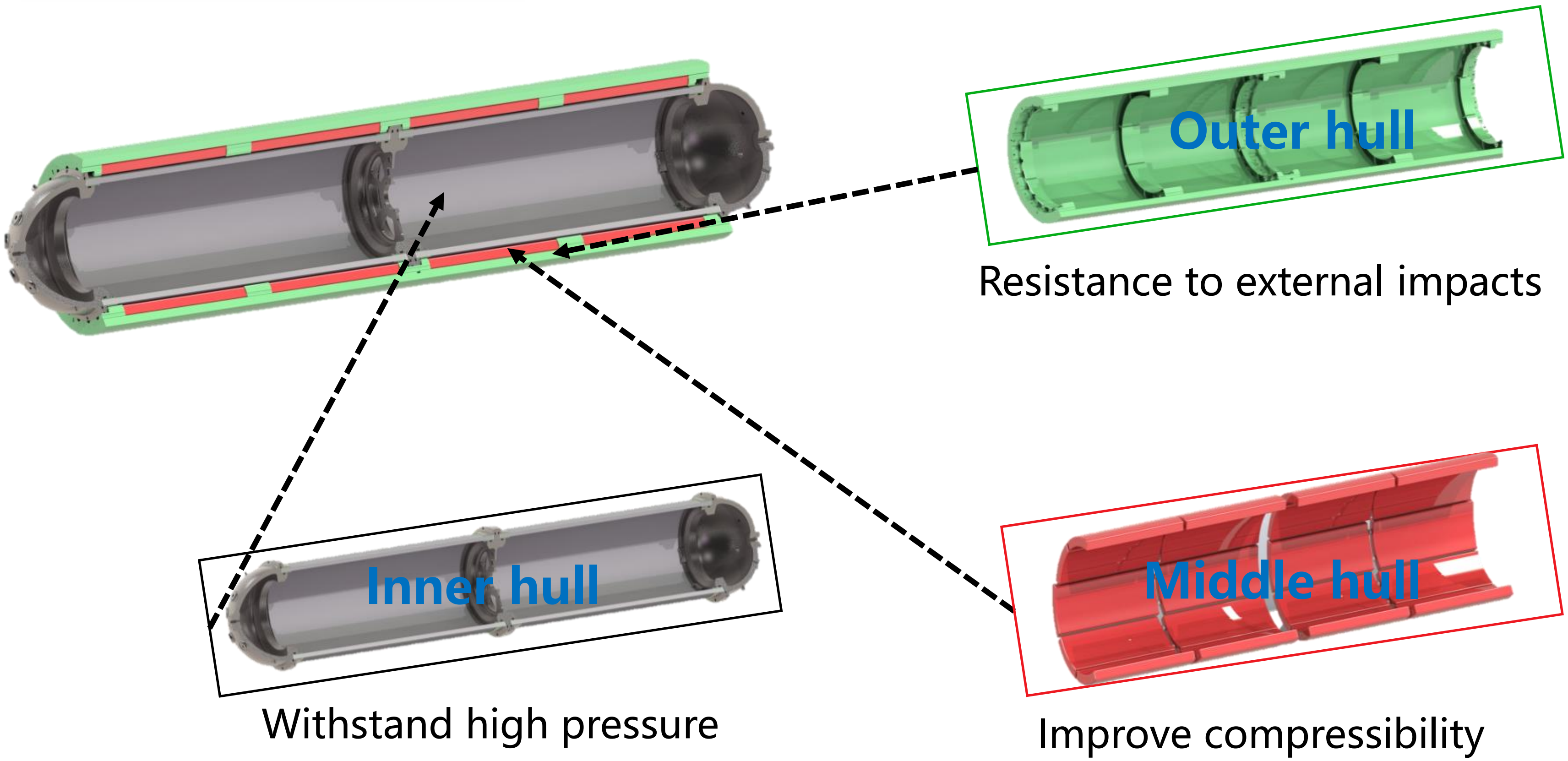
No.	Requiements	value
1	Design depth	11000 m
2	Work cycles	≥100



The noval design of the near-neutral multi-material combination pressure hull(MCPH) of the hybrid-driven hadal glider is proposed.

The Petrel-X^{PLUS} hadal glider

The MCPH



The MCPH consists of inner ceramic hull to withstand high pressure, middle silicone oil hull to improve compressibility and outer UHMWPE hull to resist external impacts.

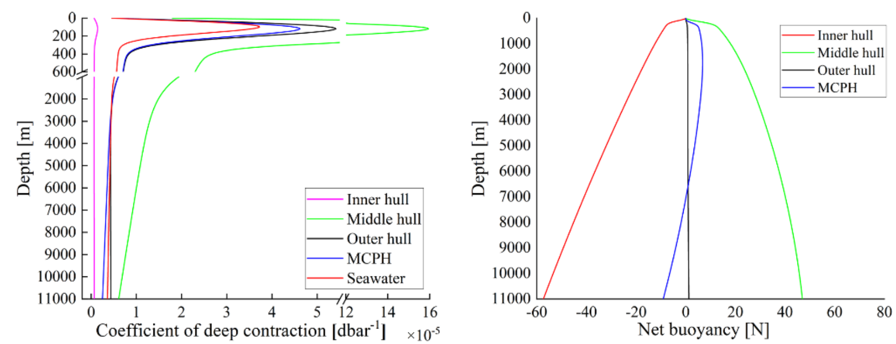
2 The Petrel-X^{PLUS} hadal glider

Design depth: 11000m		Material properties				Geometric dimension			Critical pressure
Hull	Analysis method	Material	Compressive (yield) strength σ(MPa)	Young' s modulus E(GPa)	Poisson' s ratio μ	Diameter (mm)	Length (mm)	Thickness (mm)	P_{cr} (MPa) (Safe value)
Cylindrical shell	Strength	SiC	2500	400	0.2	300	800	9	157.3 (1.43)
	Stability							13	157.3 (1.43)
	FEA							13	150.7 (1.37)
Hemispheri-cal End-cap	Strength	TC4	825	110	0.34	300	--	12.5	148.5 (1.35)
	Stability							12	156.2 (1.42)
	FEA							12.5	144.1 (1.31)

Optimization model

$$f_{\text{neu}} = g\rho_{\text{sea-0}}V_0\left\{\begin{aligned}&\exp\left[\max_{0\le h\le 10000}\int_0^h\left(\varepsilon_{\text{dep-sea}}-\varepsilon_{\text{dep-glider}}\right)\mathrm{d}x\right]\\&-\exp\left[\min_{0\le h\le 10000}\int_0^h\left(\varepsilon_{\text{dep-sea}}-\varepsilon_{\text{dep-glider}}\right)\mathrm{d}x\right]\end{aligned}\right\}$$

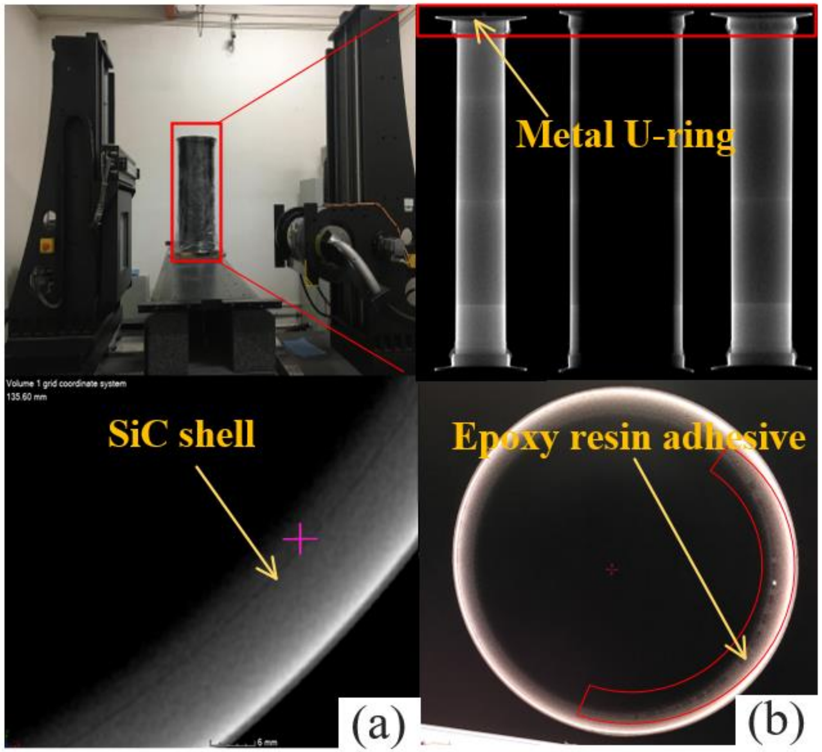
Optimization Results



The maximum net buoyancy fluctuation of the MCPH in 0~11000m is 8.87 N, which is only 15.55% of the SiC pressure hull.

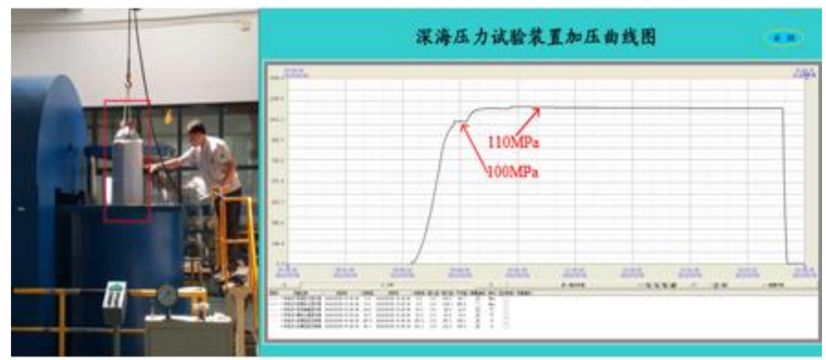
2 The Petrel-X^{PLUS} hadal glider

Detection



Industrial CT non-destructive testing:
(a) SiC hull; (b) epoxy resin adhesive

Compressive stress-strain test

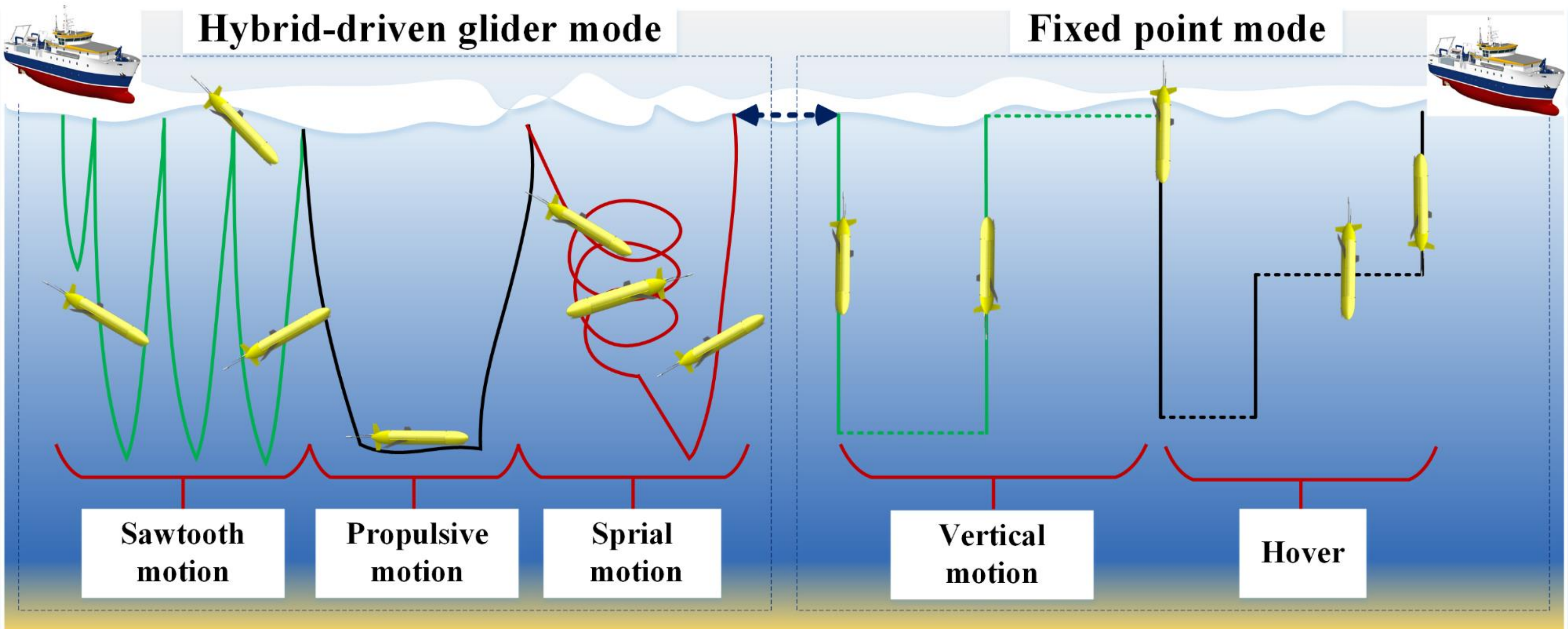


Hydrostatic pressure test(110MPa)

Industrial CT inspection, stress-strain test and hydrostatic pressure test are carried out to verify the reliability of the MCPH.

2 The Petrel-X^{PLUS} hadal glider

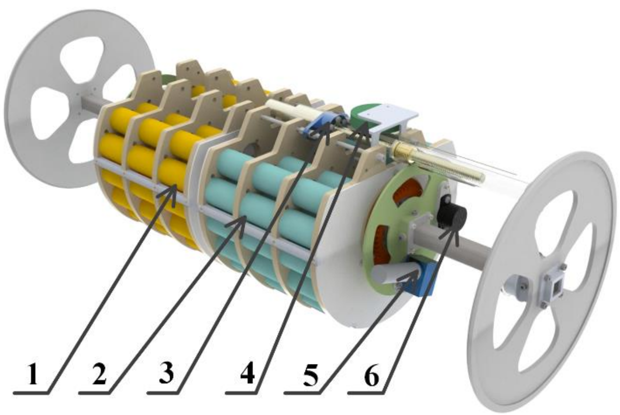
Operate mode

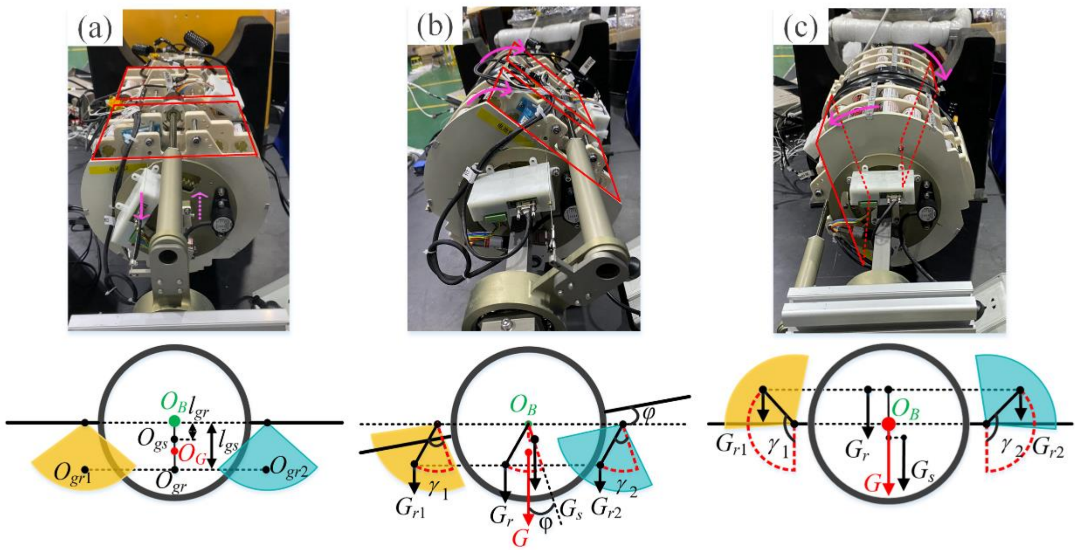


Here we propose an innovative design of attitude regulating mechanism to increase the pitch angle adjustment range from ±45° to ±90° to achieve fixed point mode, thus enriching underwater glider observation patterns.

2 The Petrel-X^{PLUS} hadal glider

The DRAM



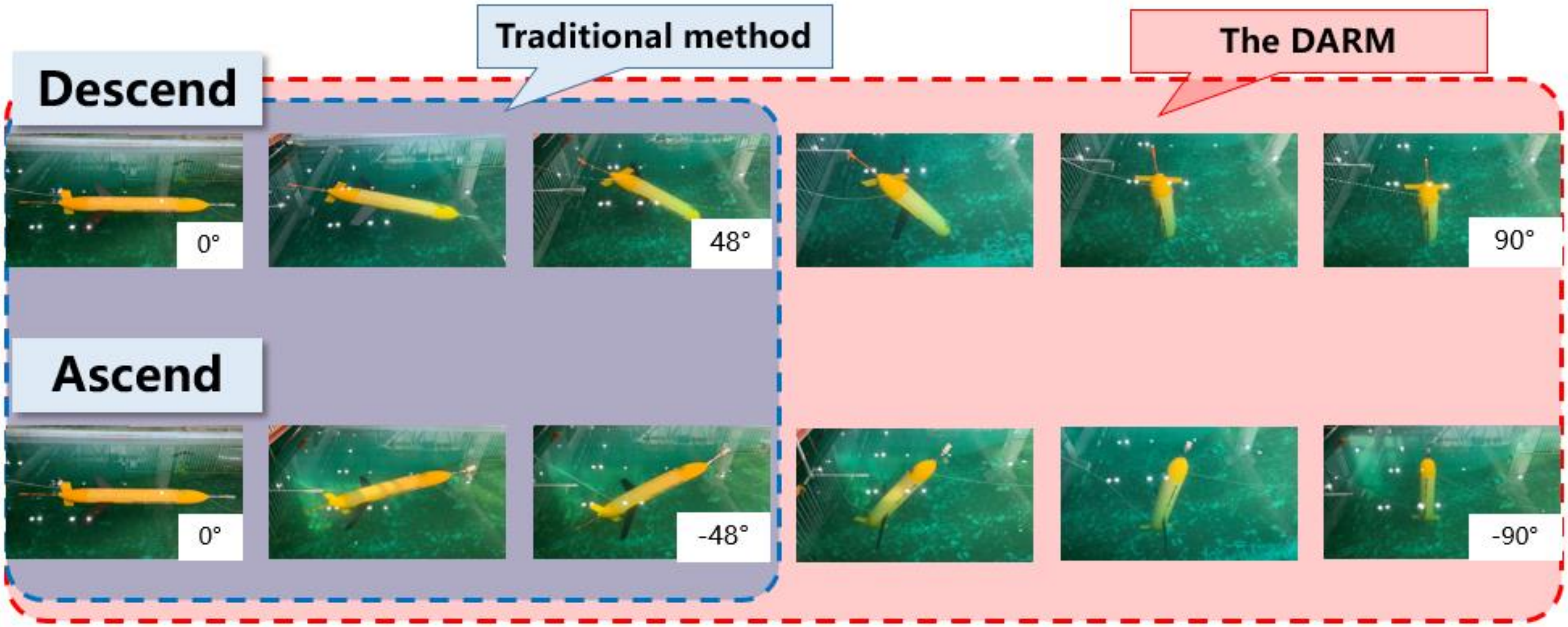


An innovative design of dual-equal eccentric attitude regulating mechanism(DARM) is proposed. Its principle diagram composes of 1, 2) eccentric battery pack, 3) pitch attitude adjusting motor, 4) linear potentiometer, 5) rotating motor, 6) angular potentiometer.

- Figure (a) represents the initial state or the sawtooth motion (γ_1=γ_2 =0°).
- Figure (b) represents the spiral motion of the glider (γ_1=γ_2).
- Figure (c) represents vertical or hover motion (γ_1=-γ_2 =120°).

2 The Petrel-X^{PLUS} hadal glider

The DRAM

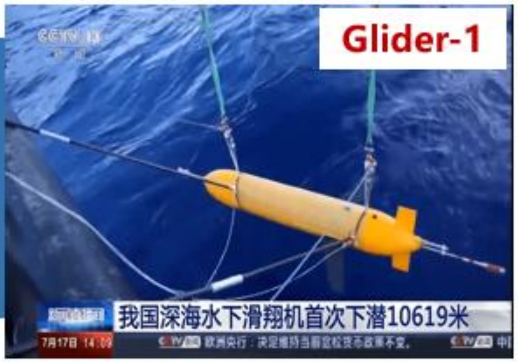


In the same space, the attitude regulating ability of DARM is 86.7% higher than that of the traditional method.

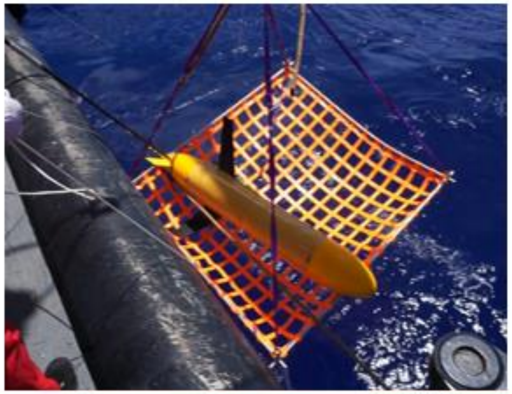
3 Sea trial in the Challenger Deep

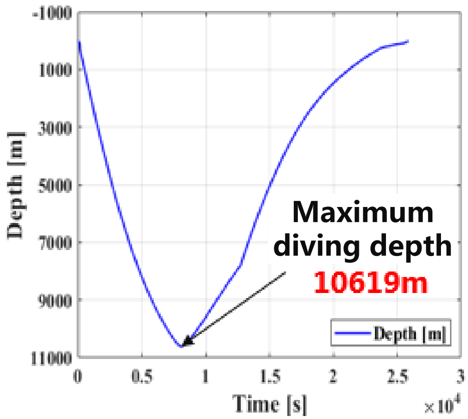
Sea trial

Deployment



Recovery





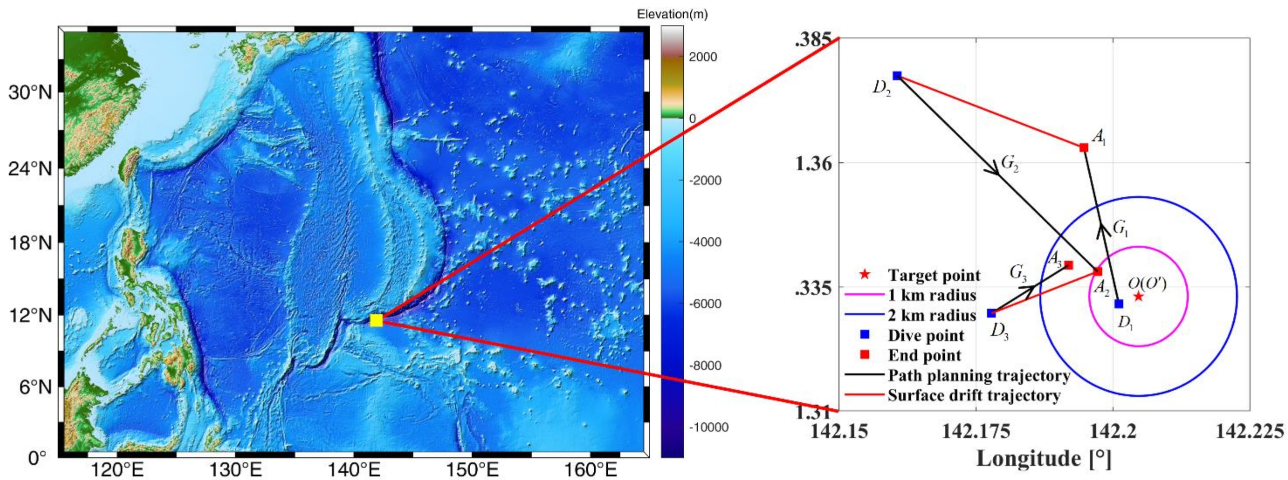
New World Record (2020)

In July 2020, the Petrel-X^{PLUS} hadal glider performed a comprehensive survey for the Challenger Deep in the Mariana Trench.

3 Sea trial in the Challenger Deep

Sea trial

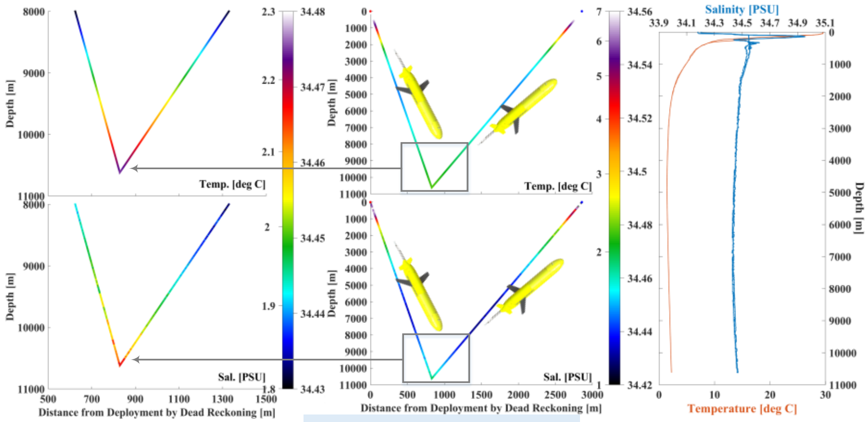
Index	Date	Starting time	Starting Position	Finish position	Depth (m)	Distance deviation (km)
G1	7/4/2020	16:14	11.3727 °N, 142.1727 °E	11.3392 °N, 142.2022 °E	10245	3.503
G2	7/5/2020	09.43	11.3775 °N, 142.1606 °E	11.3381 °N, 142.1972 °E	10347	0.989
G3	7/5/2020	18:20	11.3297 °N, 142.1777 °E	11.3394 °N, 142.1919 °E	10619	1.563



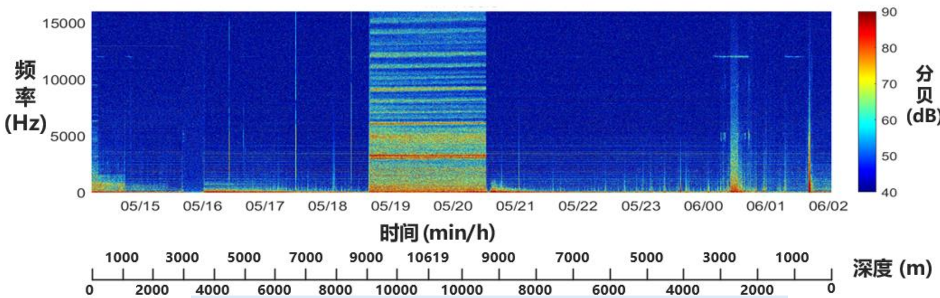
The horizontal distance deviation of the three profiles are 3.053 km, 0.989 km and 1.563 km, respectively, and the average error is 2.018 km.

3 Sea trial in the Challenger Deep

The DRAM



CTD data



Underwater environmental noise measurement

Underwater image

The relevant data of hadal zone is obtained including CTD, environmental noise and underwater image.

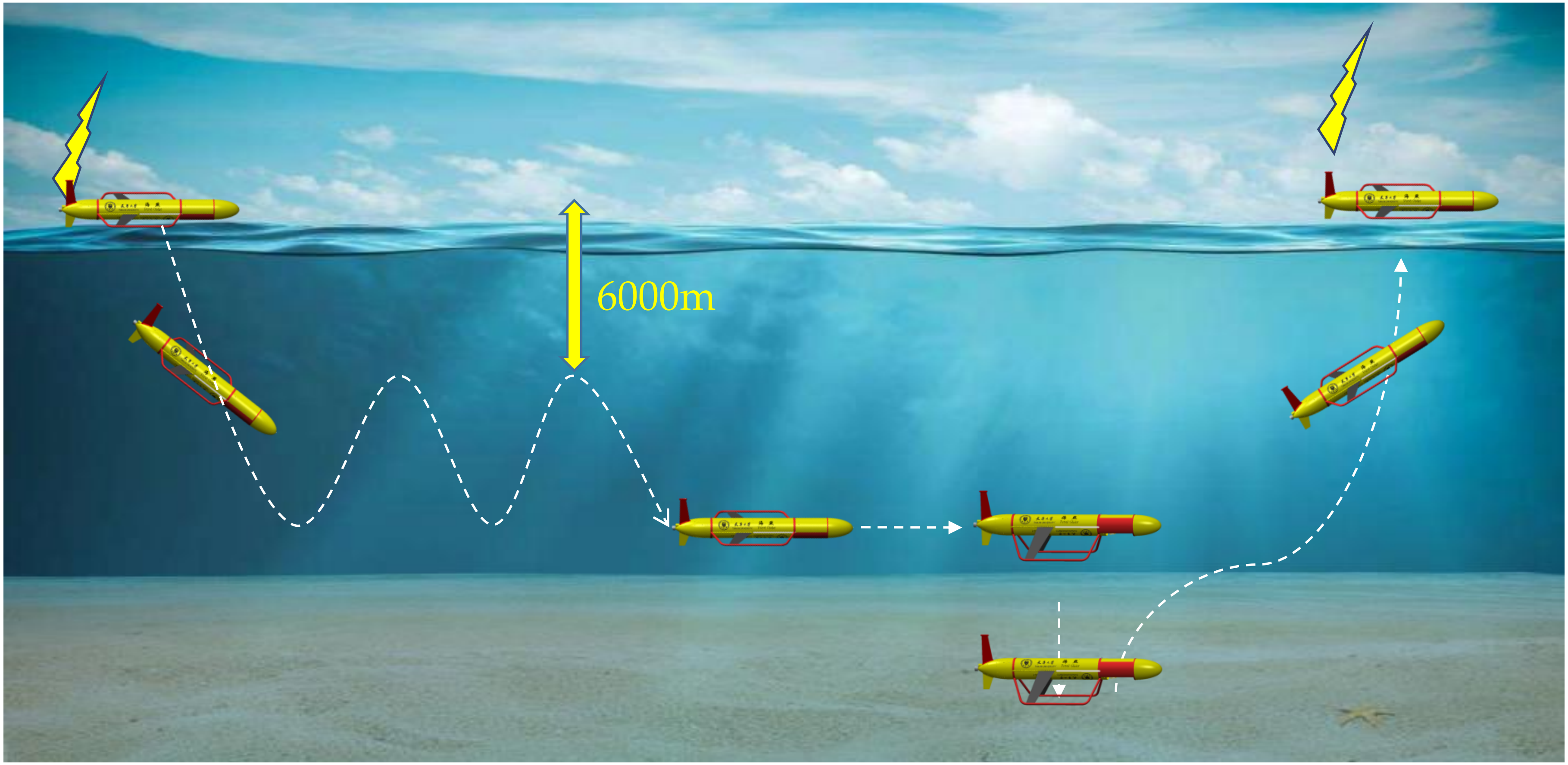
1 Background

2 Petrel-X PLUS hadal glider

3 Sea trial in the Challenger Deep

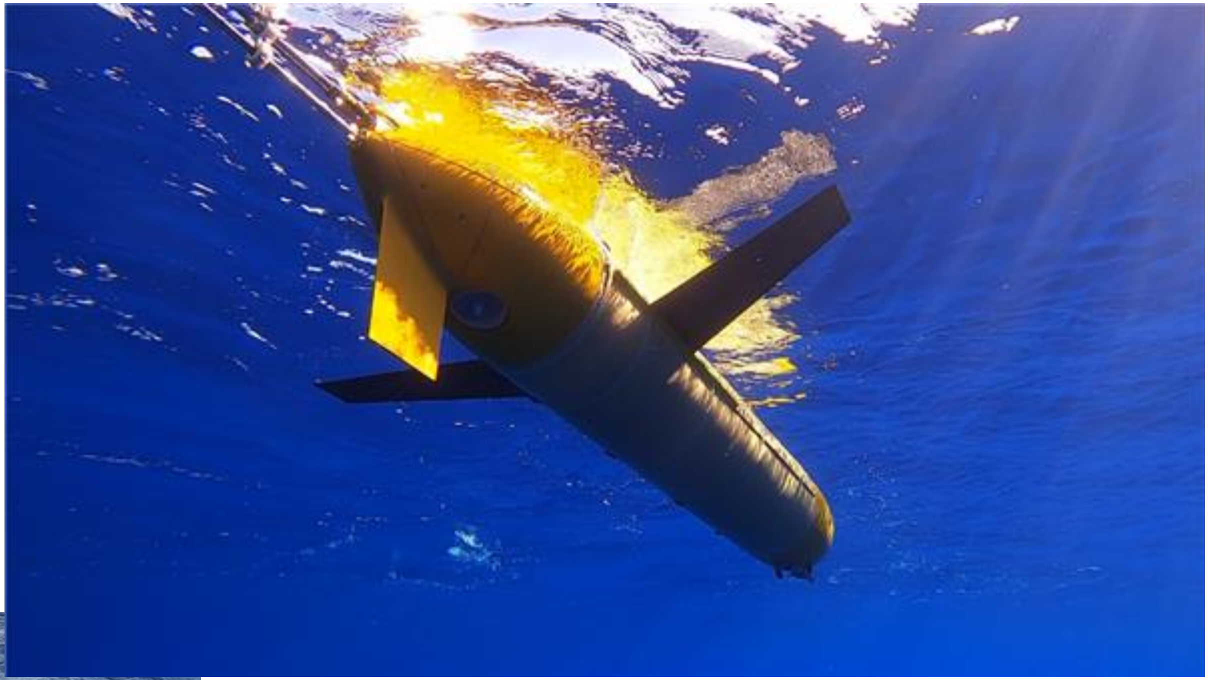
4 Future vision and work

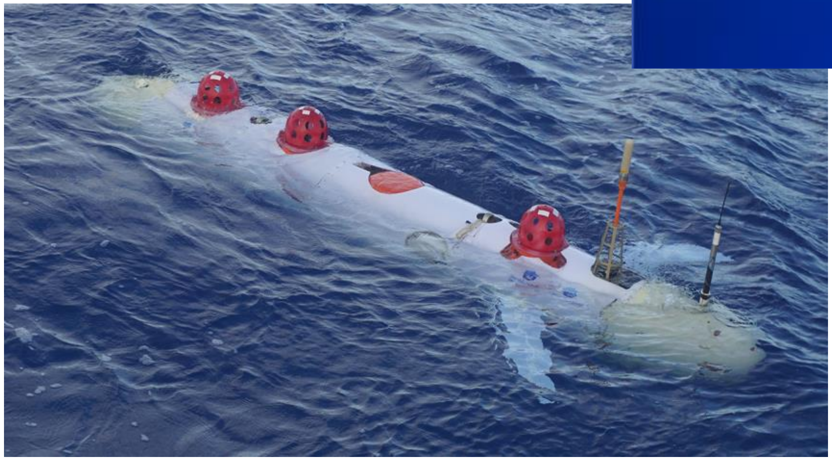
4 Future vision and work



The next step in the development of the Petrel-X^{PLUS} glider is to be able to land on the ocean bottom and take samples using a robotic hand.

Thank you.





Best Practices being applied

[1] Wang Shuxin, Li Haozhang, Wang Yanhui, Liu Yuhong, Zhang Hongwei, Yang Shaoqiong. Dynamic modeling and motion analysis for a dual-buoyancy-driven deep-sea glider[J]. Ocean Engineering, 2019, 187: 106163.