SUPPLEMENTARY MATERIAL: FRONTIERS IN MARINE SCIENCE

Response of sea urchin fitness traits to environmental gradients across the southern California oxygen minimum zone

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Table S1. Collection sites by depth zone. Agency Key: NOAA = National Oceanic and Atmospheric Administration; LACSD = Los Angeles County Sanitation District; CSD = City of San Diego; VRG = Vantuna Research Group; CLAEMD = City of Los Angeles Environmental Monitoring Division. Scripps Institution of Oceanography Student Cruise Key: MV = R/V *Melville* ; NH = R/V *New Horizon*; SP & RGS = R/V *Robert Gordon Sproul.*

* = *Strongylocentrotus fragilis* test plates measured for elemental composition only. † = Measured for elemental composition and mechanical hardness and stiffness. § = Measured for elemental composition, mechanical hardness and stiffness, and porosity.

Depth Zone	Agency/ SIO Cruise ID	Trawl Site ID	Date Collected	Latitude (˚N)	Longitude (˚W)	Depth (m)
Shelf	NOAA*	17372	7/16/2014	34.0069	-118.9009	84
	NOAA§	17262	7/15/2014	33.9044	-119.5017	93
	MV1217	T2	12/9/2012	32.9641	-117.3136	100
	LACSD	9251	8/14/2013	33.7668	-118.4605	130
	CSD	9014	8/6/2013	32.5954	-117.3286	136
	CSD	9019	8/1/2013	32.6434	-117.4277	150
	VRG	9403	8/22/2013	34.2064	-119.6327	154
	VRG	9385	8/23/2013	34.1327	-119.3699	172
	CSD	9053	8/8/2013	32.8254	-117.3660	182
	CSD	9051	8/7/2013	32.9092	-117.2951	184
	VRG*	9414	8/21/2013	34.2251	-119.7320	196
	CLAEMD	9287	9/4/2013	33.9340	-118.5905	200
	NH1414†	T4	7/27/2014	32.8075	-117.3676	200
	VRG	9432	8/21/2013	34.2778	-119.7183	200
OLZ	MV1215	T1	11/3/2012	32.6736	-117.3602	215
	VRG	9394	8/22/2016	34.1687	-119.5417	237
	LACSD	9228	8/14/2013	33.6941	-118.3465	253
	VRG	9379	8/21/2013	34.1182	-119.6289	260
	LACSD	9237	8/16/2013	33.7214	-118.4179	293
	MV1209	T5	7/8/2012	32.8786	-117.3436	300
	MV1217	T10	12/15/2012	32.6916	-117.3758	300
	MV1217	T4	12/9/2012	32.9523	-117.3184	300
	MV1217	T7	12/12/2012	32.8100	-117.4004	300
	NH1318	T1	7/27/2013	32.6694	-117.3975	300
	NH1407	T1	4/20/2014	32.6986	-117.3765	300
	LACSD	T4	2/13/2014	33.6787	-118.3276	305
	LACSD	T5	2/13/2014	33.6787	-118.3276	305
	SP1510	T6	6/13/2015	32.7209	-117.3737	325
	NOAA	17462	7/16/2014	33.9551	-118.6931	333
	SP1408	T1	11/1/2014	32.7070	-117.3760	340
	SP1504	T1	4/11/2015	32.7244	-117.3660	340
	SP1524	T1	10/18/2015	32.7244	-117.3660	340
	SP1603	T1	3/13/2016	32.7035	-117.3776	340
	SP1612§	T1	7/9/2016	32.7013	-117.3796	340
	NH1414†	T1	7/26/2014	32.7010	-117.3852	360
	CSD	9107	8/13/2013	33.0938	-117.4172	400
	MV1217	T3	12/9/2012	32.9471	-117.3416	400
	MV1217	T6	12/12/2012	32.8100	-117.4004	400
	RGS131019A	T1	10/19/2013	32.7502	-117.4127	427
	CSD	9023	8/1/2013	32.6701	-117.4209	435
	NOAA	19514	7/14/2014	33.1547	-117.5011	443
OMZ	NOAA	17547	7/20/2014	33.9203	-118.6997	459
	NOAA*	18528	7/21/2014	33.5548	-118.1257	465
	LACSD	9223	8/16/2013	33.6759	-118.3325	470
	NOAA*	20605	7/16/2014	32.8990	-118.6182	475
	VRG*	9309	8/20/2013	33.9774	-118.8764	493
	NOAA	20758	7/17/2014	32.7824	-117.4419	555
	NH1414*	T5	7/29/2014	32.8908	-117.4745	698
	NH1414	T7	7/29/2014	32.8128	-117.4670	700
	SP1506§	T1	4/18/2015	32.8109	-117.4710	715
	NOAA†	20738	10/14/2014	32.8279	-118.0311	768
LOMZ	SP1612§	T2	7/9/2016	32.8242	-117.5394	900
	NOAA	19490	7/1/2014	33.2165	-118.2318	1116

Table S2. Proposed usage of elements in biological carbonate structures as marine environmental proxies. Modified after Levin (2006).

Environmental Variable	**Proxy Elements (standardized to [Ca])**	**References**
Temperature	Mg, Sr	Levin (2006)
pH	Mn, Zn, B, U	Hönisch and Allen (2013) Frieder et al. (2014)
$[CO_3^{2-}]$	Zn, U	Marchitto et al. (2000) Russell et al. (2004)
Upwelling	Cd	Fodrie et al. (2011)
$[O_2]$	Mn, Cd	Levin (2006) Limburg et al. (2015)
Productivity	Ba, U	Tribovillard et al. (2006)
Salinity	Ba, Sr	Walther and Limburg (2012)
Structural Properties (e.g., Hardness, Elastic Modulus)	Mg, Fe, P, Ni, Pb	Byrne et al. (2014) Naleway et al. (2016)

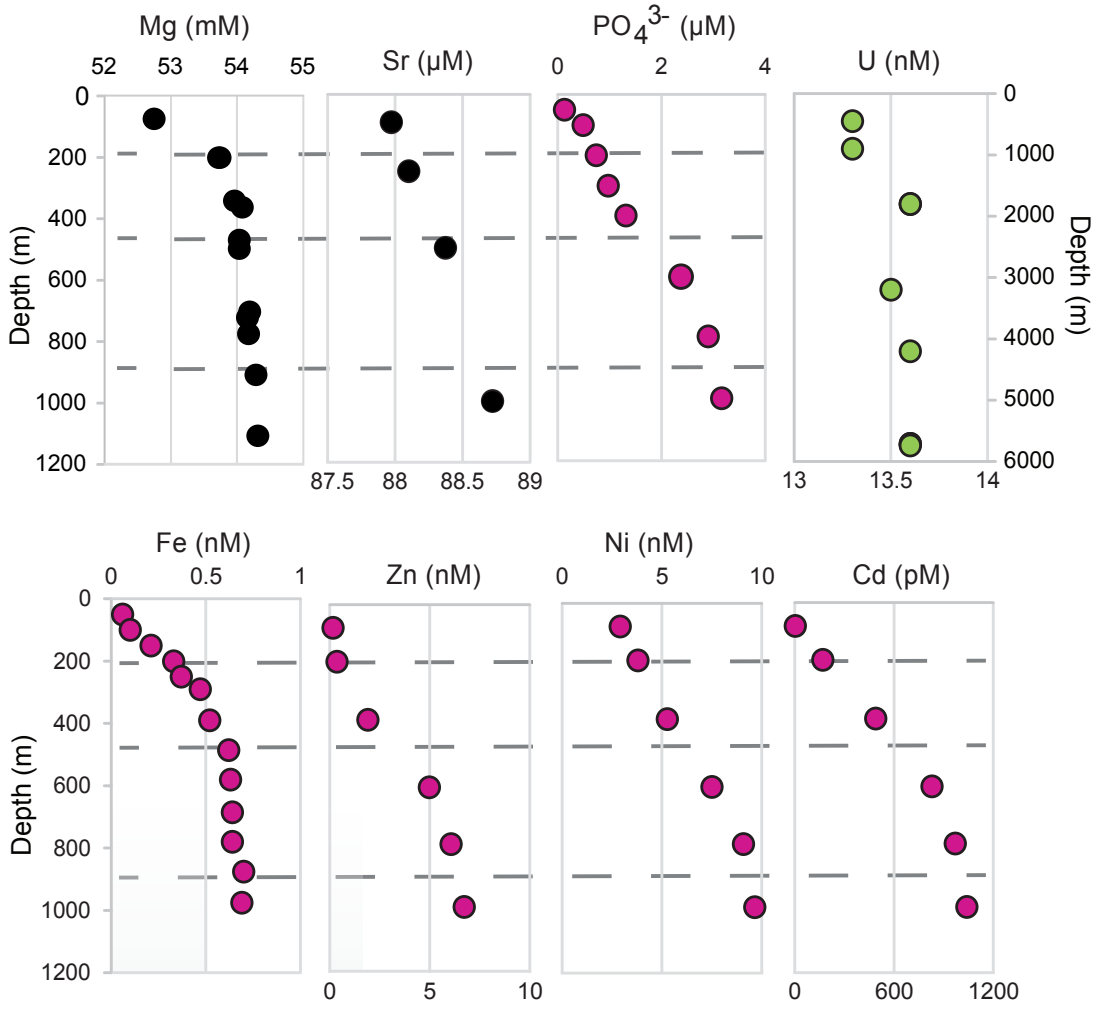

Figure S1. Elemental concentrations of various elements in seawater in the upper 1,000 m of the water column (except Uranium). Pink dots indicate elements that demonstrate a nutrient-like profile. Elemental sample locations (Pacific Ocean) and concentration data were extracted from Biller and Bruland (2013) and K. Johnson's *Periodic Table of Elements in the Ocean*. Available online at: http://www.mbari.org/science/upper-ocean-systems/chemical-sensor-group.

Figure S2. Image of a dried ossicle plate from the test of *Strongylocentrotus fragilis* sanded flat and mounted to a steel block prior to nanoindentation analysis.

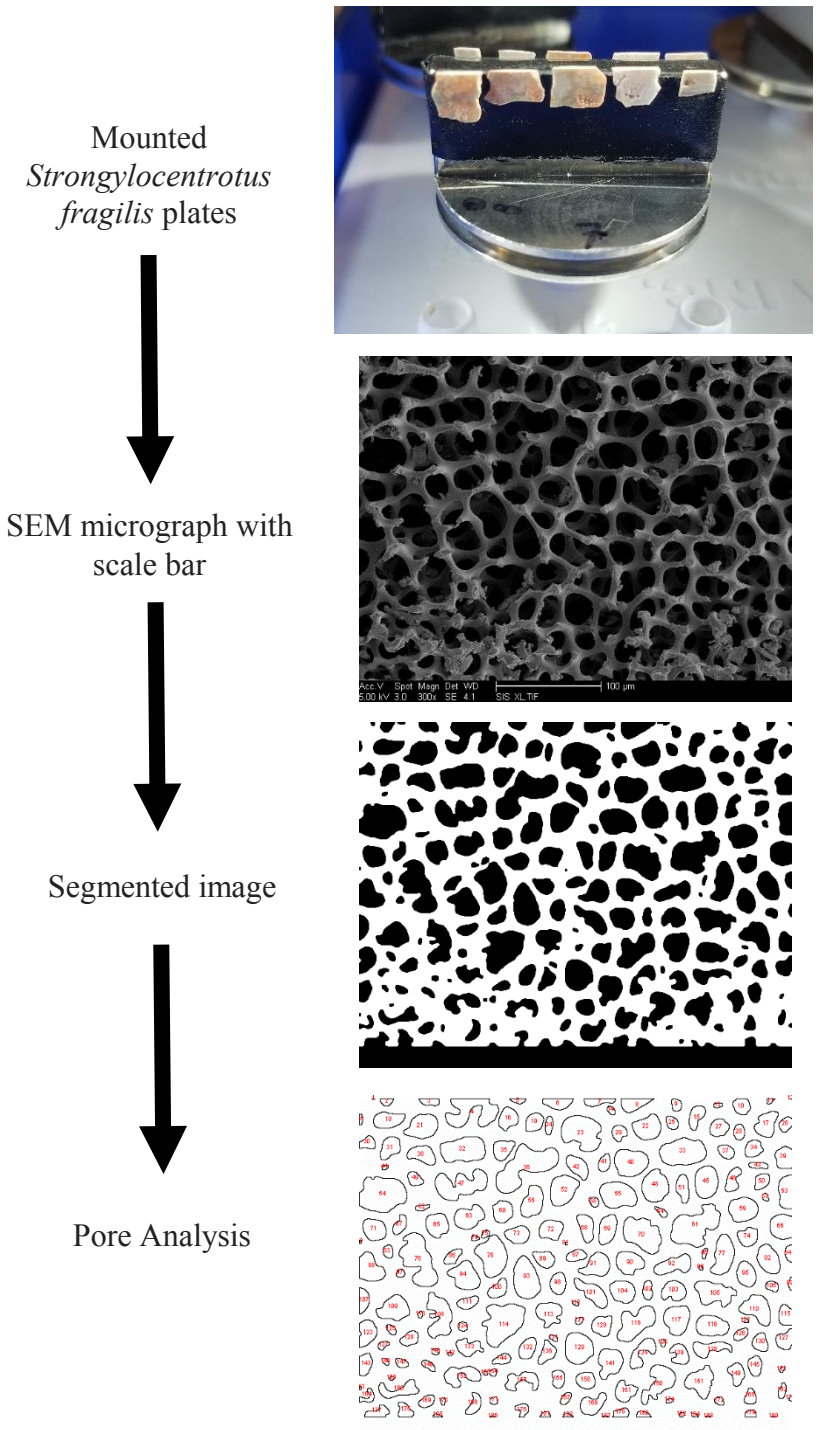

Figure S3. Flow chart of methods used for quantification of porosity and pore size from Scanning Electron Microscopy images. Segmented image and particle analysis were carried out in ImageJ. Scale bar: 100 µm.

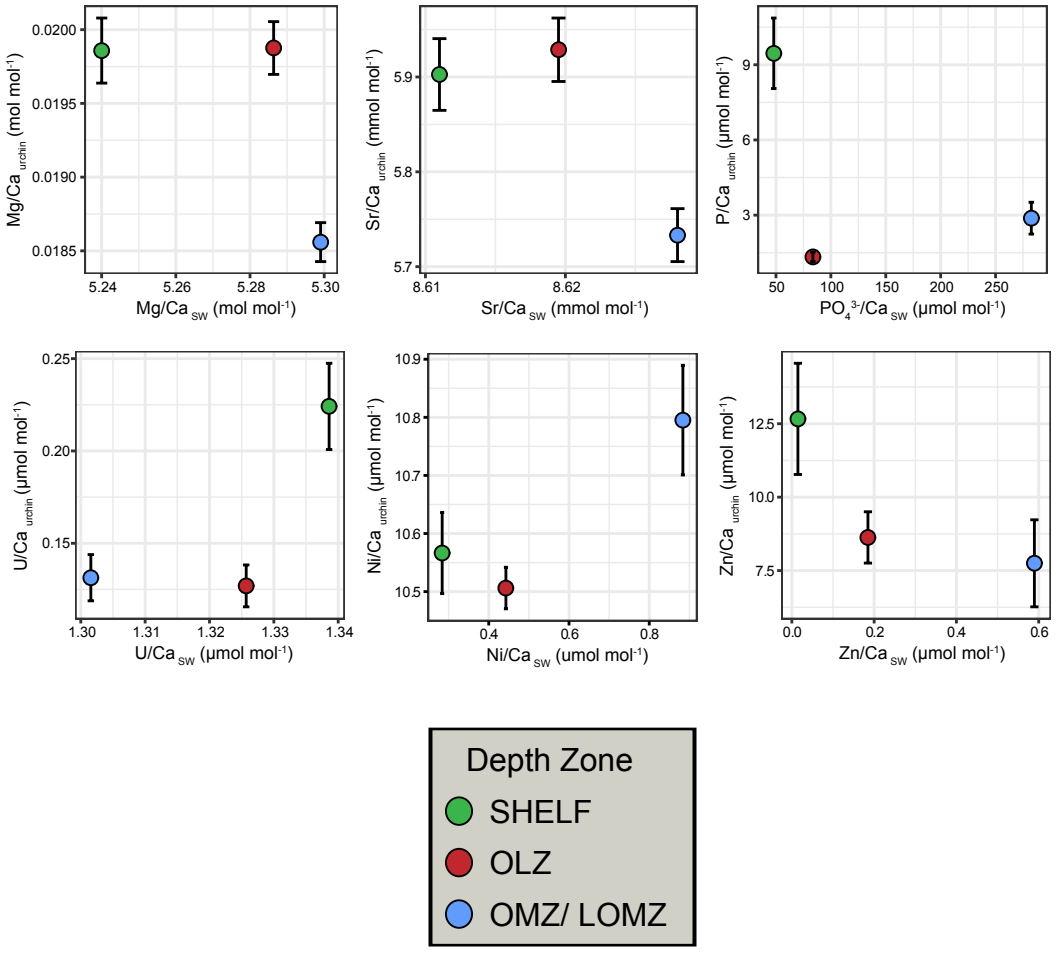

Figure S4. Relationships between element to calcium ratios in *Strongylocentrotus fragilis* test plates (E/Ca_{urchin}) and element to calcium ratios in seawater (E/Ca_{SW}) within different depth zones. E/Ca_{urchin} were averaged across depth bins: Shelf (green), Oxygen Limited Zone (red), and Oxygen Minimum Zone (blue). Black lines indicate significant linear regression relationships which yielded empirical partition coefficients (D_{metal}) for Cd and Fe only. Elemental concentrations of various elements in seawater (Mg, Sr, P, U, Ni, Zn, Cd, Fe, and Ca) in the upper 1,000 m of the water column were extracted from Biller and Bruland (2013) and Dr. Kenneth Johnson's *Periodic Table of Elements in the Ocean*. Available online at: http://www.mbari.org/science/upper-ocean-systems/chemical-sensor-group. Error bars indicate ± 1 standard error.

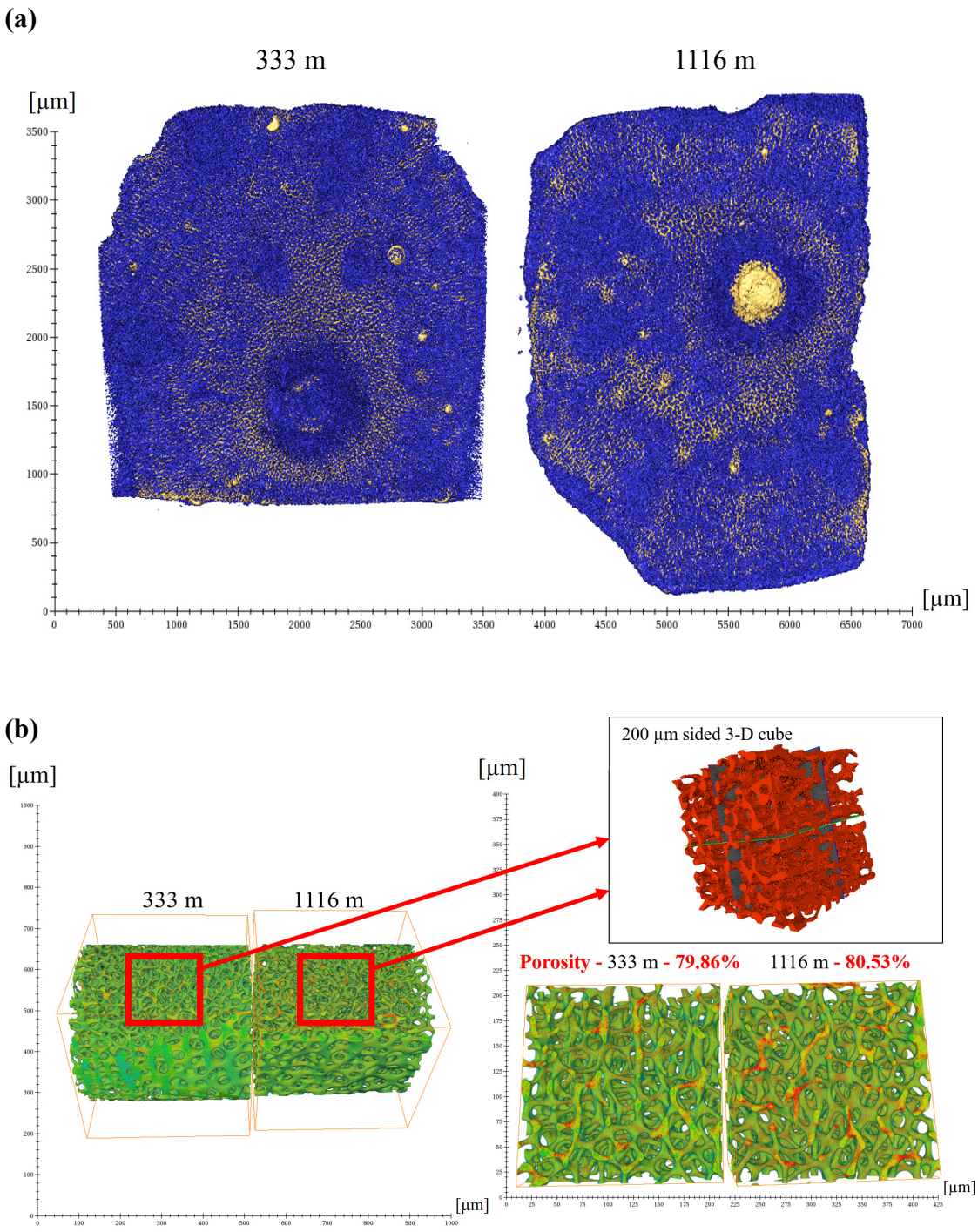

Figure S5. High-resolution micro-computed tomography (HR-µCT) images of *Strongylocentrotus fragilis* test plates from 333 m and 1116 m. **a.** Distribution of surface porosity was visualized by adjusting the threshold range limits (i.e., average range threshold limits (Purple) and upper range (low porosity) threshold limits (Gold)). **b.** 3-D porosity for each sample was measured in a 200-µm sided box calculated from Material Statistics outputs (Amira software, FEI Visualization).

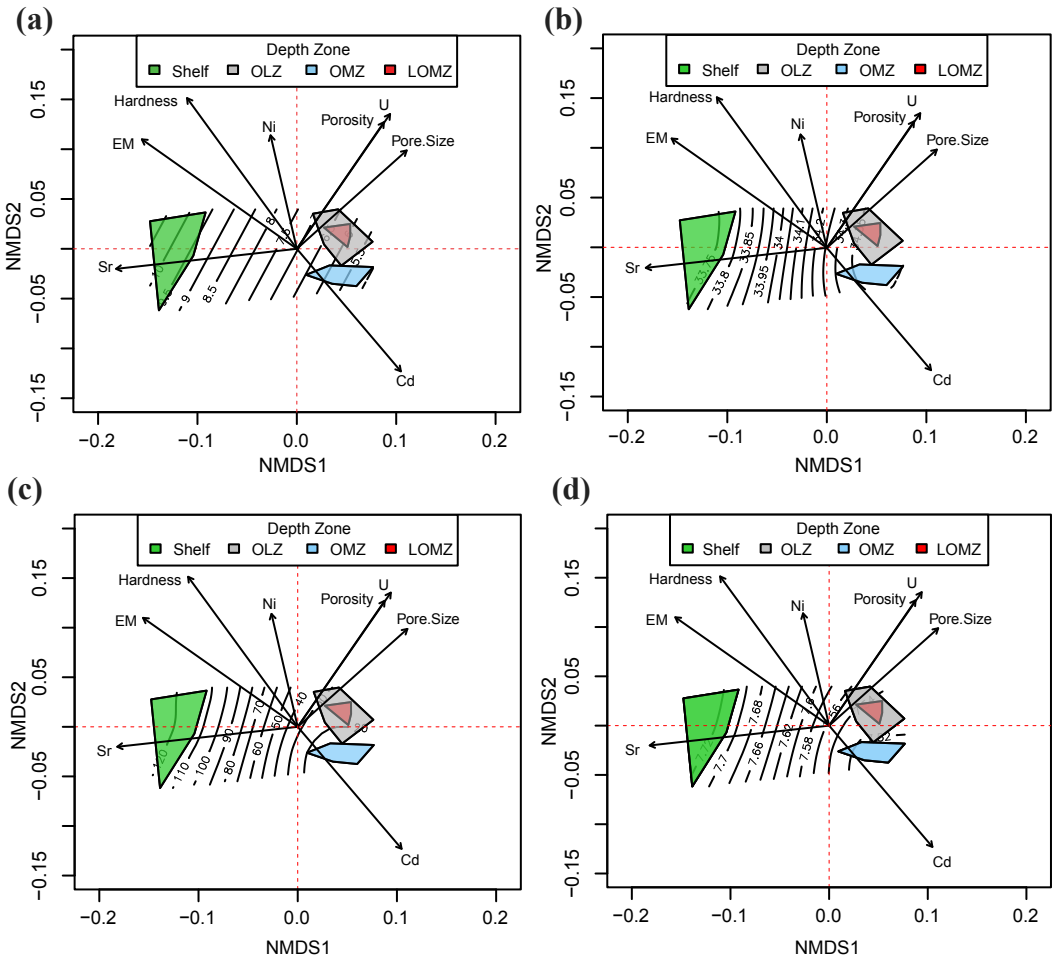

Figure S6. Nonmetric multidimensional scaling plot showing dissimilarity among *Strongylocentrotus fragilis* sites pooled into 4 depth zones overlaying environmental variables: **a.** temperature (°C), **b.** salinity (PSU), **c.** dissolved oxygen (µmol oxygen kg^{-1} seawater), and **d.** *in situ* pH_{Total}. Green: Shelf = <200 m; Red: OLZ = Oxygen Limited Zone (22-60 µmol oxygen kg^{-1}); Blue: OMZ = Oxygen Minimum Zone core (< 22 µmol oxygen kg^{-1} or 0.5 mL L^{-1}); Purple: LOMZ = Lower Oxygen Minimum Zone (>900 m where dissolved oxygen begins to increase). Vector length is proportional to the correlation between ordination axis and the environmental, elemental, or biomechanical variable. Vector direction indicates the direction of the gradient.