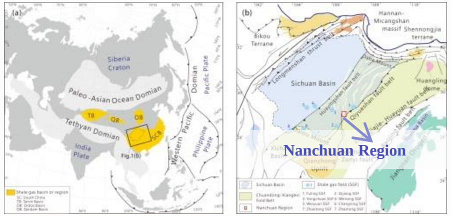
Prediction of the maximum compressive horizontal principal stress directions of medium to deep shale gas in the Nanchuan region, China

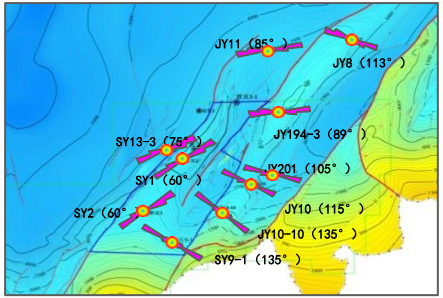
Tectonics & Basin Analysis

Ruiqing Yang, Fengli Yang, Panpan Hu

School of Ocean and Earth Science, Tongji University, Shanghai, China

Introduction





Existing Problems:

- σ_{Hmax} directions are complex
- the orientation changes rapidly (55°-135°)

SHELLS finite numerical modeling

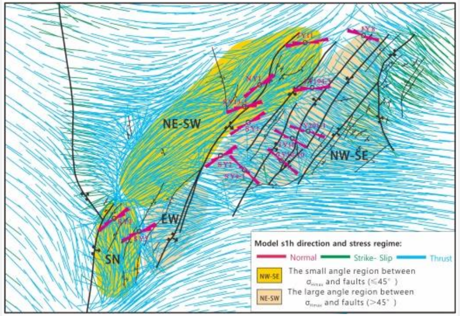
Modeling Method: SHELLS Modeling

- Developer: Prof. Peter Bird
  University of California, Los Angeles
- Website: http://www.peterbird.name/

Modeling Process

- Digitization of tectonic map
- Finite element meshing
- Model construction
  - Traces and dips of faults
  - Topography
  - Heat flow
  - Petrophysical parameters
  - Boundary condition
- Model calculate
- Output modeling result

Results



- Overall 85% agreement
- 3 wells (JY194-3, JY10-10, SY1) where the modeled and measured directions are exactly the same
- 4 wells with an error range of 5-10° (JY8, JY10, SY3, SY5)
- 4 wells with an error range of 11-18° (NY1, JY11, JY201, SY13-3)
- 2 wells with errors above 20° (SY2, SY9-1)

Summary

Summary

Taking the Nanchuan region as an example, the SHELLS stress field model was established by combining parameters such as fracture, topography and heat flow, and the distribution of the maximum compressive horizontal principal stress directions characteristics of the study area were calculate and predicted

The prediction results show that σ_{Hmax} directions in the Nanchuan region vary multi-directionally (0-180°), and are consistent with 11 of the 13 drilled wells, with only two drilled wells having minor differences. 85% of the predicted wells are consistent with the measured wells, achieving significant geological results and laying the foundation for the effective development of shale gas production capacity and optimized fracturing schemes in the area.

Acknowledgements:

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References:

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Tongji University

State Key Laboratory of Marine Geology

School of Ocean and Earth Science

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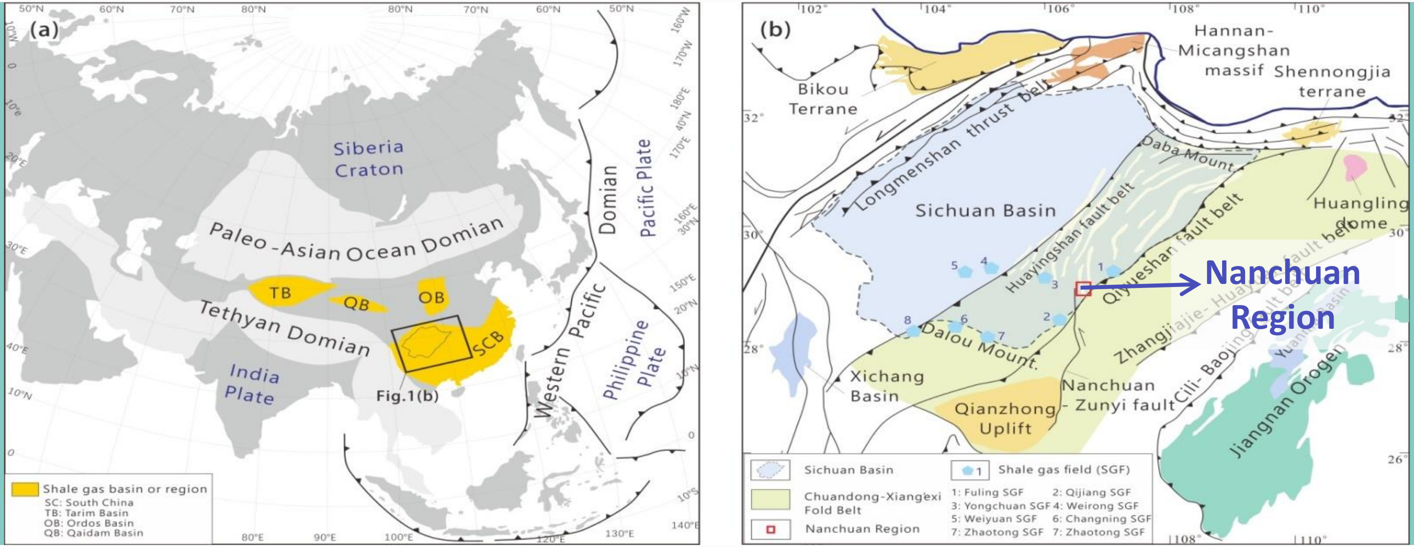
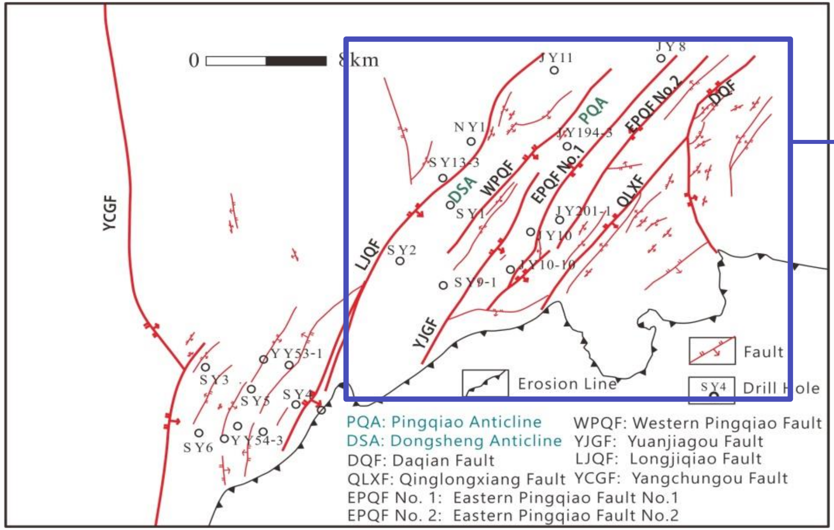
Introduction

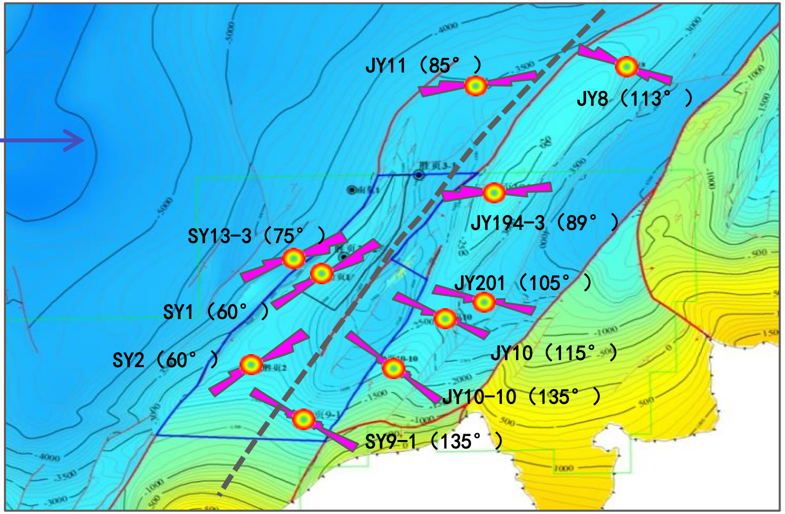


The Nanchuan region is located on the southeastern margin of the Sichuan Basin, South China. Silurian Wufeng-Longmaxi Formation, buried between 2000-4500m deep in this area, is an important shale gas-producing formation.

Nanchuan Region



σ_{Hmax} Directions



- Influenced by multi-phase tectonic action during Mesozoic- Cenozoic, the maximum compressive horizontal principal stress (σ_{Hmax}) directions are complex and the orientation changes rapidly (55°-135°).
- Effectively predicting the maximum compressive horizontal principal stress (σ_{Hmax}) is important for improving the shale gas production capacity and optimizing the fracturing scheme development.

SHELLS finite numerical modeling

- **Modeling Method—— SHELLS Modeling**

Peter Bird:
Professor of Geophysics and Geology,
Department of Earth and Space Sciences, University of California, Los Angeles

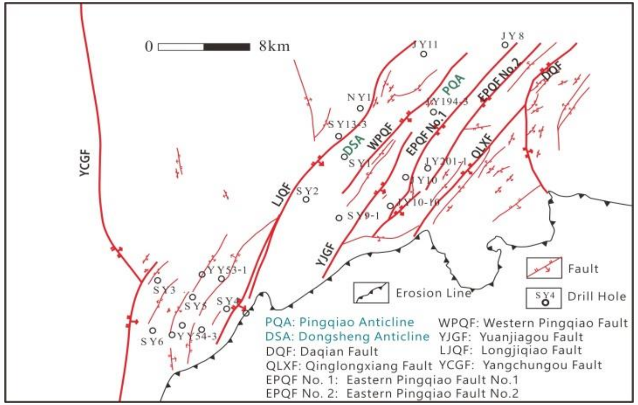
Website: http://www.peterbird.name/

- Modeling Process

Digitization of tectonic map → Finite element meshing → Model construction → Model calculation → Output the modeling result

- Digitization of tectonic map:

Digitise the tectonic map of the Wufeng-Longmaxi Formation in the study area

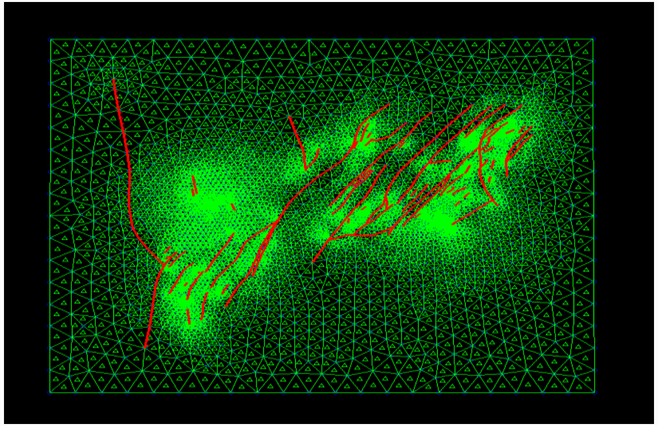


- Modeling Process

Digitization of tectonic map → **Finite element meshing** → Model construction → Model calculation → Output the modeling result

- ## Finite element meshing:

Import the data into SHELLS software for finite element meshing.



- Modeling Process

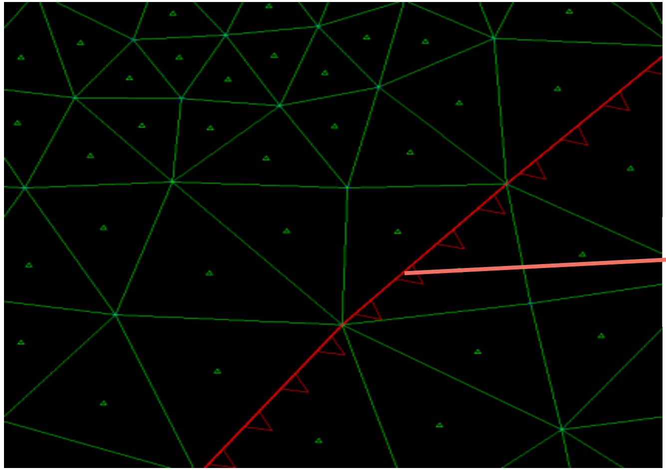
Digitization of tectonic map → Finite element meshing → **Model construction** → Model calculation → Output the modeling result

- ## Model Construction:

Assign data to nodes and grids.

Five types of data:

- **Traces and dips of faults**
- Topography
- Heat flow
- Petrophysical parameters
- Boundary Condition



Assign traces and dips of faults

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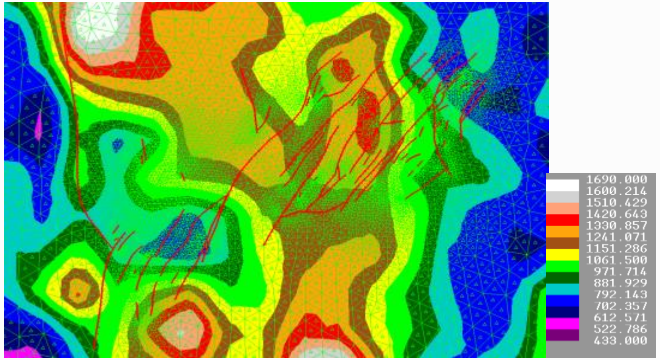

Obtained from satellite elevation data

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表 2　四川盆地各区域古今地温梯度比较

Tab.2　Comparison of present and ancient geothermal gradients in different districts of Sichuan Basin

区域	地温梯度/(℃·km^{-1})		热流/(mW·m^{-2})		古地温梯度对应的时间
	现今	古时	现今	古时	
川东北	20～21	0～23.7	47.3	0～52	早白垩世末
川东	20～21	0～25.2	～47	～57	早白垩末一晚白垩世
川中	22～26	0～23.3	65～72	<65	早白垩末一晚白垩世
川南	26～30	0～24.6	—	—	晚白垩世
川西	米仓山前：0～25	25.8	—	—	晚白垩世一古新世
	中段山前：20～22	21.2	55.3	55	古新世
	南段：22～23	21.7～23.2	—	—	古新世

Wang et al., 2011 (in Chinese Version)

Heat Flow: 47mW/m^2

- Modeling Process

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- # Model Construction:

Assign data to nodes and grids.

Five types of data:

- Traces and dips of faults
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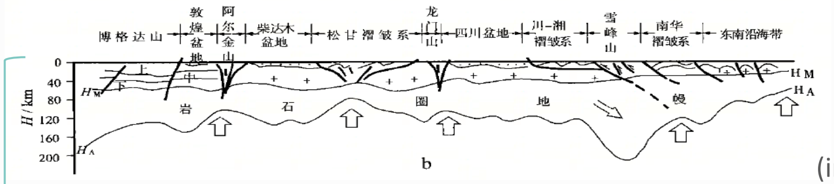
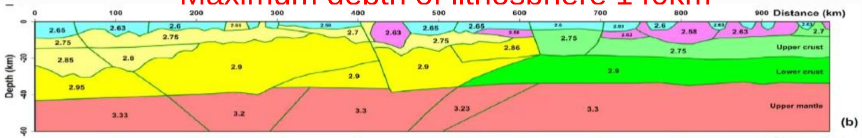
- Boundary Condition

- Based on the use of the results of previous research in the Nanchuan area and its regional South China (eg: Maximum depth of lithosphere, etc)
- Other parameters assigned with commonly accepted constants



Fan et al., 2005 (in Chinese Version)

Maximum depth of lithosphere 140km



Guo et al., 2018

Average density of the rock （crust） 2836

Table 1
Model parameters.

Parameter	Symbol	Value	Reference
Upper crustal density	ρ_{uc}	2700 kg/m³	Wang et al., 2016
Middle-lower crustal density	ρ_{mlc}	2900 kg/m³	Wang et al., 2016
Mantle density	ρ_m	3200 kg/m³	Wang et al., 2016
Present heat production of upper crust	A_{uco}	1.12 μW/m³	He et al., 2011
Present heat production of middle-lower crust	A_{mlco}	0.45 μW/m³	He et al., 2011
Present heat production of lithospheric mantle	A_{mo}	0.03 μW/m³	
Thermal conductivity of crust	k_c	2.7 W/m·K	
Thermal conductivity of mantle	k_m	3.0 W/m·K	
Thermal capacity	C_p	1200 J/kg·K	Michaut and Jaupart, 2007
Basal temperature	T_{bo}	1372 °C	Michaut and Jaupart, 2007
Characteristic time of radioactive decay	τ_r	3.96 Ga	Michaut and Jaupart, 2007
Characteristic time of basal temperature decrease	τ_s	35 Ga	Michaut and Jaupart, 2007

He et al., 2020

Thermal conductivity （crust） 2.7 （mantle） 3.0

Petrophysical parameters in the SHELLS modelling.

Modified after Bird (1999); Fan et al. (2013), Guo et al. (2018) and He et al.(2020).

Parameter	Values
Fault friction coefficient	0.10
Continuum fricyion coefficient	0.85
Biot effective stress concentration factor	1.00
Main fracture strength reduction factor	0.00
Dislocation creep shear stress coefficient	2.3×10^{9} (crust), 9.5×10^{4}(mantle)
Q/nR/K	4000 (crust), 18314 (mantle)
Maximum shear stress (Bird and Kong, 1994)	5×10^{8} (crust), 5×10^{8}(mantle)
Constant N	3
Upper mantle adiabatic temperature and temperature and temperature gradient/K	2.3×10^{9} (crust), 9.5×10^{4}(mantle)
Maximum depth of lithosphere/m	1.4×10^{5}
Motion reference point (Euler pole)	EU(61.066–85.819)
Maximum traction in bottom	2.0×10^{7}
Maximum shear stress of subduction shear band /$N\cdot m^{-1}$	2.0×101^{2}
Density of pore water /$m^{3}\cdot kg^{-1}$	1 032
Average density of the rock /$m^{3}\cdot kg^{-1}$	2836 (crust), 3332 (mantle)
Asthenosphere density /$m^{3}\cdot kg^{-1}$	3125
Coefficient of thermal expansion	2.4×10^{-5}(crust), 3.94×10^{-5}(mantle)
Thermal conductivity	2.7 (crust), 3.0 (mantle)
Thermal radiation (Unit volume)	3.5×10^{-7}(crust), 3.2×10^{-8}(mantle)
Crust/mantle lithosphere maximum temperature/K	1 223(crust), 1 673(mantle)
Acceptable level of velocity errors/$m\cdot s^{-1}$	1.00E-14

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Assign data to nodes and grids.

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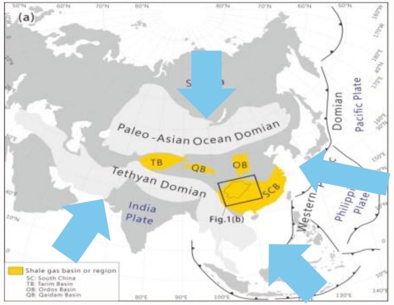
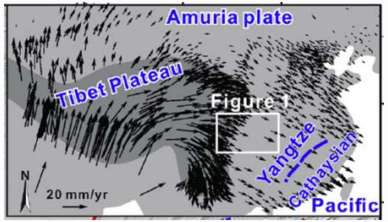
Geodynamic &Tectonic Setting



GPS velocity field (relative to stable Eurasia)

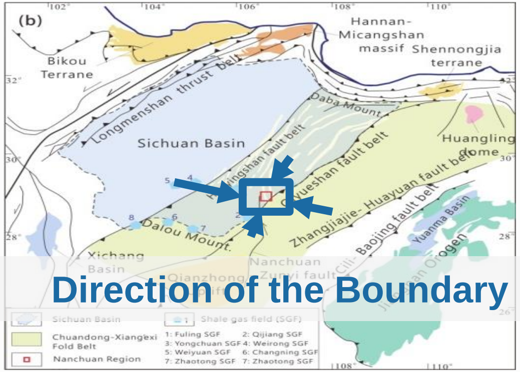


Xu et al., 2019

Direction of the Boundary

Integrated analysis

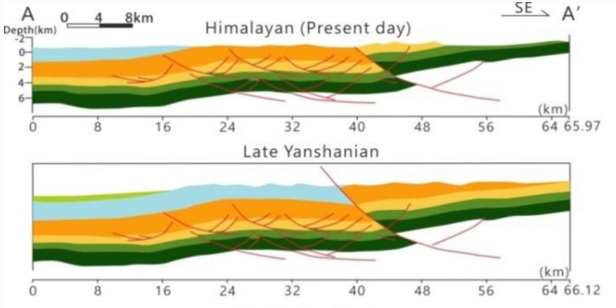
- Geodynamic &Tectonic Setting
- GPS velocity field

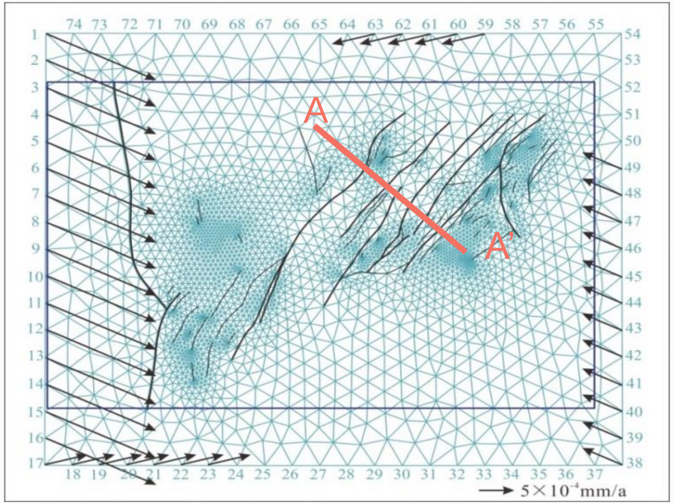


Direction and Magnitude Setting of Boundary Condition

Magnitude of the Boundary

Calculated from balanced cross- section





Boundary condition setting table for SHELLS stress field in the Nanchuan

Boundary	No.	Direction/°	Magnitude (mm/a)
West	1-16	116	1.73×10^{-3}
South	17-23	75	6.3×10^{-4}
	24-37	Free boundary	
East	38-49	296	6.3×10^{-4}
	50-54	Free boundary	
North	55-58	Free boundary	
	59-63	255	6.3×10^{-4}
	63-74	Free boundary	

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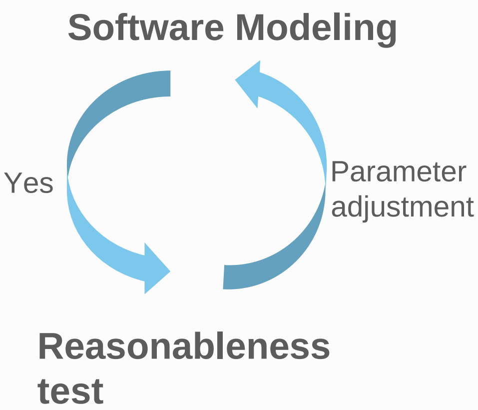
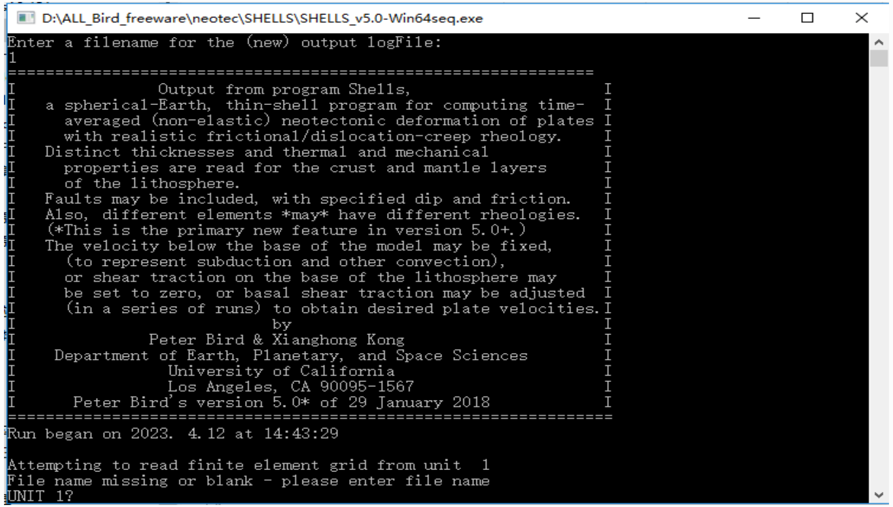
- Calculating SHELLS software model：





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I                Output from program Shells,                   I
I    a spherical-Earth, thin-shell program for computing time- I
I      averaged (non-elastic) neotectonic deformation of plates I
I      with realistic frictional/dislocation-creep rheology.   I
I    Distinct thicknesses and thermal and mechanical            I
I      properties are read for the crust and mantle layers     I
I      of the lithosphere.                                     I
I    Faults may be included, with specified dip and friction.  I
I    Also, different elements *may* have different rheologies. I
I    (*This is the primary new feature in version 5.0+.)       I
I    The velocity below the base of the model may be fixed,    I
I      (to represent subduction and other convection),         I
I      or shear traction on the base of the lithosphere may    I
I      be set to zero, or basal shear traction may be adjusted I
I      (in a series of runs) to obtain desired plate velocities.I
I                             by                               I
I               Peter Bird & Xianghong Kong                    I
I     Department of Earth, Planetary, and Space Sciences       I
I                University of California                      I
I                Los Angeles, CA 90095-1567                    I
I      Peter Bird's version 5.0* of 29 January 2018            I
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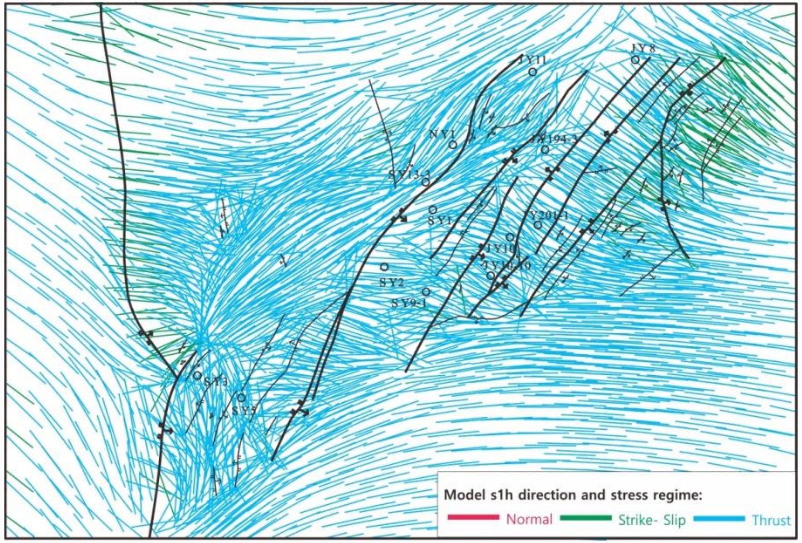
- Modeling Process

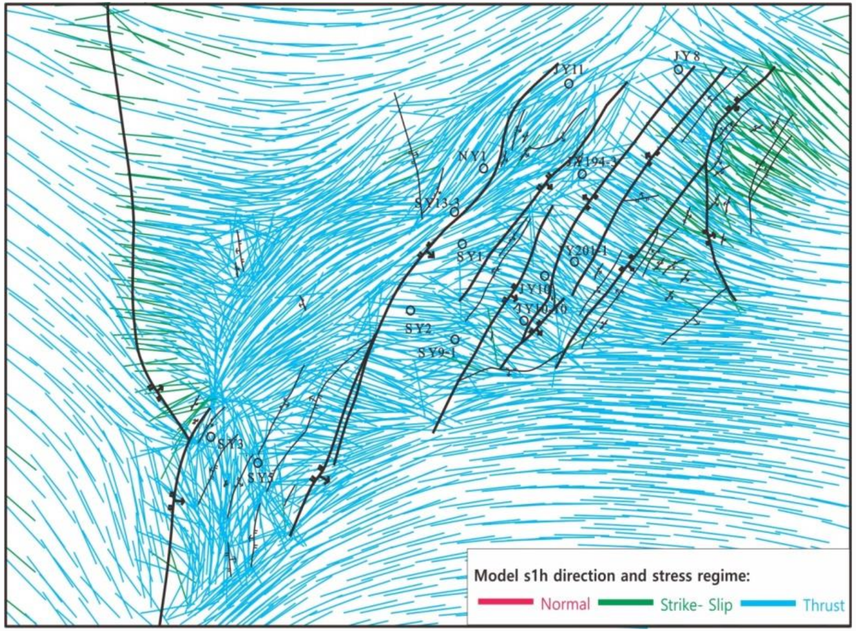
Digitization of tectonic map → Finite element meshing → Model construction → Model calculation → Output the modeling result

- Output of the modeling result



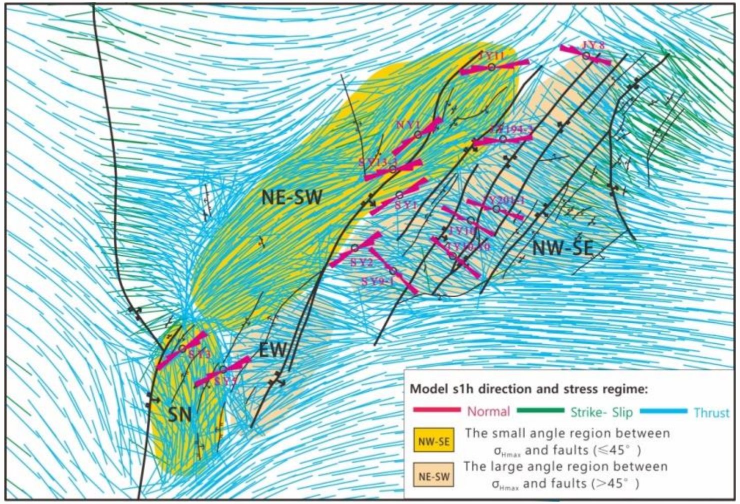
The maximum compressive horizontal principal stress (σ_{Hmax})

Results



- σ_{Hmax} Directions : Vary multi-directionally (0-180°)
- σ_{Hmax} Regime : Dominated by the thrust regime

- Comparision between modeled and measured results



Drill Name	Measured results/°	Modeled results/°	Differences/°
JY194-3	89	89	0
JY10-10	135	135	0
SY1	60	60	0
JY8	113	111	2
JY10	115	120	5
SY3	60	51	9
SY5	65	75	10
NY1	55	44	11
JY11	85	73	12
JY201	105	120	15
SY13-3	75	57	18
SY9-1	135	114	21
SY2	60	95	35

- ✓ Overall 85% agreement
- ✓ 3 wells (JY194-3, JY10-10, SY1) where the modeled and measured directions are exactly the same
- ✓ 4 wells with an error range of 5-10° (JY8, JY10, SY3, SY5)
- ✓ 4 wells with an error range of 11-18° (NY1, JY11, JY201, SY13-3)
- ✓ 2 wells with errors above 20° (SY2, SY9-1) are probably due to the fact that these the two wells are right at the intersection of the stress transitions, making it difficult for the SHELLS software to achieve resolution.

Summary

- Summary

1. Taking the Nanchuan region as an example, the SHELLS stress field model was established by combining parameters such as fracture, topography and heat flow, and the distribution of the maximum compressive horizontal principal stress directions characteristics of the study area were calculate and predicted

2. The prediction results show that σ_{Hmax} directions in the Nanchuan region vary multi-directionally (0-180°), and are consistent with 11 of the 13 drilled wells, with only two drilled wells having minor differences. 85% of the predicted wells are consistent with the measured wells, achieving significant geological results and laying the foundation for the effective development of shale gas production capacity and optimized fracturing schemes in the area.

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Thank you

Get in Touch

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