SPATIAL DECISION SUPPORT SYSTEM, FUZZY LOGIC MODELLING AND ILLUSTRATIVE MAPS OF POTENTIAL NODULE RESOURCES IN THE CCZ

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objective of SPATIAL DECISION SUPPORT SYSTEM (SDSS) MODELLING

- to estimate the mineralization potential in areas of the CCZ where polymetallic nodule abundance and metal content data are not available

techniques employed in SDSS modelling

- Weights of Evidence
- Fuzzy Logic
- Logistic Regression
- Artificial Neural Network (ANN)

ore-forming key controlling factors for nodule mineralization= valuable proxies might be used in SDSS modelling

- age and growth rate of nodules
- size and/or composition of the nodule nucleus
- water depth and paleo-water depth
- seafloor topography
- primary productivity
- deep water massess/currents and paleo-masses/currents
- CCD (Carbonate Compensation Depth)
- chemical composition of sea water
- Eh at the interface between bottom water and sediments
- composition thickness and age of sediments,
- geothermal gradient
- hydrothermal input
- benthic biological activity (bioturbation)
- ……

Proxies and Data used in this SDSS Modelling

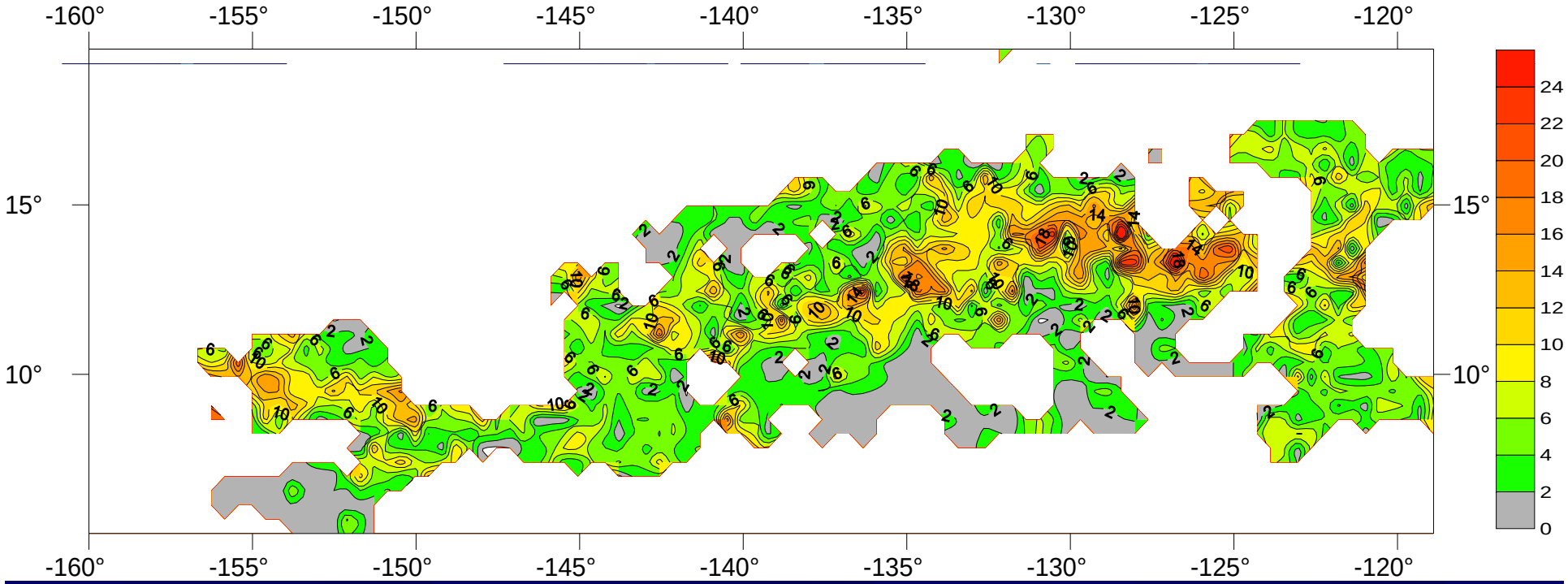
- Abundance
  - Grid data in the CCZ from Morgan, 2008
- Sediments
  - Figures in the CCZ from Kazmin, 2003 and Halbach et al., 1988
  - Samples in COMRA's areas collected from 1,606 stations by grab samplers

- Primary productivity
  - Figure in the CCZ from Morgan, 2000
- CCD
  - Data in the CCZ provided by Cronan, 2006 at intervals of 5° longitude and 1° latitude
- Regional bathymetric regimes
  - Classified according to bathymetric map in the CCZ

- Bathymetric data
  - The bathymetry of the COMRA was determined at high resolution using SeaBeam multi-bean echo-sounding systems

NODULE ABUNDANCE AND METAL CONTENT

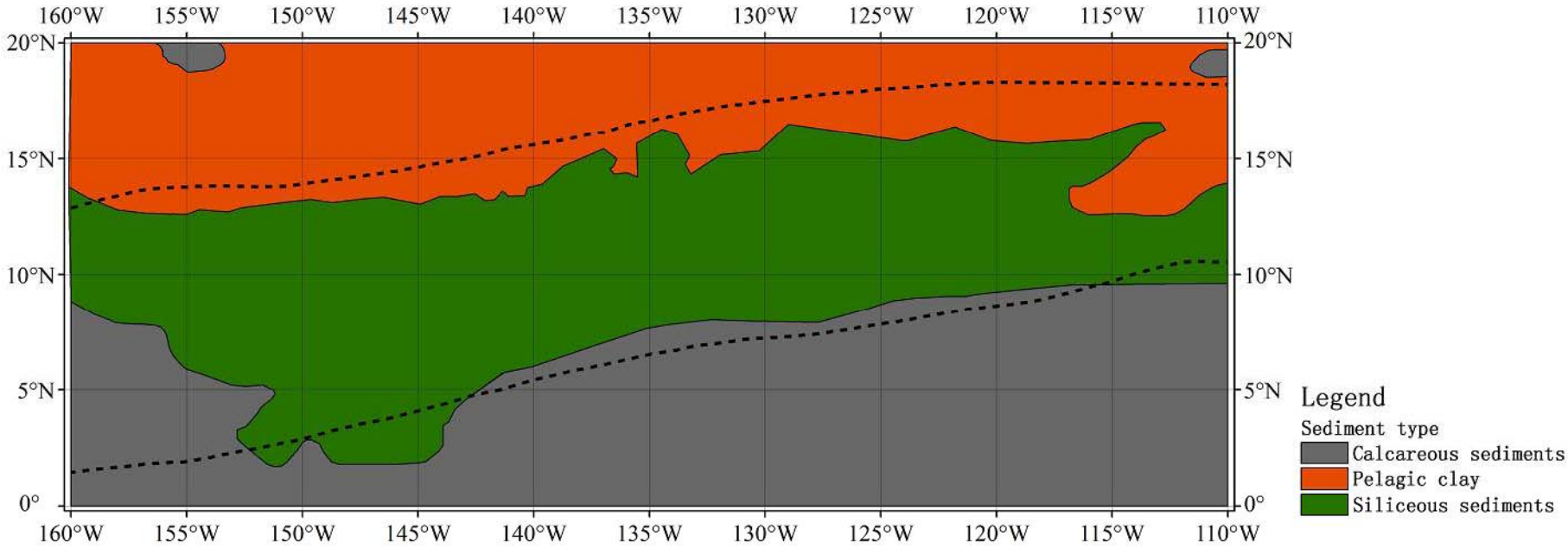
we choose those areas with abundance of manganese nodules higher than 2 kg/m^2 as defining the area that contains the known deposit .



(edited after grid data from Morgan, 2008)

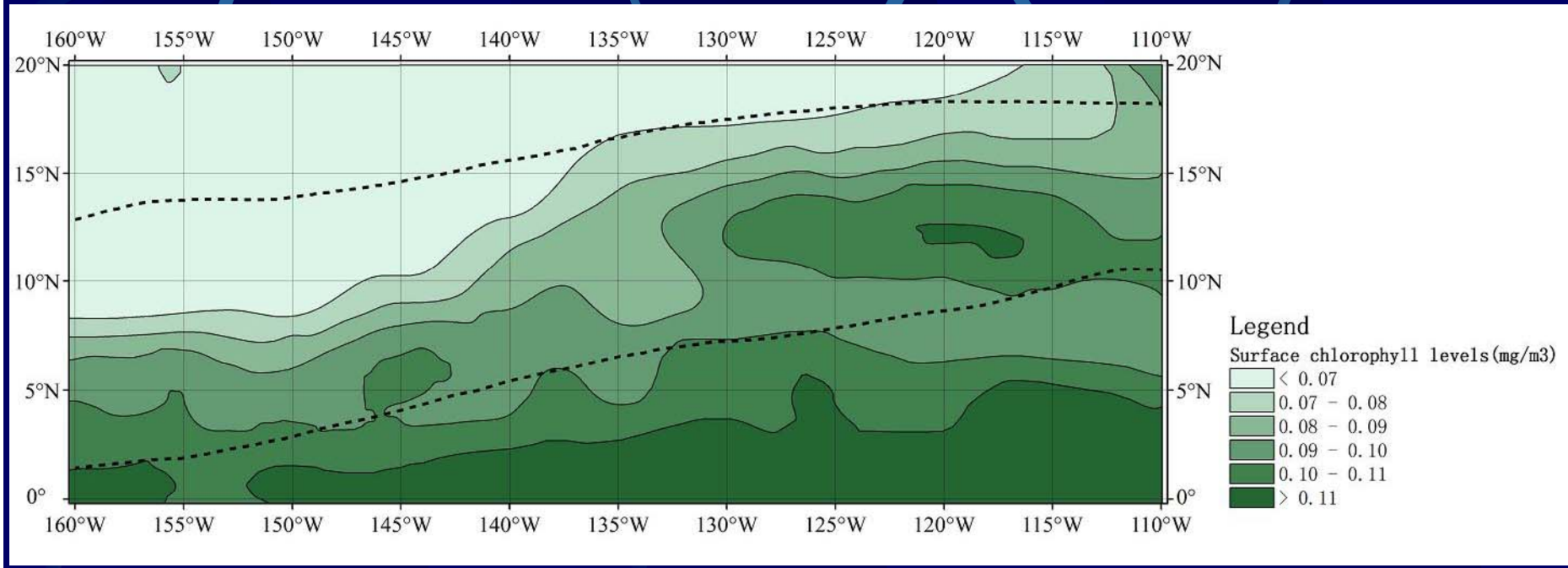
SEDIMENT TYPES

the areas covered with siliceous sediments as the most favorable areas for nodule formation, these areas covered with pelagic clays as less favorable sites, but the areas covered with calcareous sediments are designated as unfavorable for deposit occurrence.



(modified from Kazmin, 2003 and Halbach et al., 1988)

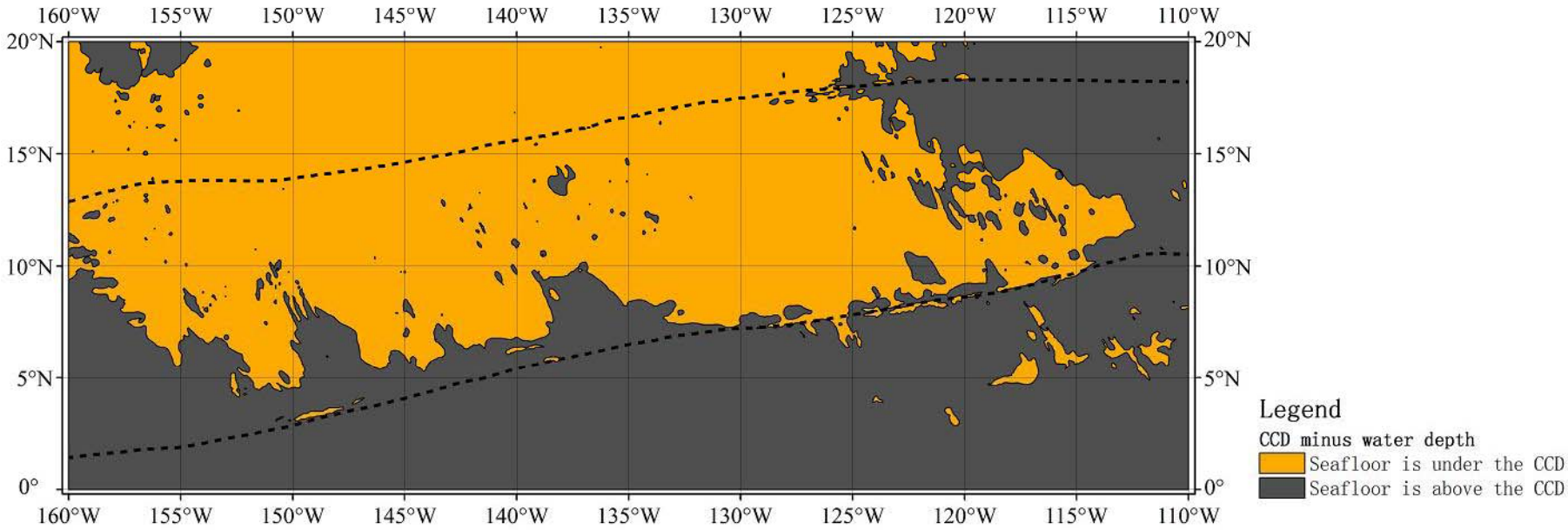
PRIMARY PRODUCTIVITY



(modified from Morgan, 2000)

CCD MINUS WATER DEPTH

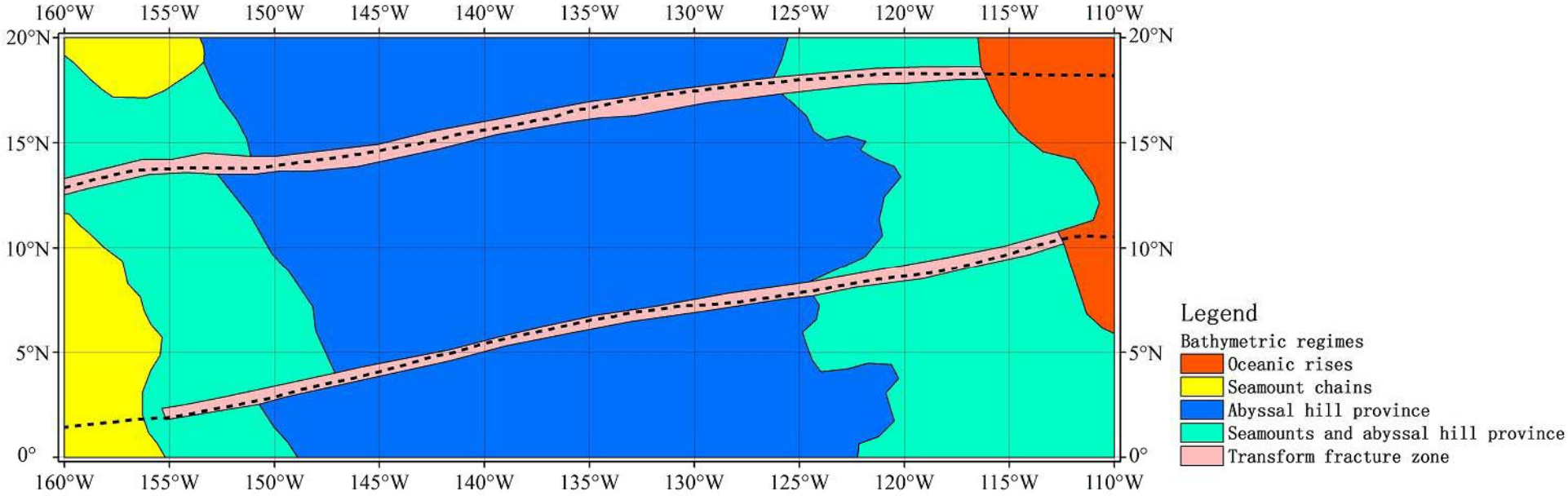
sites where the CCD is at or above the seafloor are favorable for the formation of nodules, while sites where the seafloor is shallower than the CCD are unfavorable for the formation of nodules.



(generated from CCD data provided by Cronan, 2006 at intervals of 5° longitude and 1° latitude)

REGIONAL BATHYMETRIC REGIMES

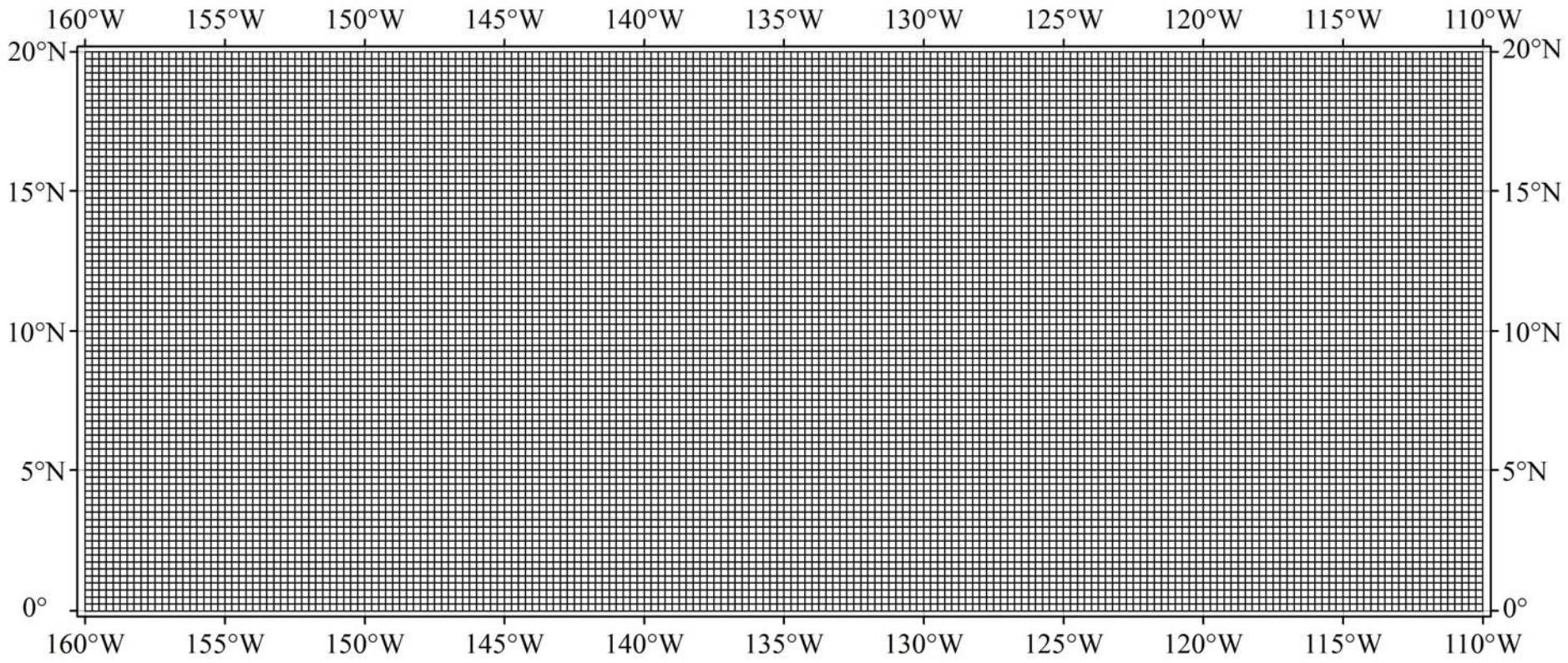
ranging from most favorable for nodule deposit occurrence to least favorable:
Abyssal Hill Province > Seamounts and Abyssal Hill Provinces > Oceanic Rise = Seamount Chains = Transform Fracture Zones



GRID CELLS

- **Grid Cell Specification in the CCZ**

15’ latitude x 15’ longitude, total of 16,000 grid cells



INPUT DATA, WEIGHTS OF EVIDENCE AND LOGISTIC REGRESSION

Variable	Criterion	Value Assigned
Abundance (kg/m^2)	≥2	1
	< 2	0
Sediment Type	Siliceous	1
	Pelagic clay	1
	Calcareous	0
Surface Water Chlorophyll (mg/m^3)	**<** 0.07	0
	0.07~0.11	1
	> 0.11	0
Carbonate Compensation Depth (CCD)	CCD at or above seafloor	1
	Seafloor above CCD	0
Bathymetric Regime	Abyssal Hills	1
	Seamounts & Abyssal Hills	1
	Oceanic Rise, Seamount chains, Fracture Zones	0

INPUT DATA, FUZZY LOGIC AND RADIAL BASIS FUNCTION NETWORK MODELING

Variable	Criterion	Value Assigned
Abundance (kg/m^2)	≥2	1
	< 2	0
Sediment Type	Siliceous	0.9
	Pelagic clay	0.3
	Calcareous	0.1
Surface Water Chlorophyll (mg/m^3)	< 0.07	0.1
	0.07~0.08	0.8
	0.08~0.09	0.9
	0.09~0.1	0.8
	0.1~0.11	0.4
	> 0.11	0.2
Carbonate Compensation Depth (CCD)	CCD at or above seafloor	0.9
	Seafloor above CCD	0.1
Bathymetric Regime	Abyssal Hills	0.8
	Seamounts & Abyssal Hills	0.7
	Oceanic Rise, Seamount chains, Fracture Zones	0.1

RESULTS of WEIGHTS OF EVIDENCE

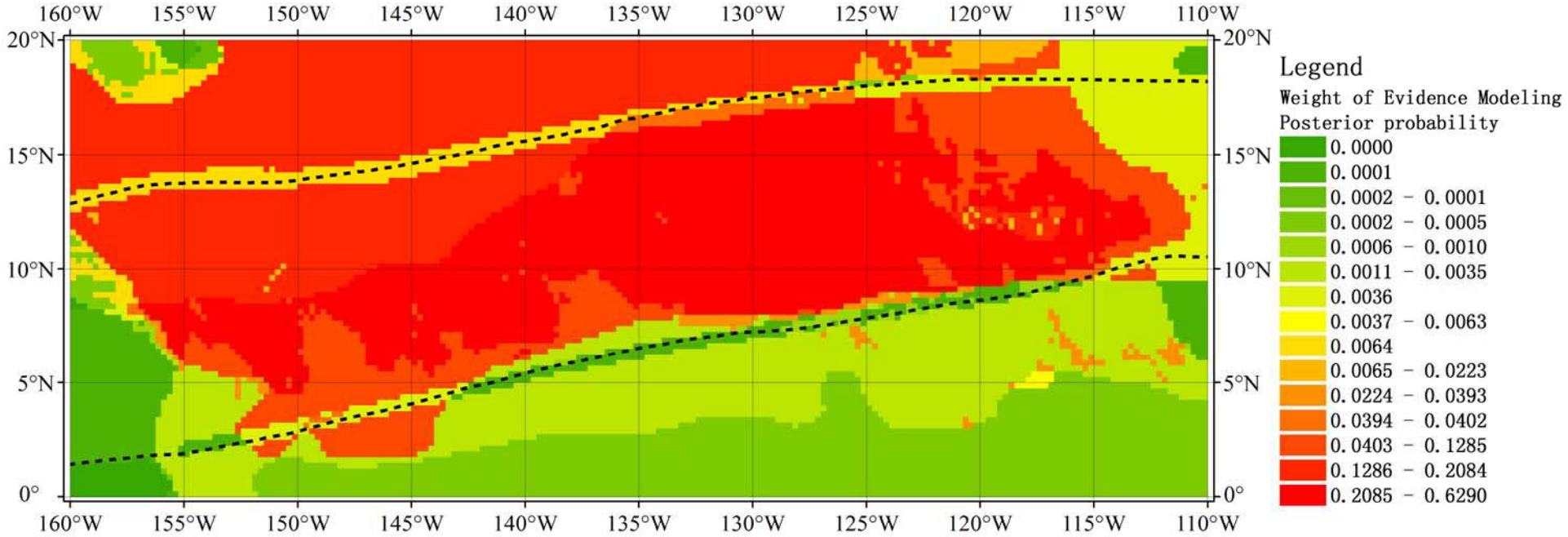
Geological Evidence Variable	Status	Total Grid Cells (*T*)	Total with Deposit Present (*M*)	Prior Probability (*P*)	Prior Odds (*O*)	Weight for Presence (W^+)	Weight for Absence (W^-)	Contrast (*C*)
Siliceous Sediments or Pelagic Clay	Present	10,398	3,046	0.2929	0.4143	0.5252		3.7235
	Absent	5,602	103	0.0099	0.0100		-3.1983	
Surface Water Chlorophyll	Favorable	9,367	2,617	0.2794	0.3877	0.4588		1.8623
	Unfavorable	6,633	532	0.0568	0.0602		-1.4035	
CCD Above Seafloor	Present	8,081	2,794	0.3457	0.5285	0.7686		2.4425
	Absent	7,919	355	0.0439	0.0459		-1.6739	
Hills or Seamounts & Abyssal Hills	Present	13,435	3,052	0.2272	0.2939	0.1820		3.6993
	Absent	2565	97	0.0072	0.0073		-3.5173	

The higher the Contrast, the closer the correlation between the evidence variable and nodule occurrence.

Contrasts from this table show decreasing correlations as follows:

Sediment Types > Bathymetric Regime > CCD minus water depth > surface water chlorophyll.

- **Weights of Evidence Results, Posterior Probabilities in the CCZ**



the highest probabilities are located at the middle and northern part of the CCZ and the lowest probabilities are located at the southern, southwestern, southeastern, northwestern, and northeastern parts of the CCZ.

6.5.2 LOGISTIC REGRESSION

- **Calculated Regression Coefficients, Logistical Regression**

Geological Evidence Variable	Sediment Type (b_1)	Primary Productivity (b_2)	CCD minus Water Depth (b_3)	Bathymetric Regime (b_4)	Regression Constant (b_0)
Regression Coefficient	3.3527	3.2830	2.4690	2.6289	-10.9658

The higher the regression coefficient, the closer the correlation between the evidence variable and nodule occurrence.

Regression coefficients from this table indicate the following sequence of decreasing correlation of the evidence variables with deposit occurrence:

Sediment Type > Surface Water Chlorophyll > Bathymetric Regime > CCD minus Water Depth

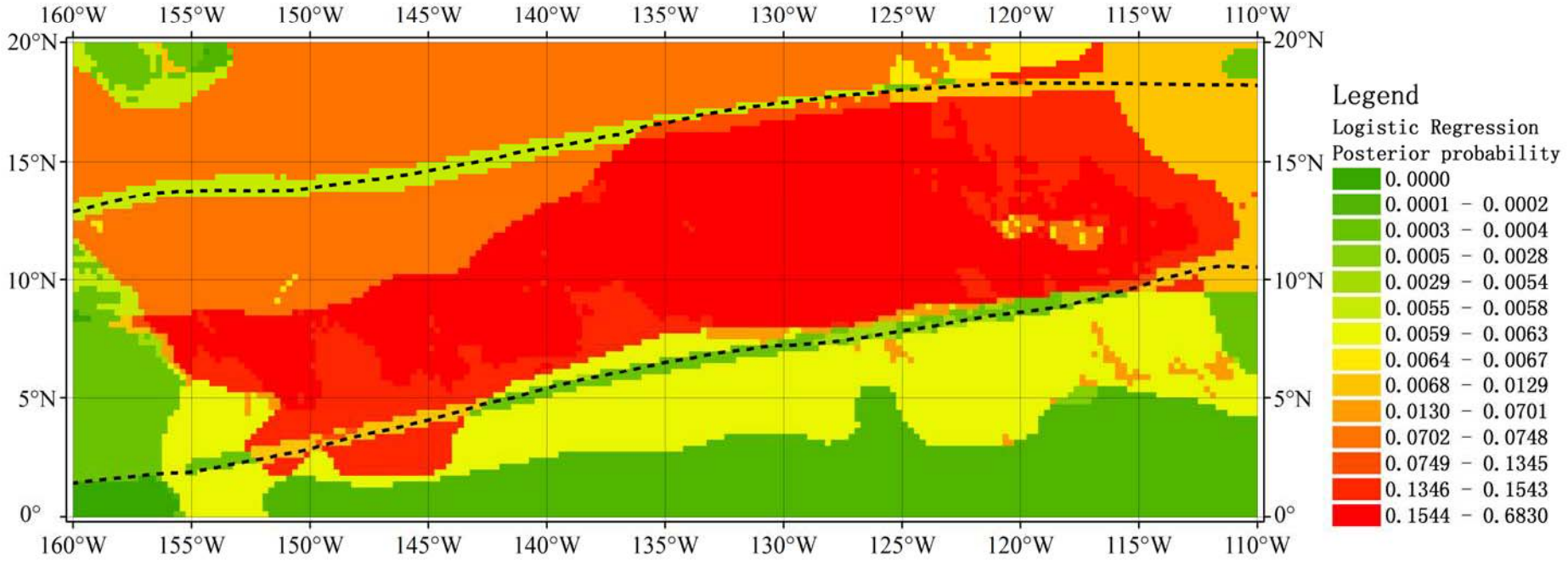
Though not completely consistent with the Weights of Evidence results, they both indicate that sediment type is the best indicator among the variables considered.

- These regression coefficients can be used to calculate the predicted probability of finding nodule deposits, as discussed above

- The resultant regression equation is:

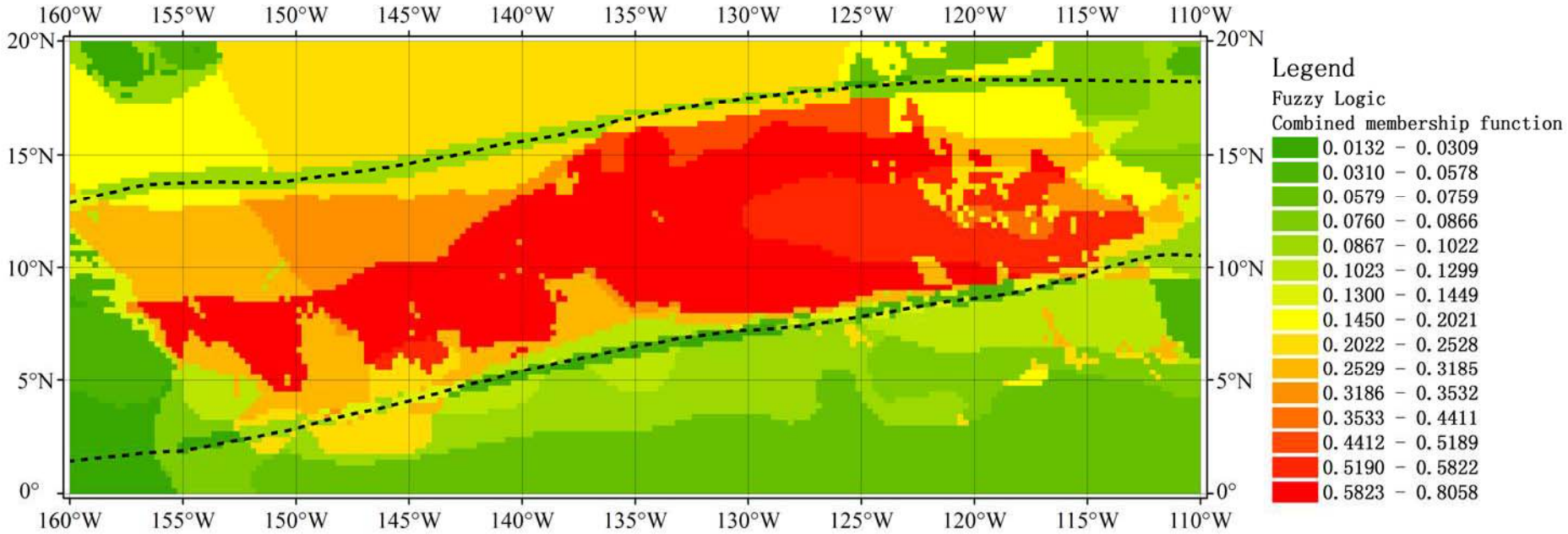
$$P_{post} = \frac{\exp(-10.9658 + 3.3527x_1 + 3.2830x_2 + 2.4690x_3 + 2.6289x_4)}{1 + \exp(-10.9658 + 3.3527x_1 + 3.2830x_2 + 2.4690x_3 + 2.6289x_4)}$$

Logistic Regression Results, Posterior Probabilities in the CCZ



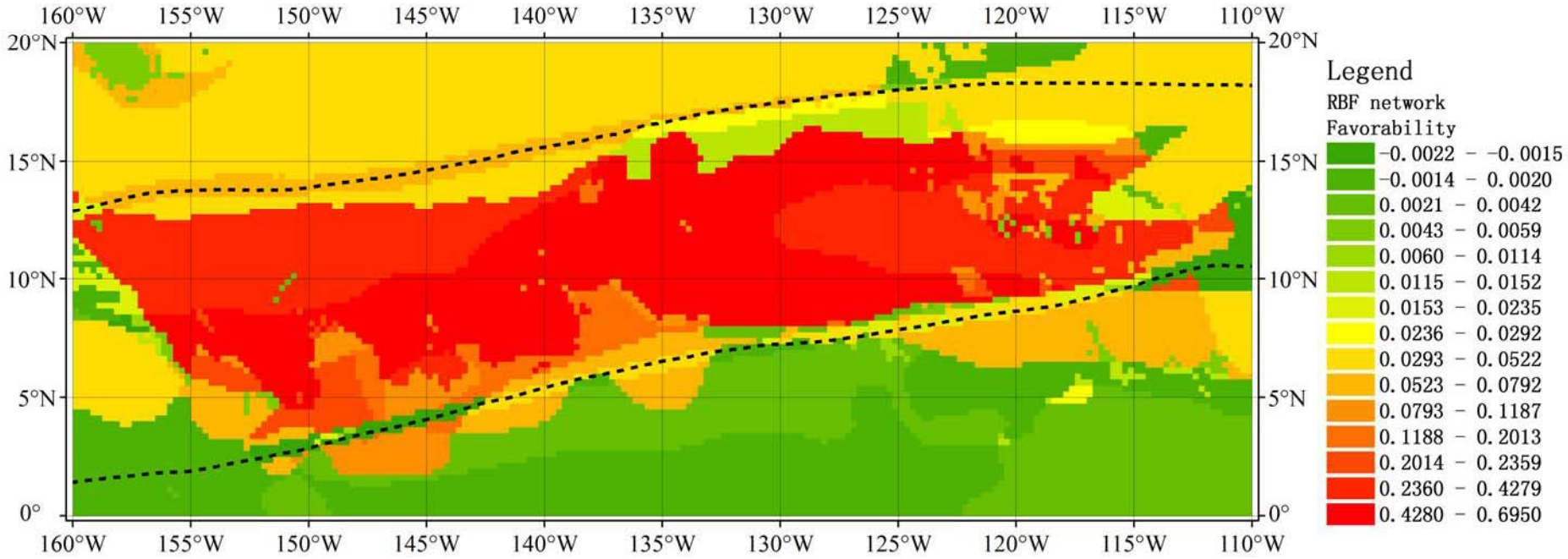
These results are similar to those for the Weights of Evidence calculations and indicate that middle and northern parts of the CCZ are relatively favorable for finding undiscovered nodule deposits, while the southern, southwestern and southeastern part of the CCZ are likely to be less likely to host nodule deposits.

Fuzzy Logic Results, Combined Membership Function Values in the CCZ



This figure shows high combined membership function values located at the middle part of the CCZ, suggesting that these areas are favorable for nodule occurrence, but low combined membership function values located at the southern, northern, southwestern and southeastern part of the CCZ, suggesting low favorability for nodule occurrence in these areas.

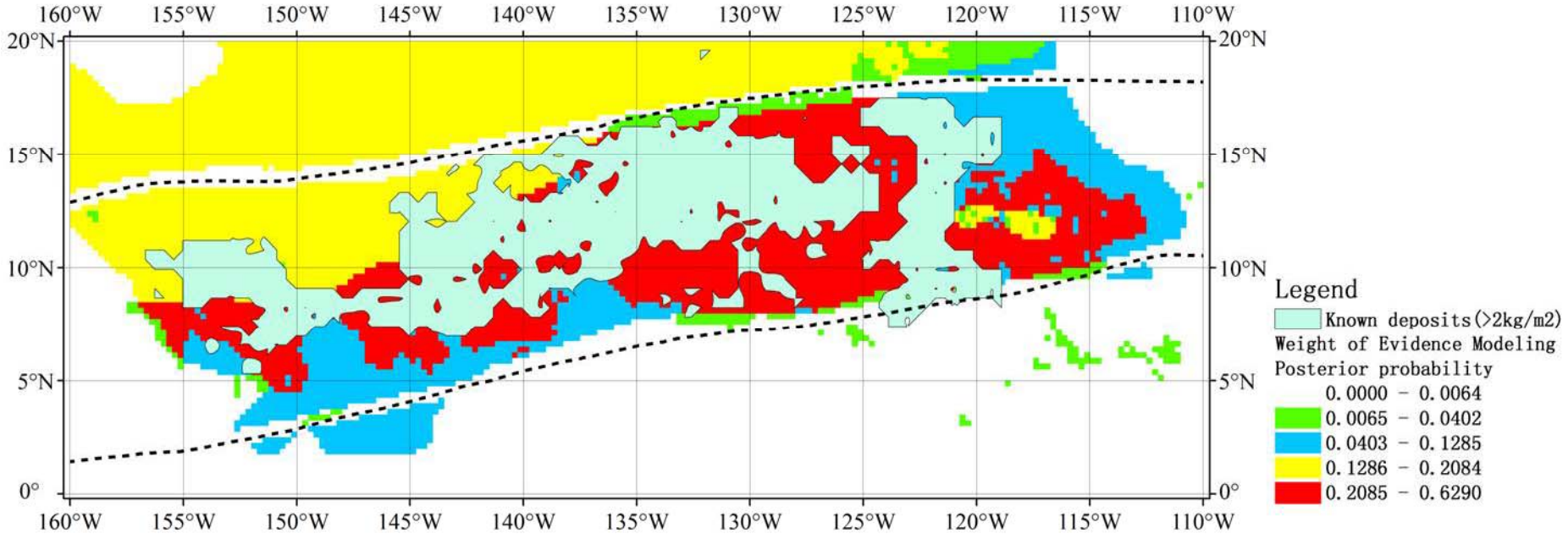
RBF Network Modeling, Favorability for Deposit Occurrence in the CCZ



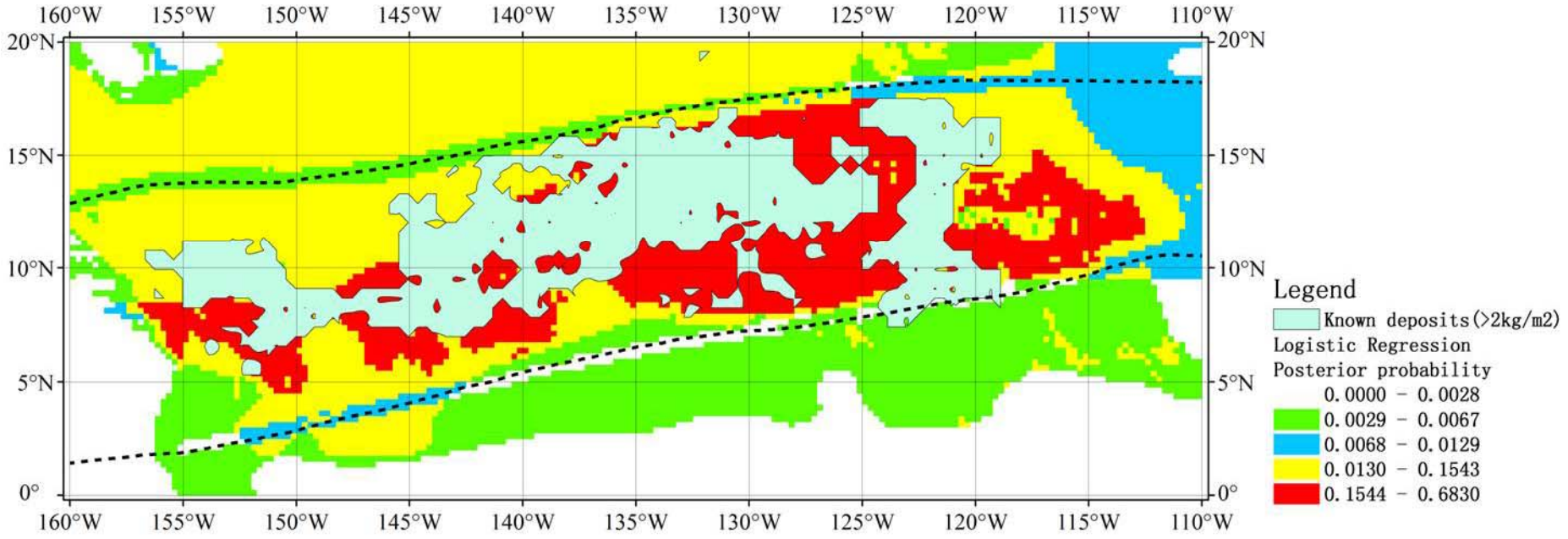
They are similar to those from the fuzzy logic modeling, and suggest that the relatively high probabilities for finding nodules in the CCZ occur at the middle and northern parts of the CCZ, but low probabilities for finding nodules occur at the southern, southwestern and southeastern part of the CCZ.

6.6 MAPS OF POTENTIAL NODULE RESOURCE AREAS

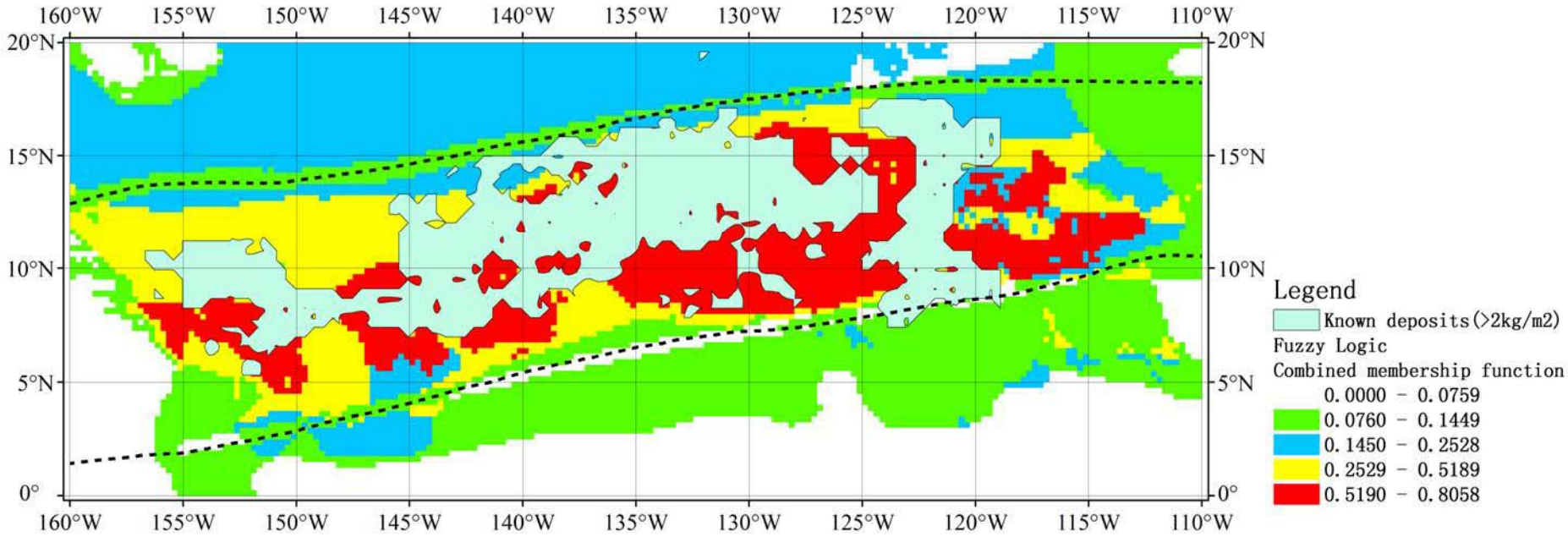
- **Likely Prospects for Nodule Occurrence, Weights of Evidence Modeling**



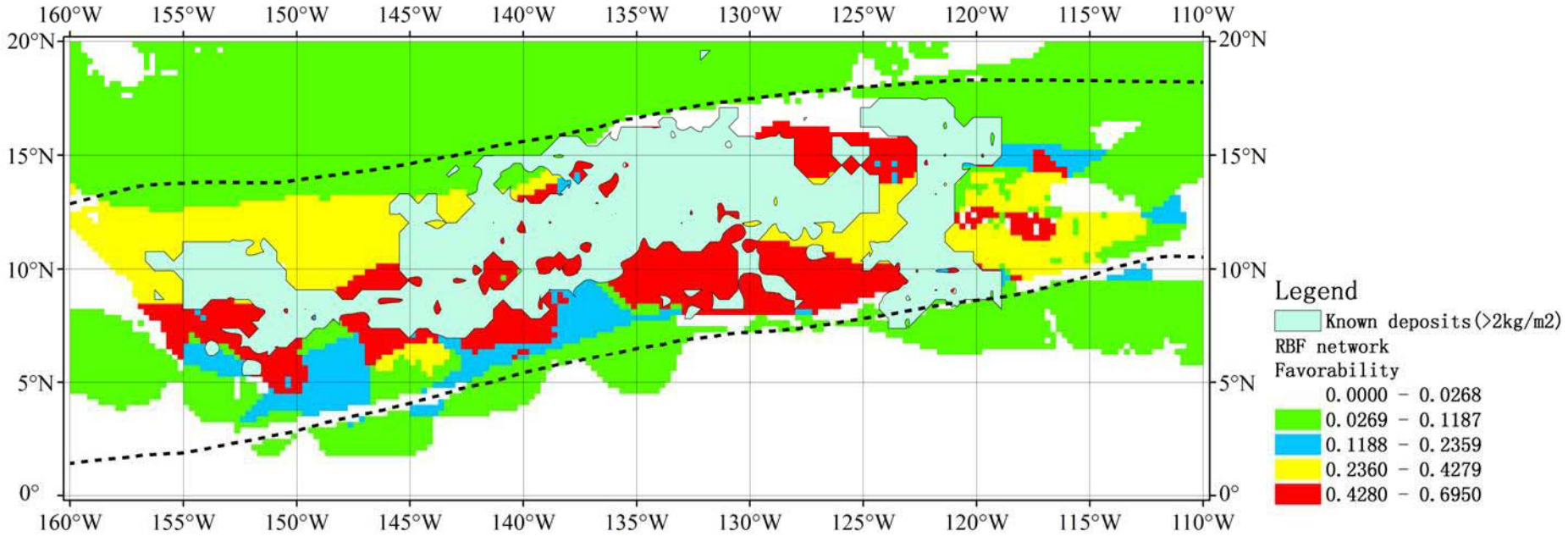
Likely Prospects for Nodule Occurrence, Logistic Regression



Likely Prospects for Nodule Occurrence, Fuzzy Logic



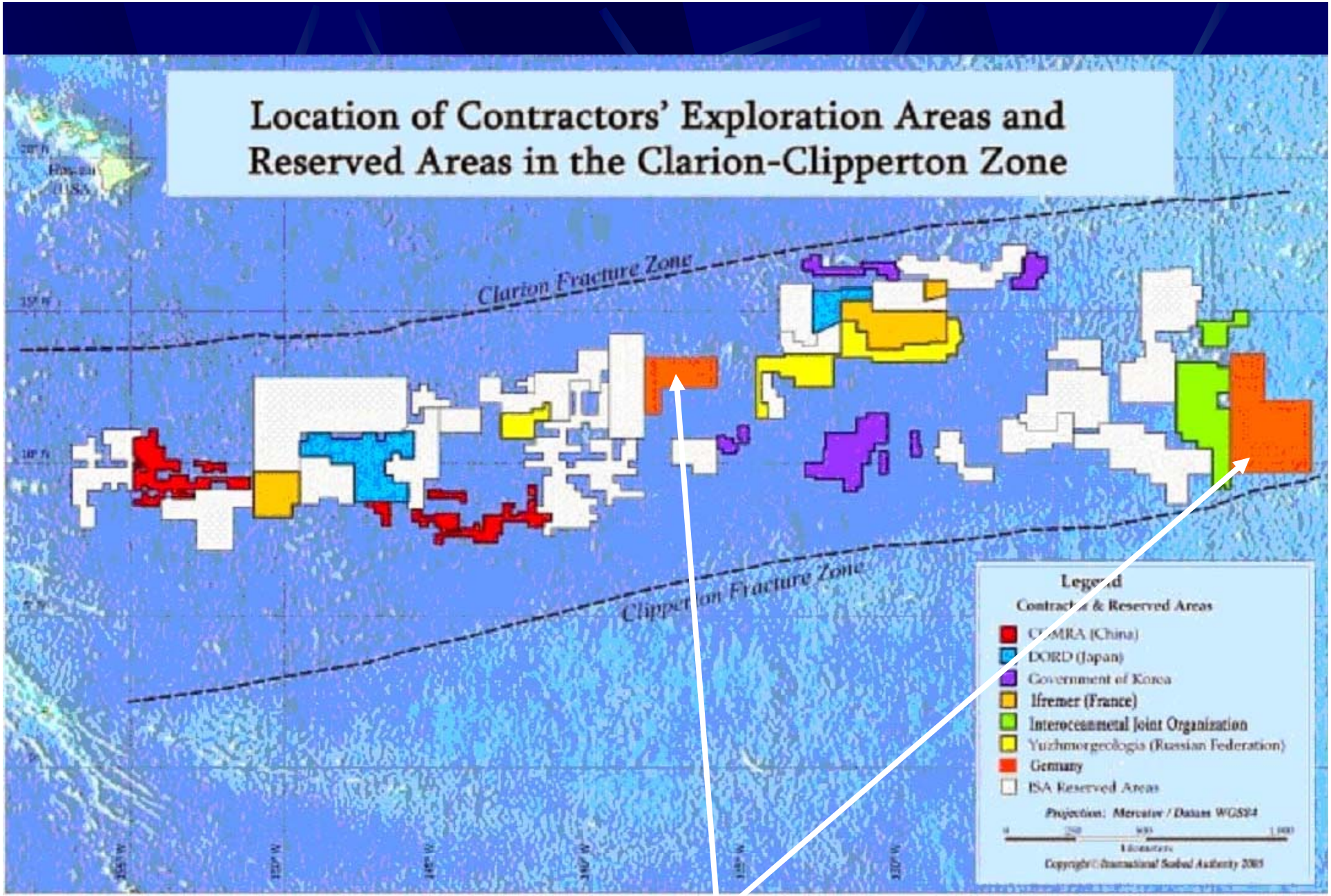
- **Likely Prospects for Nodule Occurrence, Radial Basis Factor Network**



- These predictions are represented by color from the most likely to least likely areas to host nodule deposits as follows:

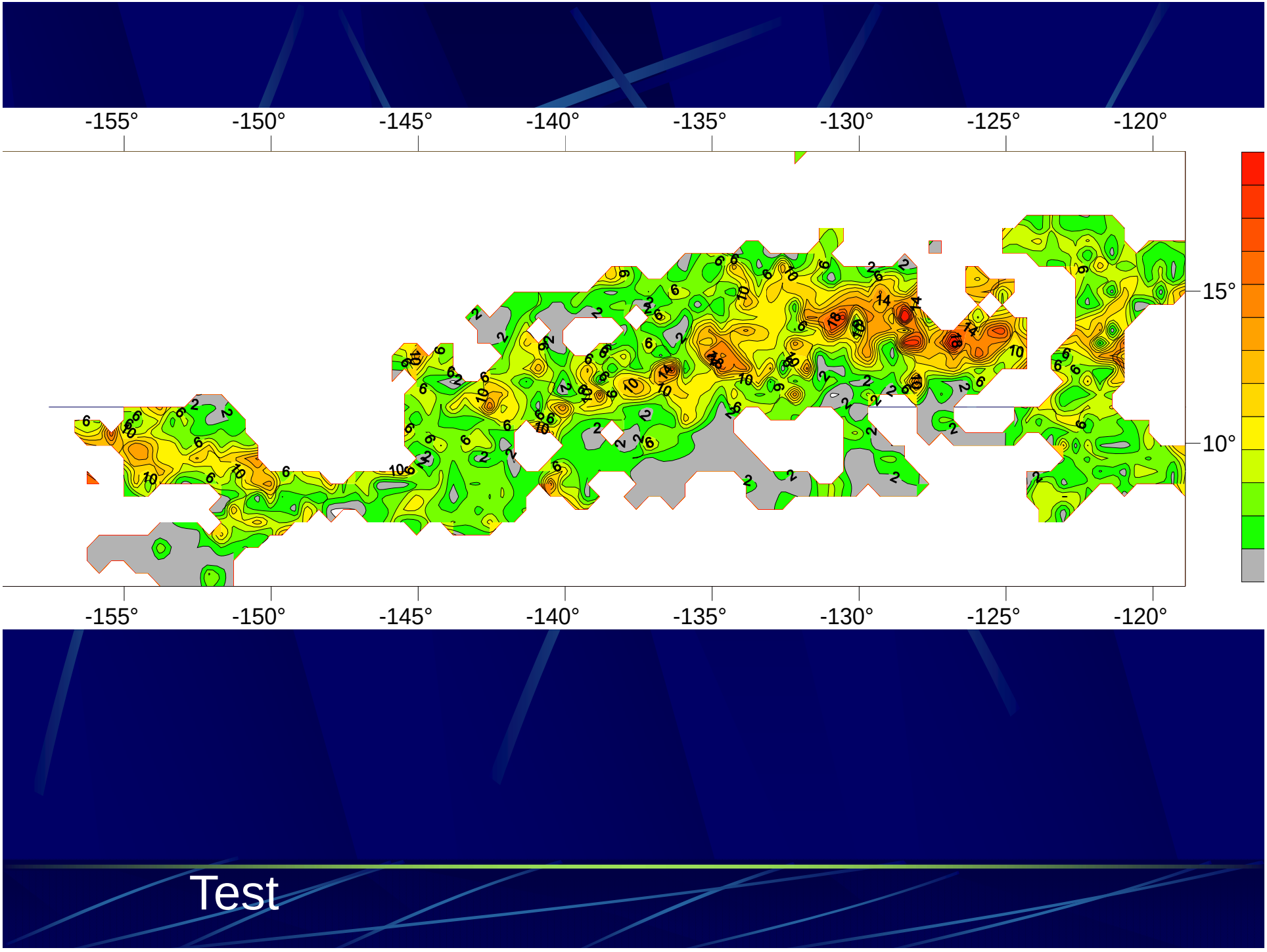
Red > Yellow > Blue > Green

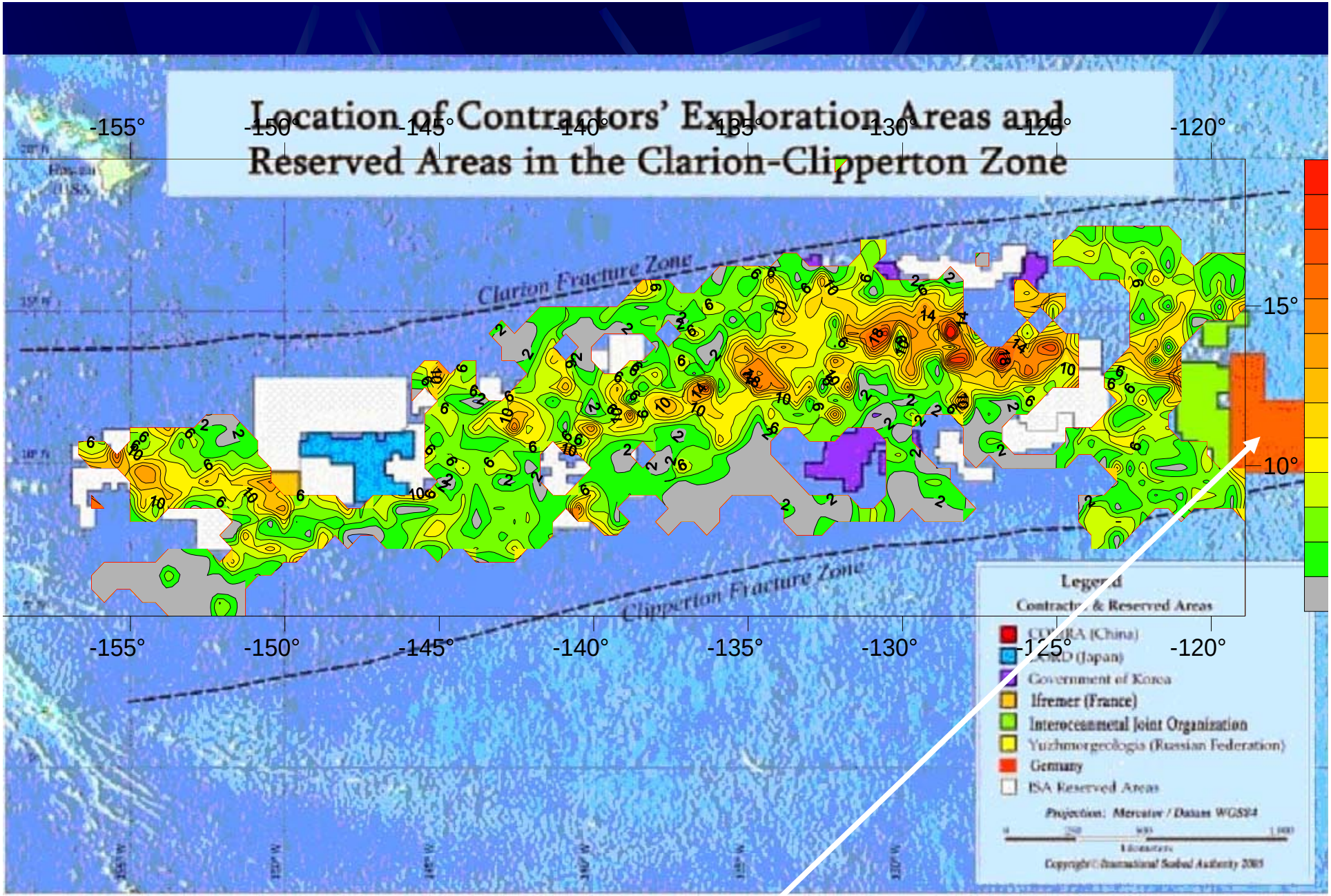
- Thus, future explorers might expect to get better results from exploration efforts that focus on the center and northern areas of the CCZ than the southern, southwesters, or eastern areas.



Test

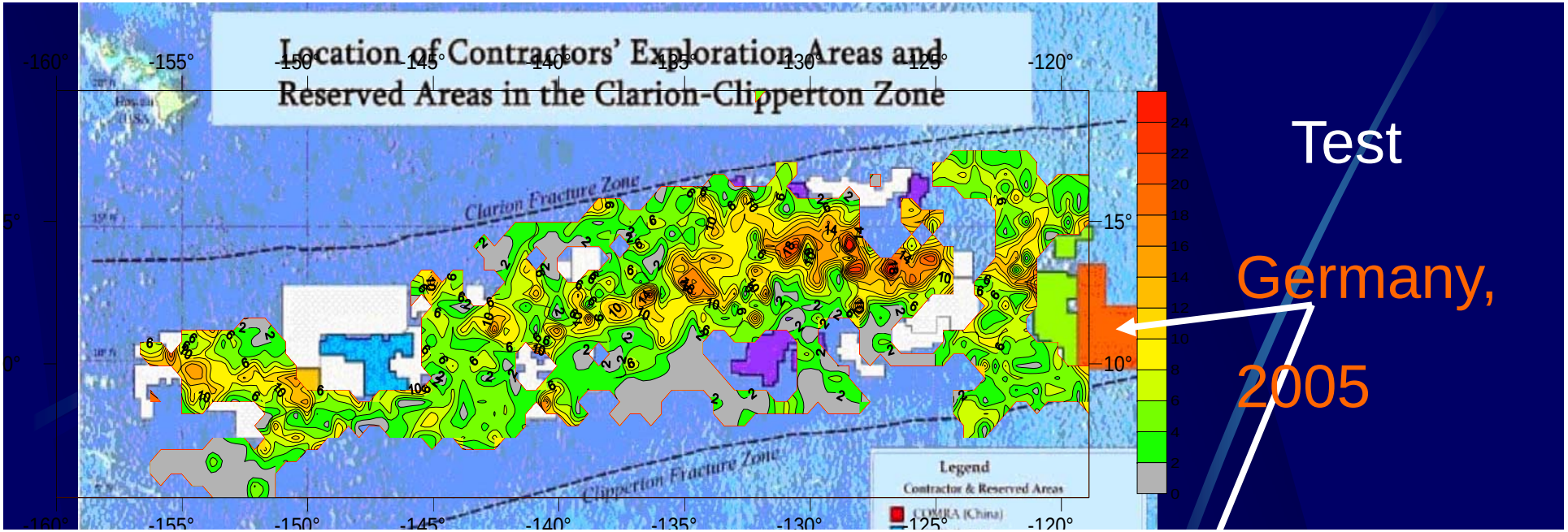
Germany,2005

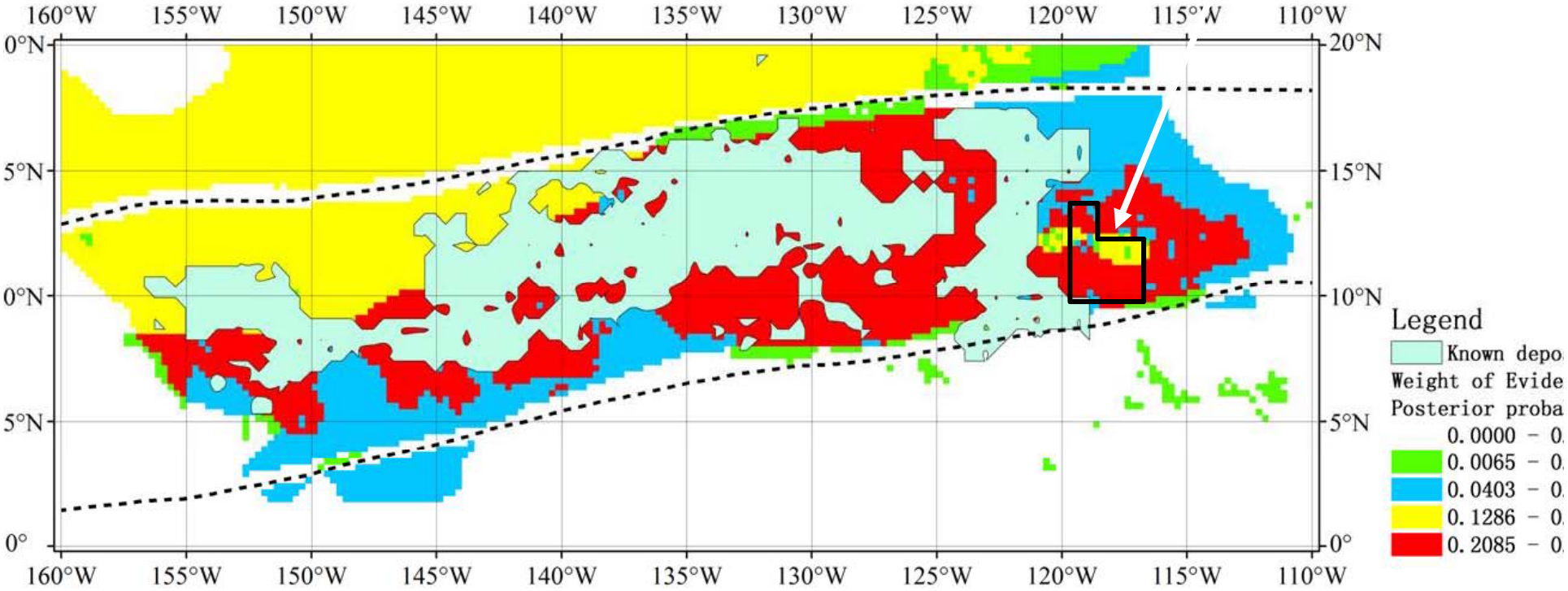

-155°
-150°
-145°
-140°
-135°
-130°
-125°
-120°
15°
10°
Test



Test

Germany,2005


Location of Contractors' Exploration Areas and Reserved Areas in the Clarion-Clipperton Zone
Clarion Fracture Zone
Clipperton Fracture Zone
Legend
Contractor & Reserved Areas
COMRA (China)
Test
Germany,
2005


160°W
155°W
150°W
145°W
140°W
135°W
130°W
125°W
120°W
115°W
110°W
0°N
5°N
20°N
15°N
10°N
Legend
Known depo
Weight of Evide
Posterior proba
0.0000 - 0.
0.0065 - 0.
0.0403 - 0.
0.1286 - 0.
0.2085 - 0.