使用三维地壳成像
研究雅江盆地锂矿形成机制

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提纲

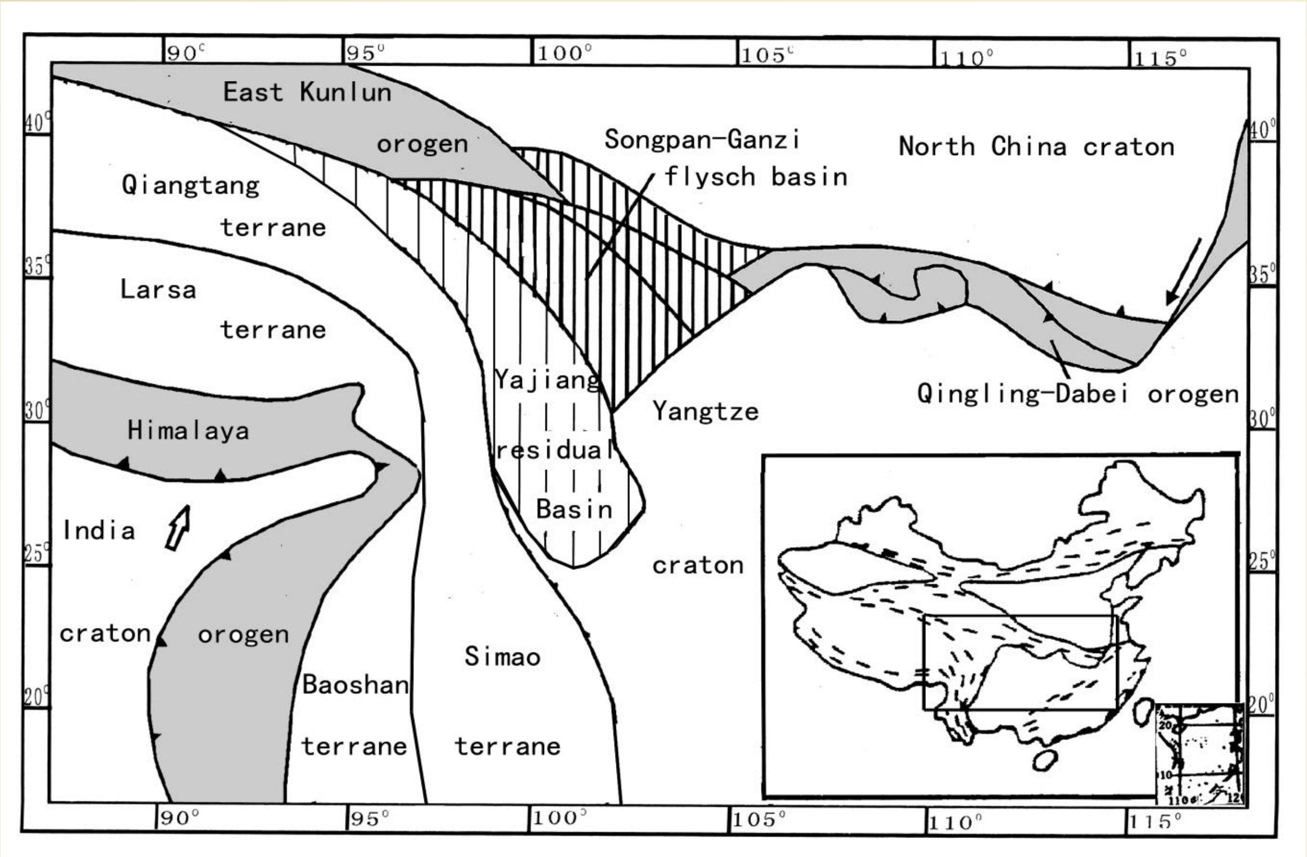
- **I. 简介和科学问题**
- **II. 三维地壳密度成像方法**
- **III. 雅江残留盆地的动力学过程和锂矿构造模型**
- **IV.雅江锂矿成矿作用模型的验证**

I.简介和科学问题

- 锂矿矿藏是实现人类社会可持续发展所需能源
- 锂矿矿藏是怎样形成的？
- 锂矿矿藏是否足够支持人类社会的可持续发展？
- 本研究目的是使用三维地球成像的新技术，研究雅江复理石盆地的地壳结构和演化过程，来回答以上问题

雅江复理石残留盆地位于中国四川省西部，是近几年世界上发现的最大的锂辉石矿

图中灰色区域是由大陆碰撞造成的山脉



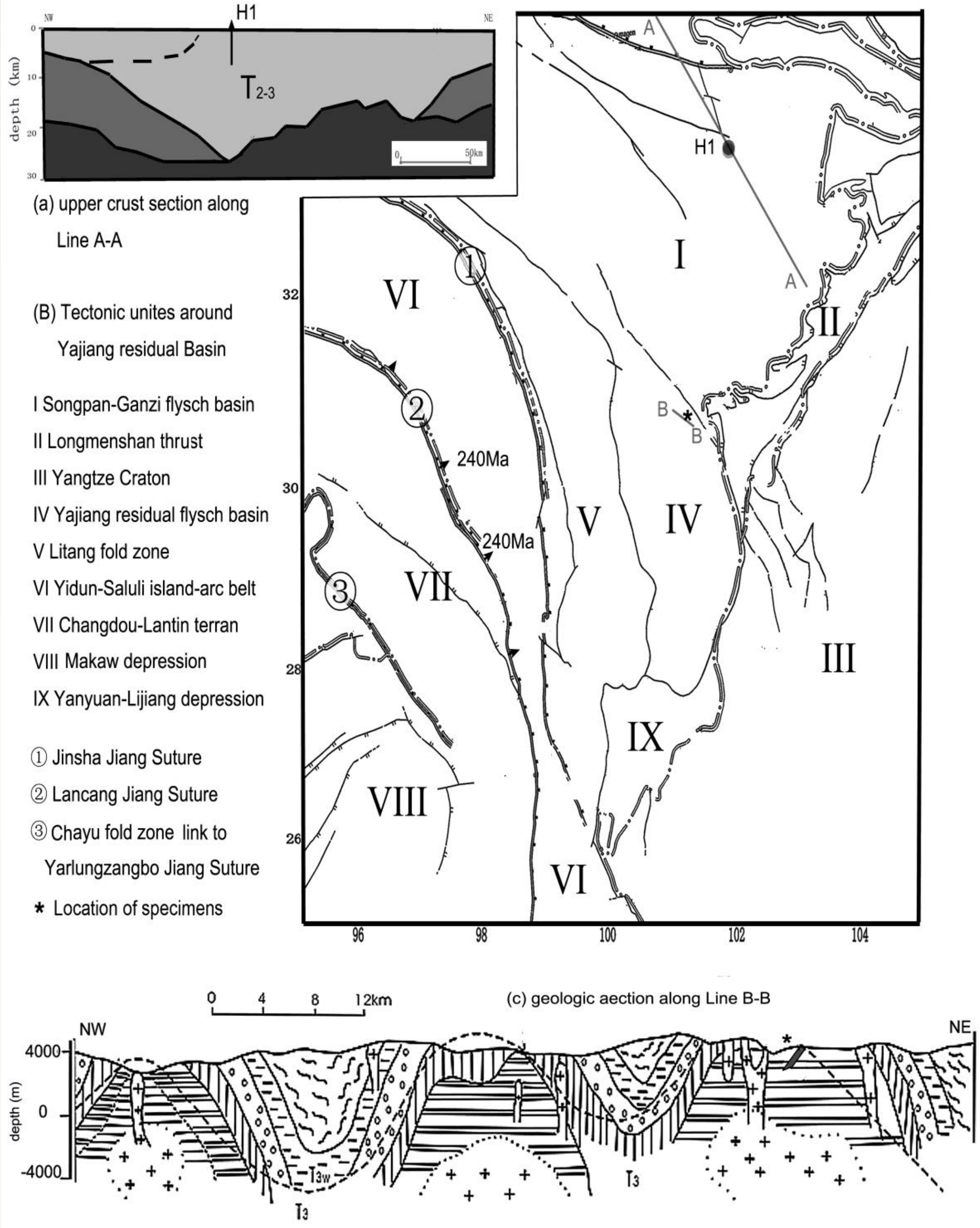
松潘-甘孜-雅江复理石盆地构造简图

（a）由地球物理调查和钻井资料推断的沿A-A线的地壳截面图

（b）构造单元和碰撞缝合线的

（c）沿B-B线的地壳截面图（许志琴测量）

“*”为甲基卡矿区位置和标本采集点

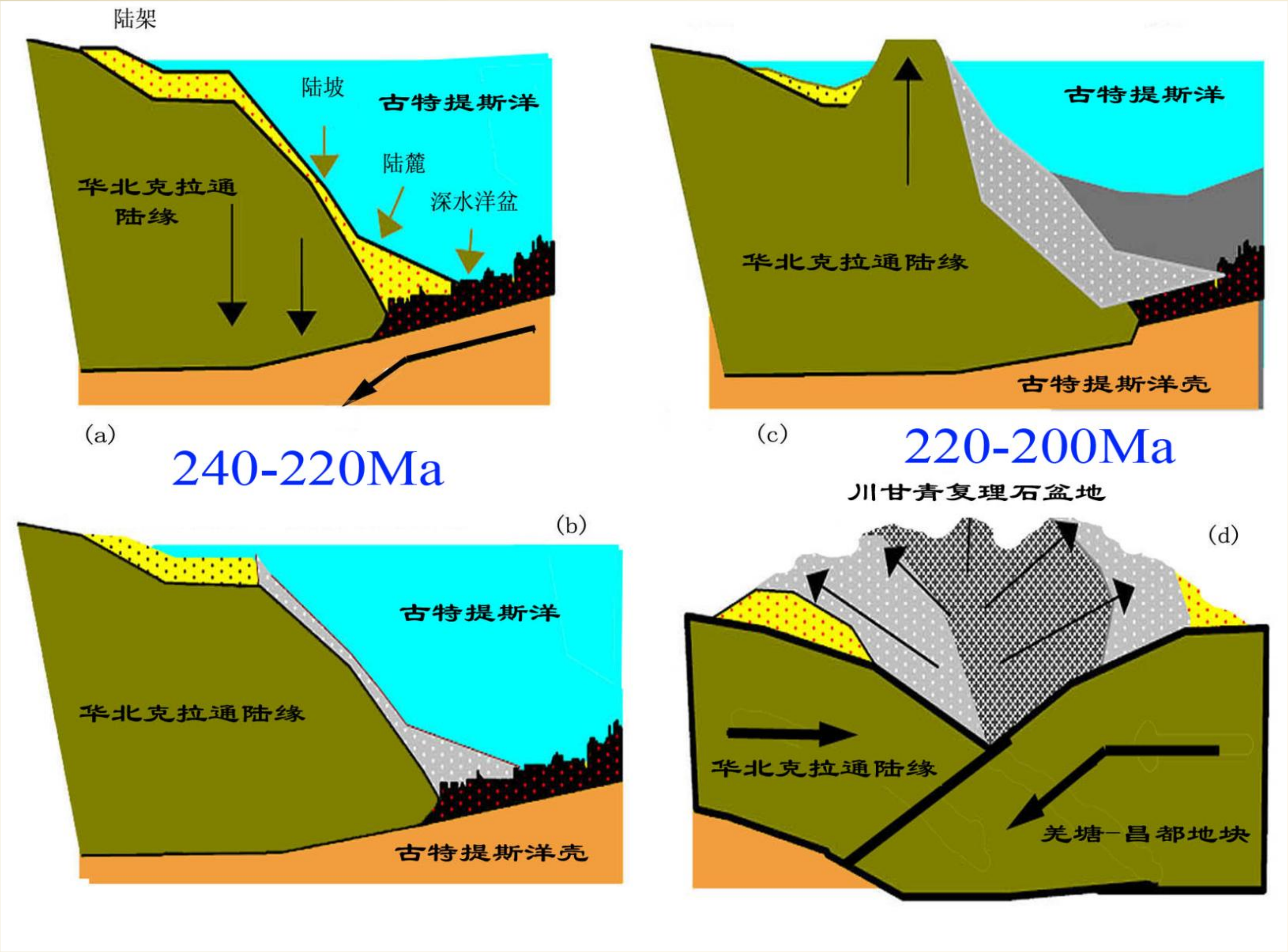


松潘-甘孜复理石盆地-三叠纪沉积
主要是大陆边缘斜坡的浊积岩相矿床

与浊积岩相矿床相似的泥岩和灰岩

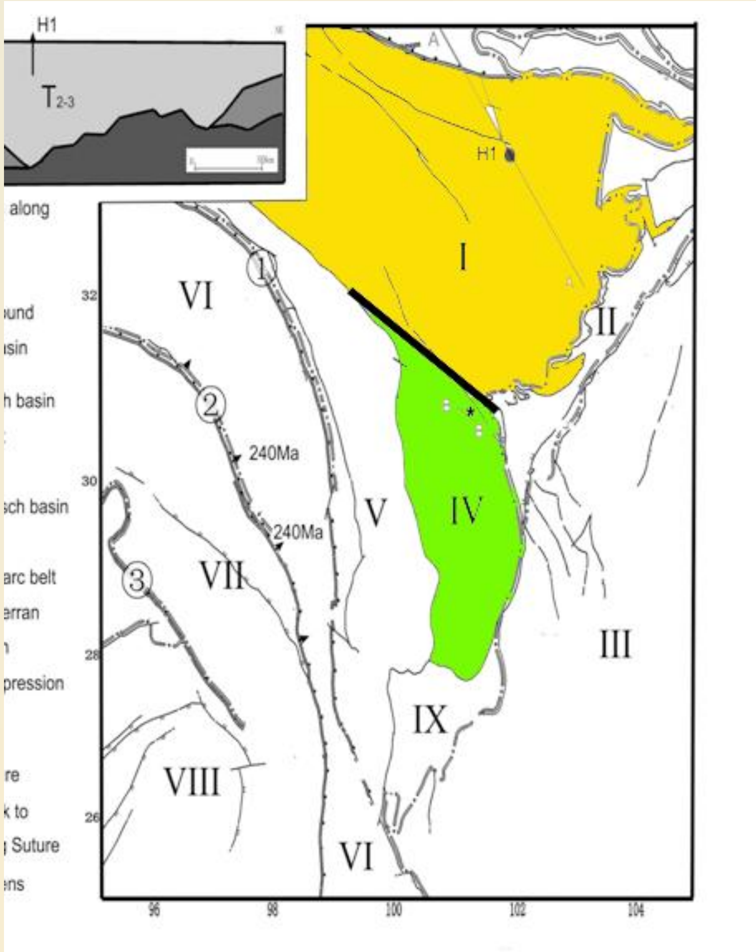
位于被深水覆盖的大陆坡上的三叠纪浊流环境

松潘-甘孜复理石盆地构造演化



雅江地区-复理石残留盆地

- 雅江地区的复理石沉积不是非常厚
- 雅江地区包括一些结晶基地岩石穹窿，表现为出露的复理石盆地的根



甲基卡锂辉石矿物标本

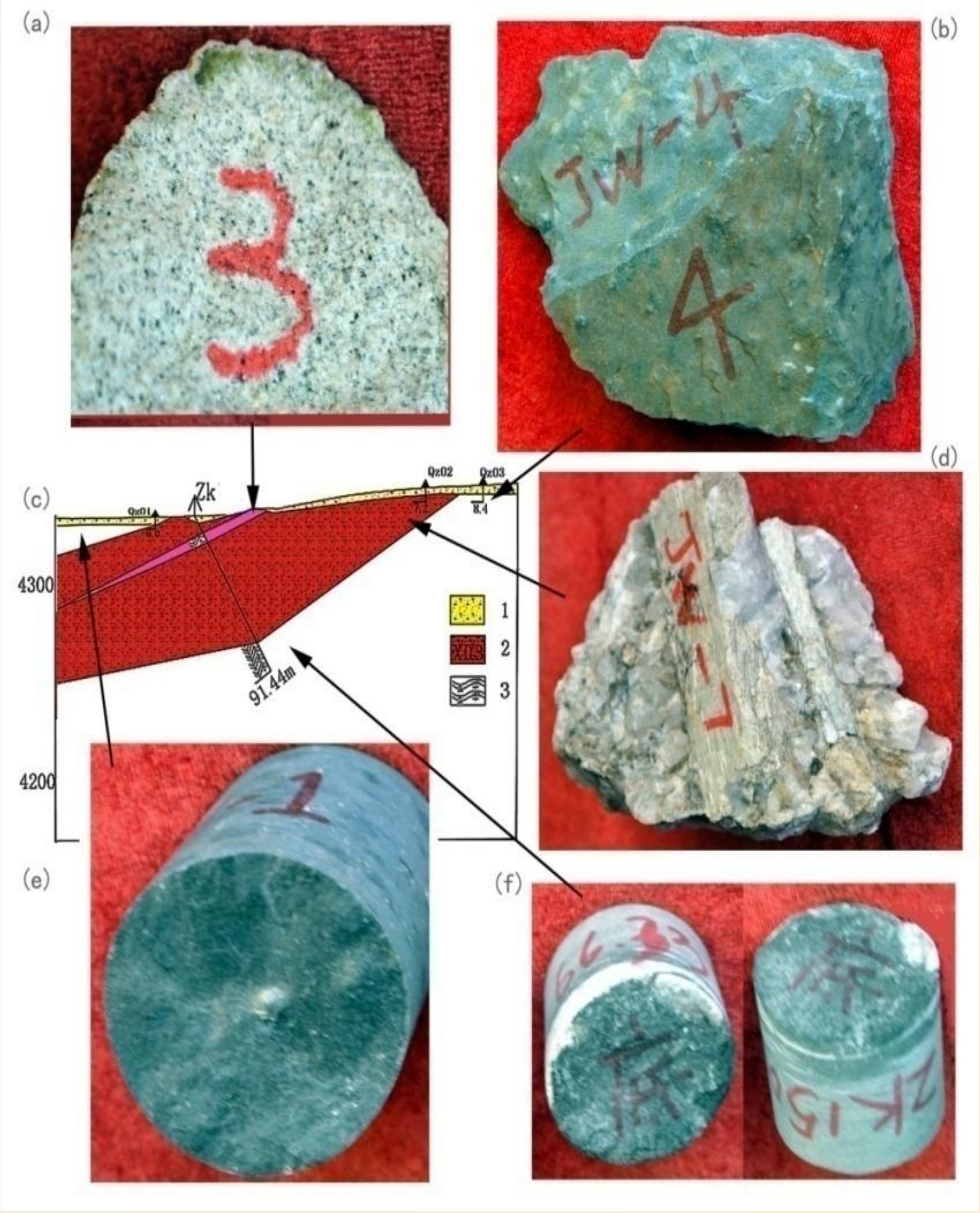
（a）花岗岩露头

（b）T_3复理石岩

（d）锂辉石矿样品

（e）矿体之上的复理石岩

（f）矿体之下的复理石岩



三个科学问题

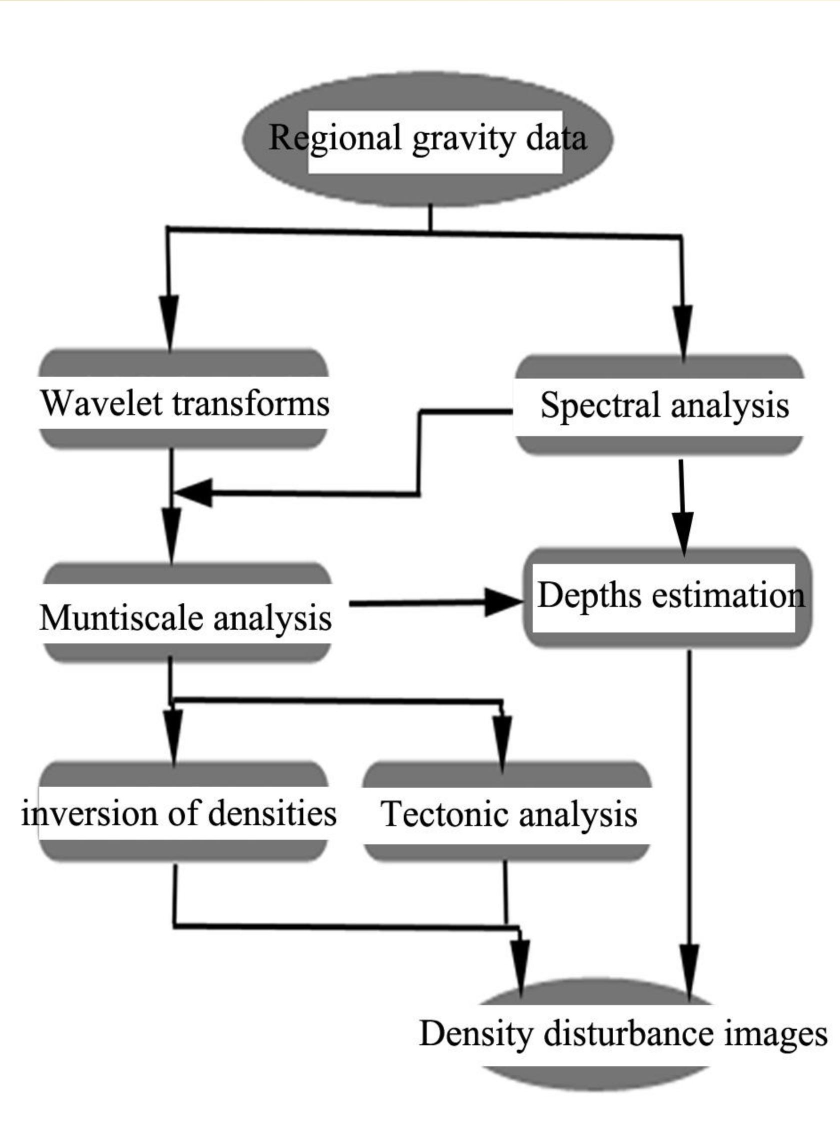
- **为什么锂出现在雅江复理石残留盆地中?**
- **锂怎样变成锂辉石矿?**
- **锂辉石矿怎样抬升接近地表，成为可开采的矿?**

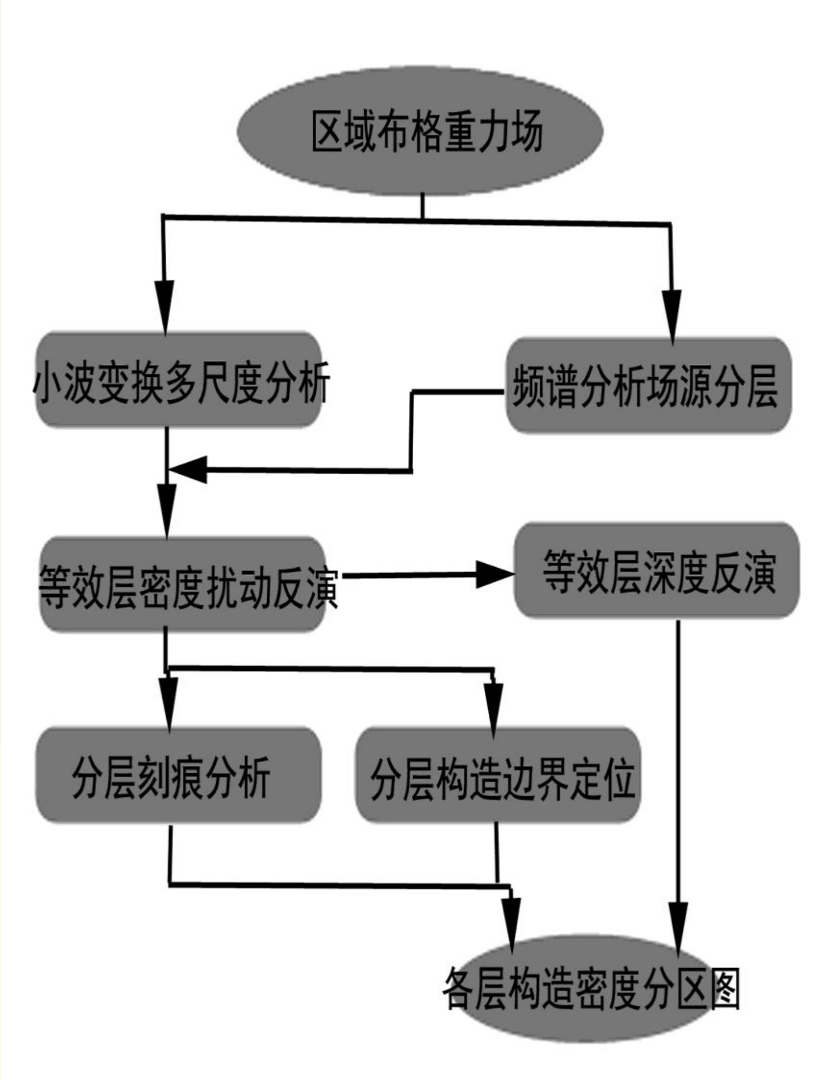
- 为了回答这些问题，我们需要知道：
- 雅江盆地的构造演化和锂辉石矿化的成因

II三维地壳密度成像方法

- 为了研究构造演化，我们必须首先了解地壳结构
- 使用地球物理调查数据
- 地壳成像的物理参数
- 密度是构造演化过程的地球动力学重建最重要的参数

三维密度成像方法

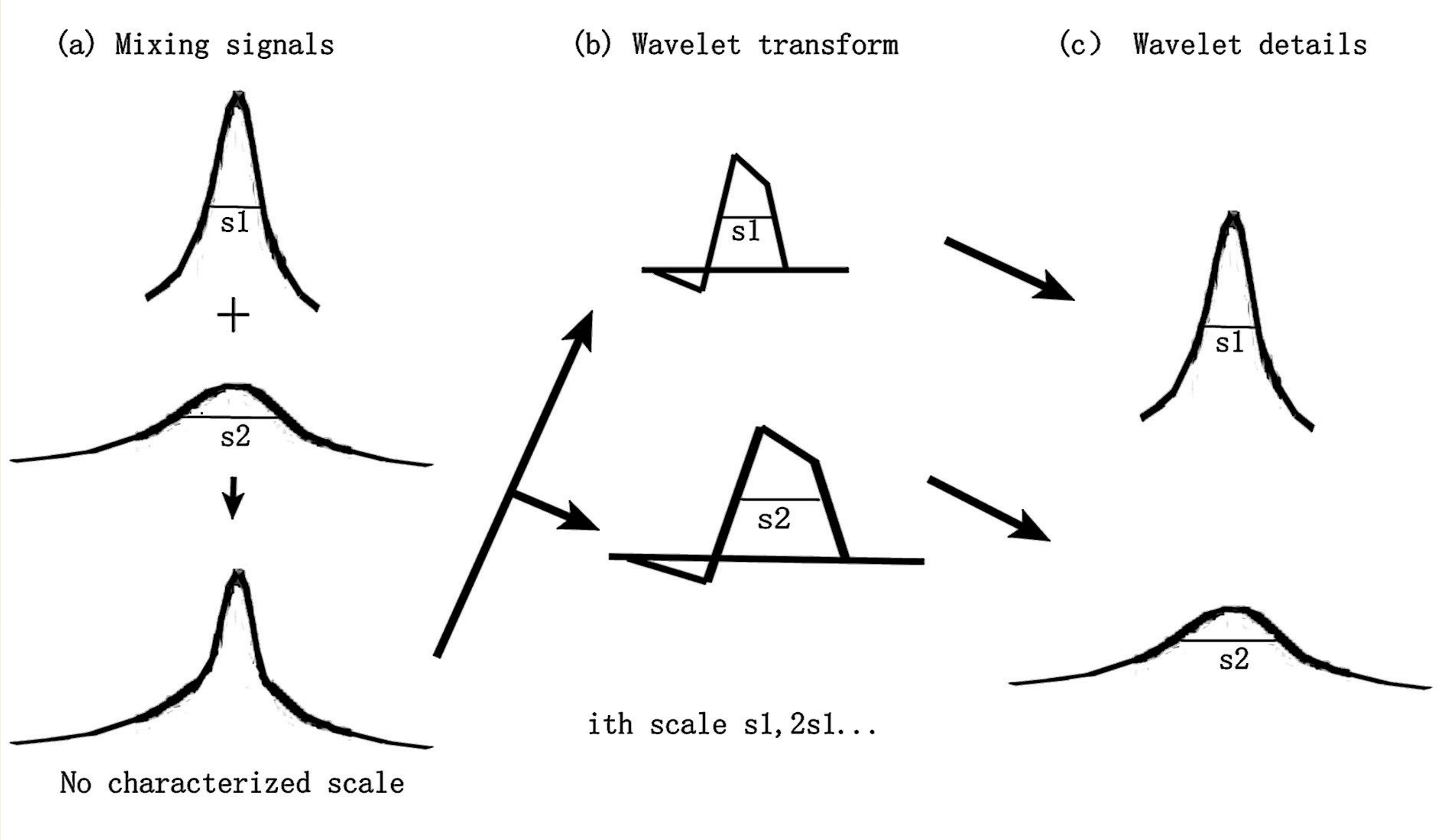

Regional gravity data
Wavelet transforms
Spectral analysis
Muntiscale analysis
Depths estimation
inversion of densities
Tectonic analysis
Density disturbance images


区域布格重力场
小波变换多尺度分析
频谱分析场源分层
等效层密度扰动反演
等效层深度反演
分层刻痕分析
分层构造边界定位
各层构造密度分区图

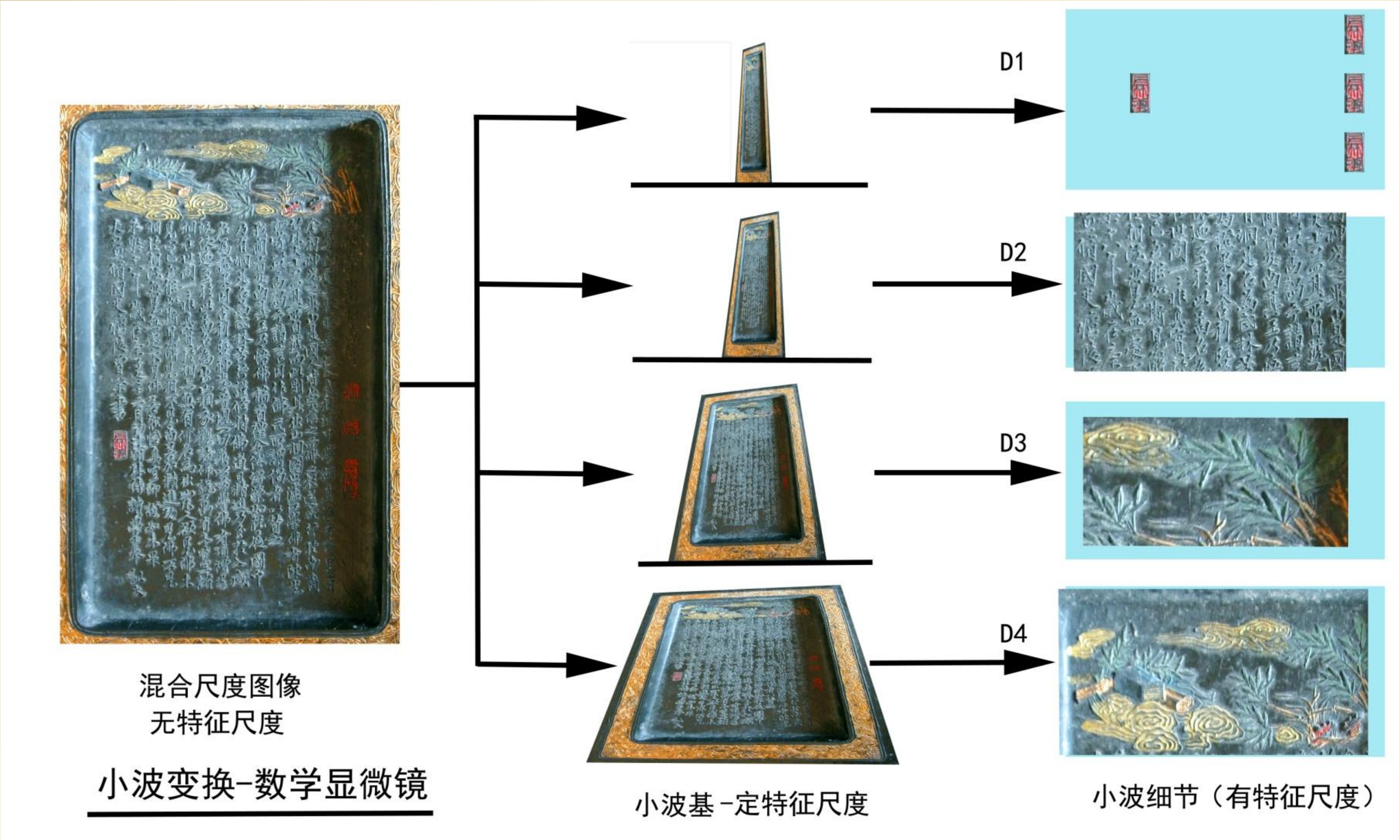
区域重力场小波多尺度分析

- 单一来源的重力异常有其特征空间标量
- 特征空间标量等于半振幅点之间的距离
- 此距离与重力异常源的埋深深度成正比

小波多尺度分析分解重力场



小波多尺度分析–数学显微镜



区域重力场的分解

- 小波多尺度分析能够分解区域重力场，并能恢复它们的特征标量
- 分解后的小波细节图像反映不同深度等效层的重力场场源
- 使用广义反演方法刻画三维地壳密度结构

如何计算重力源层的平均深度

- 重力异常的对数能量谱的斜率反比于重力异常源的埋深深度。
- 能量谱曲线是异常叠加的结果，在能量谱曲线上有可识别不同倾斜斜率的直线段，代表不同等效层的埋深深度 。通过这种分析，我们就知道多少等效层可以从地表重力数据中被分解出来。
- 使用分解得到的小波细节能量谱，能够计算每一个等效重力源层的平均深度

有关论文在国际刊发表

Pure Appl. Geophys.

DOI 10.1007/s00024-015-1153-3

Pure and Applied Geophysics

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Multi-Scale Scratch Analysis in Qinghai-Tibet Plateau and its Geological Implications

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Abstract—Multi-scale scratch analysis on a regional gravity field is a new data processing system for depicting three-dimensional density structures and tectonic features. It comprises four modules including the spectral analysis of potential fields, multi-scale wavelet analysis, density distribution inversion, and scratch analysis. The multi-scale scratch analysis method was applied to regional gravity data to extract information about the deformation belts in the Qinghai-Tibet Plateau, which can help reveal variations of the deformation belts and plane distribution features from the upper crust to the lower crust, provide evidence for the study of three-dimensional crustal structures, and define distribution of deformation belts and mass movement. Results show the variation of deformation belts from the upper crust to the lower crust. The deformation belts vary from dense and thin in the upper crust to coarse and thick in the lower crust, demonstrating that vertical distribution of deformation belts resembles a tree with a coarse and thick trunk in the lower part and dense and thin branches at the top. The dense and thin deformation areas in the upper crust correspond to crustal shortening areas, while the thick and continuous deformation belts in the lower crust indicate the structural framework of the plateau. Additionally, the lower crustal deformation belts recognized by the multi-scale scratch analysis coincide approximately with the crustal deformation belts recognized using single-scale scratch analysis. However, deformation belts recognized by the latter are somewhat rough while multi-scale scratch analysis can provide more detailed and accurate results.

Key words: Qinghai-Tibet Plateau, regional gravity field, multi-scale scratch analysis, crustal deformation belts, crust shortening.

1. Introduction

The Qinghai-Tibet Plateau typifies continent collision and is one of the regions that underwent violent lithosphere tectonic deformation. Unique structures and geophysical conditions make the Qinghai-Tibet Plateau a critical region for the study of orogenic belts and continental dynamics. Examination of the crustal density structure and the deformation belts can improve our understanding of matter distribution, deformation features, and crustal structure. However, even though numerous studies investigating the crustal structures in Qinghai-Tibet Plateau have been performed (e.g., HELENE and PETER 1983; KIND *et al.* 2002; ZHANG *et al.* 2004), few have focused on the three-dimensional density structures and distributions of deformation belts (FENG and XU 1997; KE *et al.* 2009).

It has become one of the main directions in regional geophysical studies that geoscientists apply regional gravity data to reveal three-dimensional density structures and tectonic patterns because the gravity field contains information about the crustal density with low observation cost and high efficiency. After years of research, we have developed a systematic and sophisticated gravity data processing procedure by combining four techniques: multi-scale wavelet analysis, spectral analysis of potential fields, geophysical inversion, and scratch analysis. We refer to the data processing system as multi-scale scratch analysis, which can produce crustal three-dimensional density images, images of deformation belts, and auto-divided images of continental tectonic units with clearly defined depths. Our previous two papers (YANG *et al.* 2015a, b) introduced the method of multi-scale scratch analysis using Qinghai-Tibet as an example, and discussed the three-dimensional density

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Acta Geophysica
vol. 64, no. ?, month 2016, pp. ?-?
DOI: 10.1515/acgeo-2015-0056

Three Dimensional Crustal Density Structure of Central Asia and its Geological Implications

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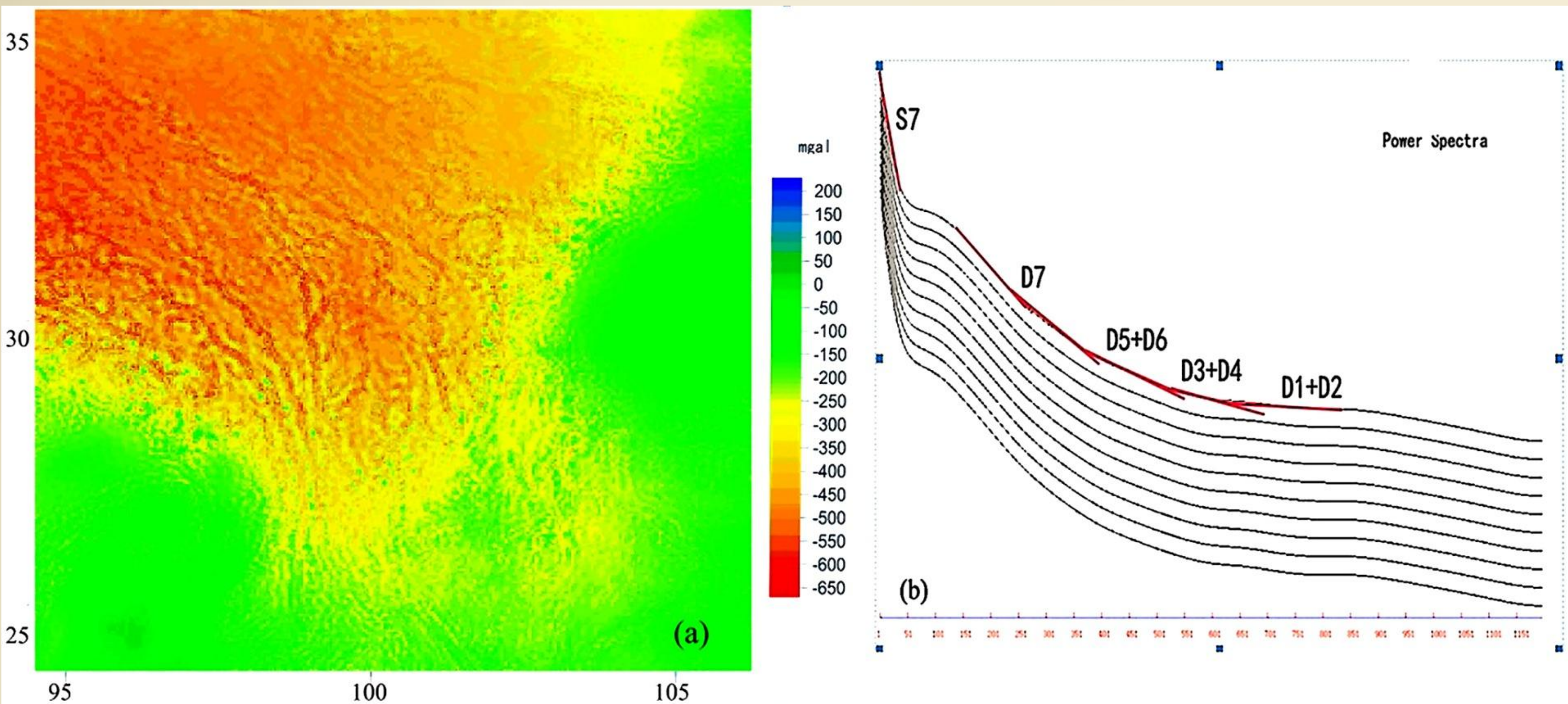
Abstracts

This paper introduces the scale-depth law of multi-scale wavelet analysis for regional gravity data processing, and presents the results of its application to Central Asia for computation of the 3D crustal density structures. The wavelet analysis method is applied for characterizing 3D crustal density structure, producing five maps of density disturbance corresponding to different depths of equivalent layers in the crust. The results provide important evidence for the study of crustal structures and mass movement in Central Asia: (i) the small-scale and intensive linear density disturbances in the upper crust indicate Phanerozoic orogenic belts; (ii) there exists a horseshoe-shaped low-density belt in the middle crust coinciding with the Kazakhstan orocline; (iii) there is a very low density zone in the lower crust, extending from western Kunlun to Tianshan, probably indicating a lower-crust flow; (iv) there are a few low-density spots in the middle crust, which might be caused by low-density mass squeezing upward from the lower crust flows.

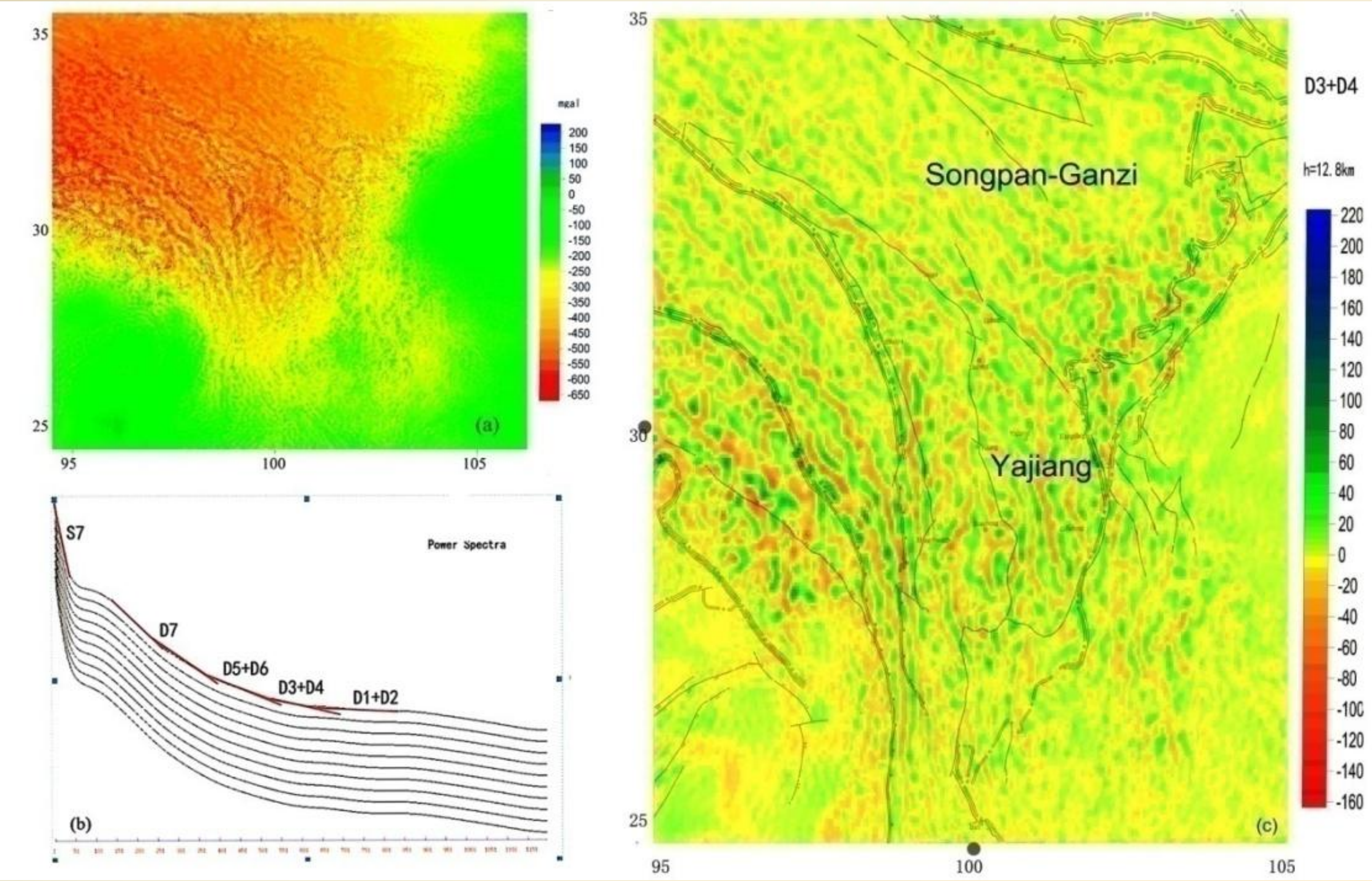
Key words: Central Asia, multi-scale wavelet analysis, density disturbance, lower-crust flows, orocline.

雅江地区的异常叠加


35
30
25
95
100
105
(a)
mgal
200
150
100
50
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
-550
-600
-650
S7
Power Spectra
D7
D5+D6
D3+D4
D1+D2
(b)

深度为12.8km的上地壳密度扰动平面图

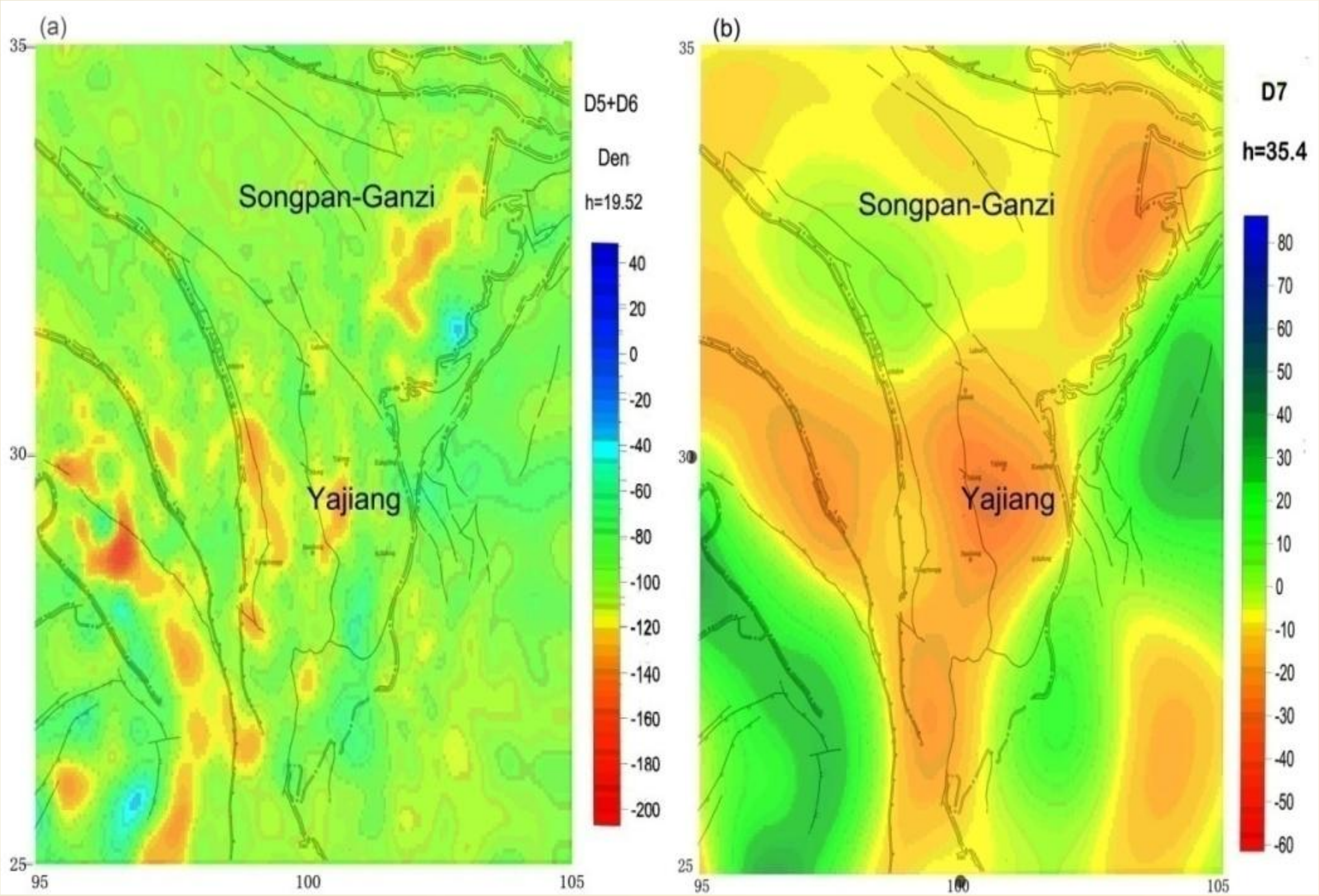
密度扰动单位是mg/cm^3



（a）深度为19.5km的中地壳密度扰动平面图

（b）深度为35.4km的下地壳密度扰动平面图

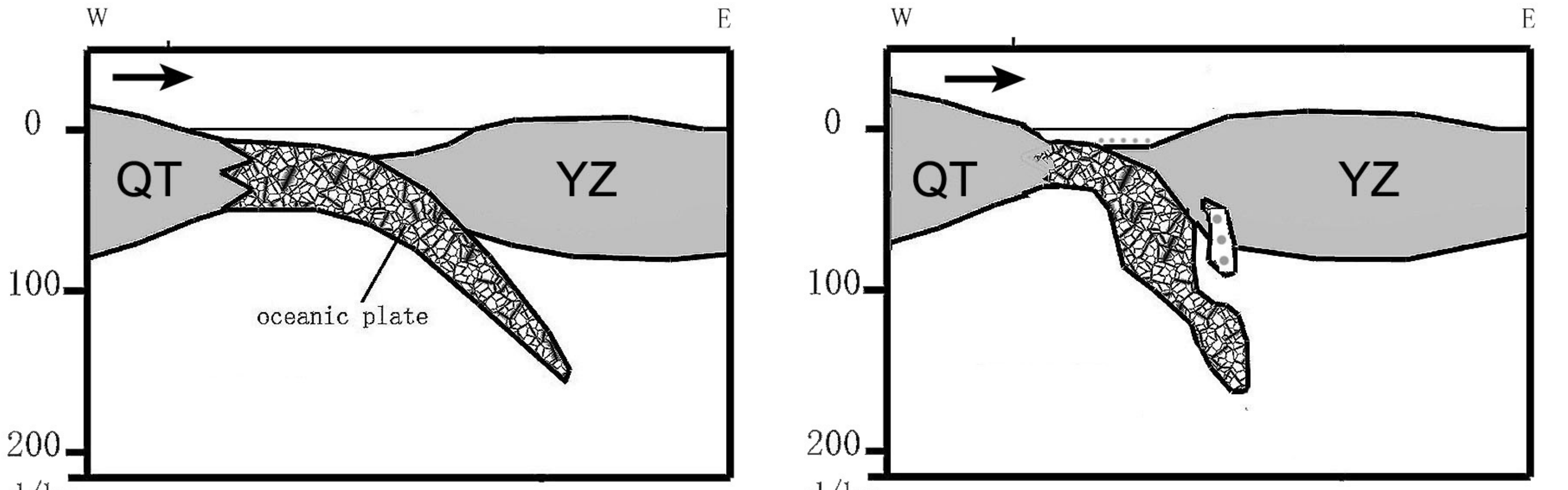
（b）the density perturbation image on plane of depth 35.4 km in the lower crust



III. 雅江复理石盆地的动力学过程和锂矿构造模型

- 新生代之前，雅江地区的构造演化与松潘-甘孜地块相同
- 但在新生代，雅江地区的地壳结构与松潘-甘孜发生明显的差异
- 松潘-甘孜和雅江地区在下地壳有一个明显的分界线

（1）松潘-甘孜和雅江复理石盆地的形成（240-210Ma）。深海，羌塘地体俯冲到其西边的古特提斯洋中

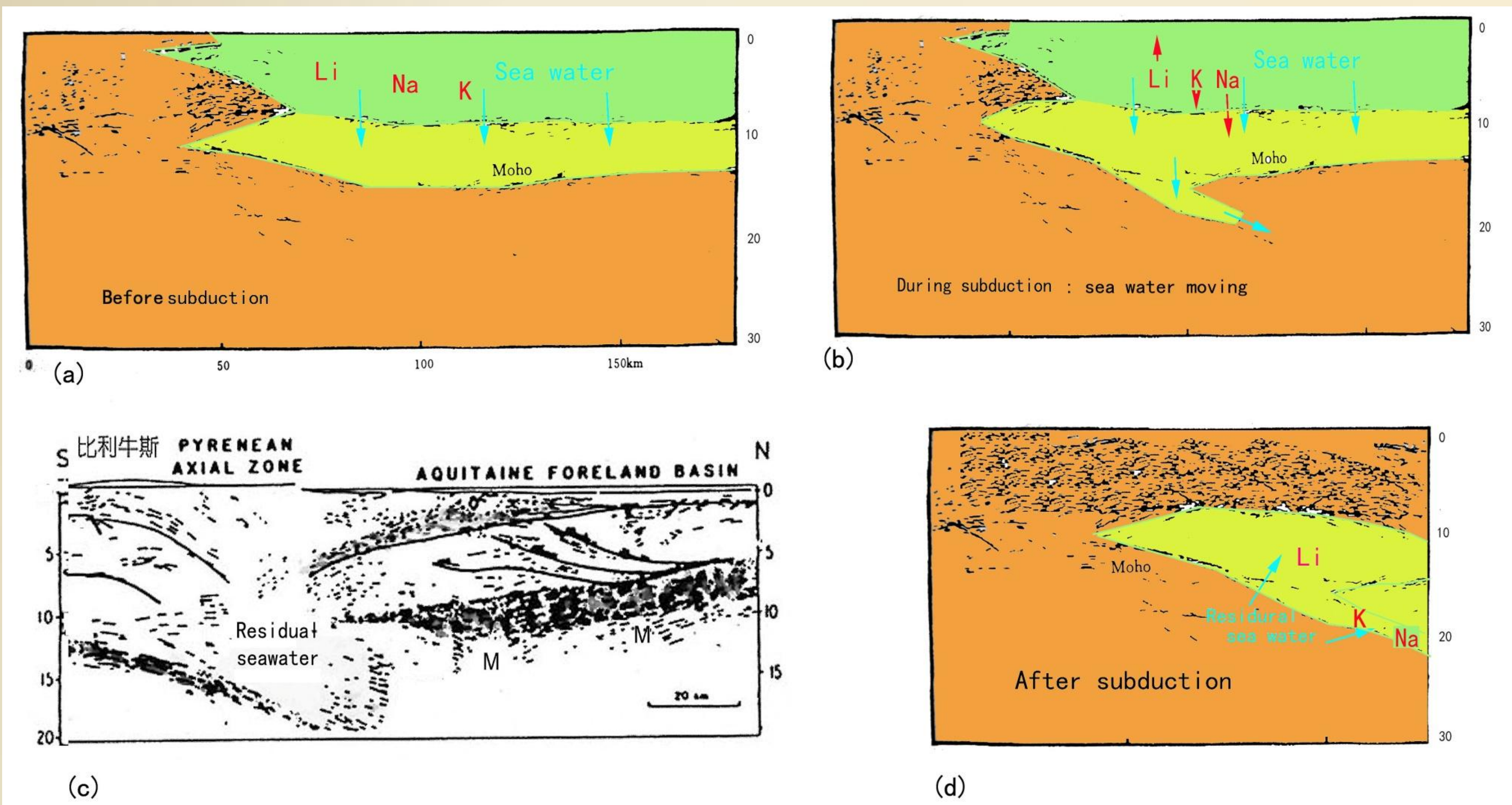


(a) ~250Ma (b) ~225Ma

古特提斯洋的海水在俯冲过程中向下渗入地幔

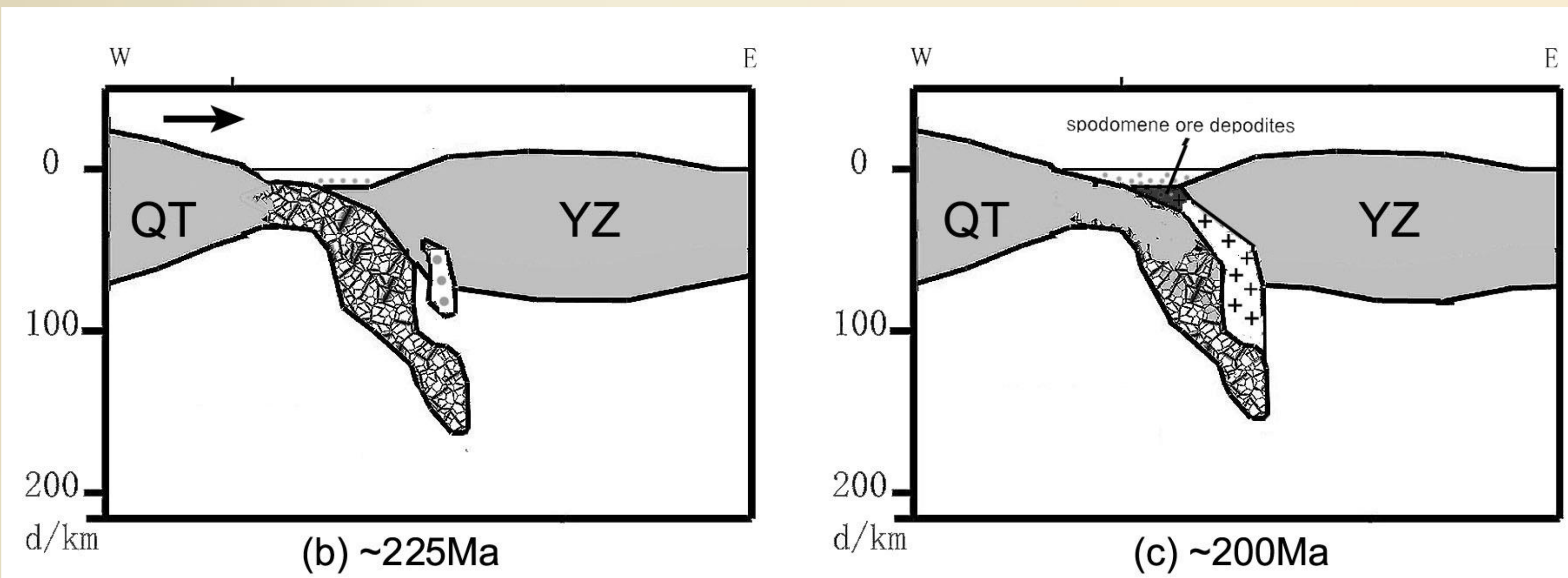
- 锂的密度为0.534 g/cm^3，远远轻于海水中的Na (0.97 g/cm^3) 和 K (0.86 g/cm^3)
- 因为浮力，锂相对难在俯冲过程中以向下渗入地幔
- 古特提斯洋的海水中的锂可以累积在海底，在俯冲过程中沉积在复理石盆地中，为后来锂辉石矿化提供了物质来源

古特提斯洋的海水中的锂可以累积在海底，在俯冲过程中沉积在复理石盆地中，为后来锂辉石矿化提供了物质来源



（2）锂辉石矿在复理石盆地底部形成 (215-195Ma).

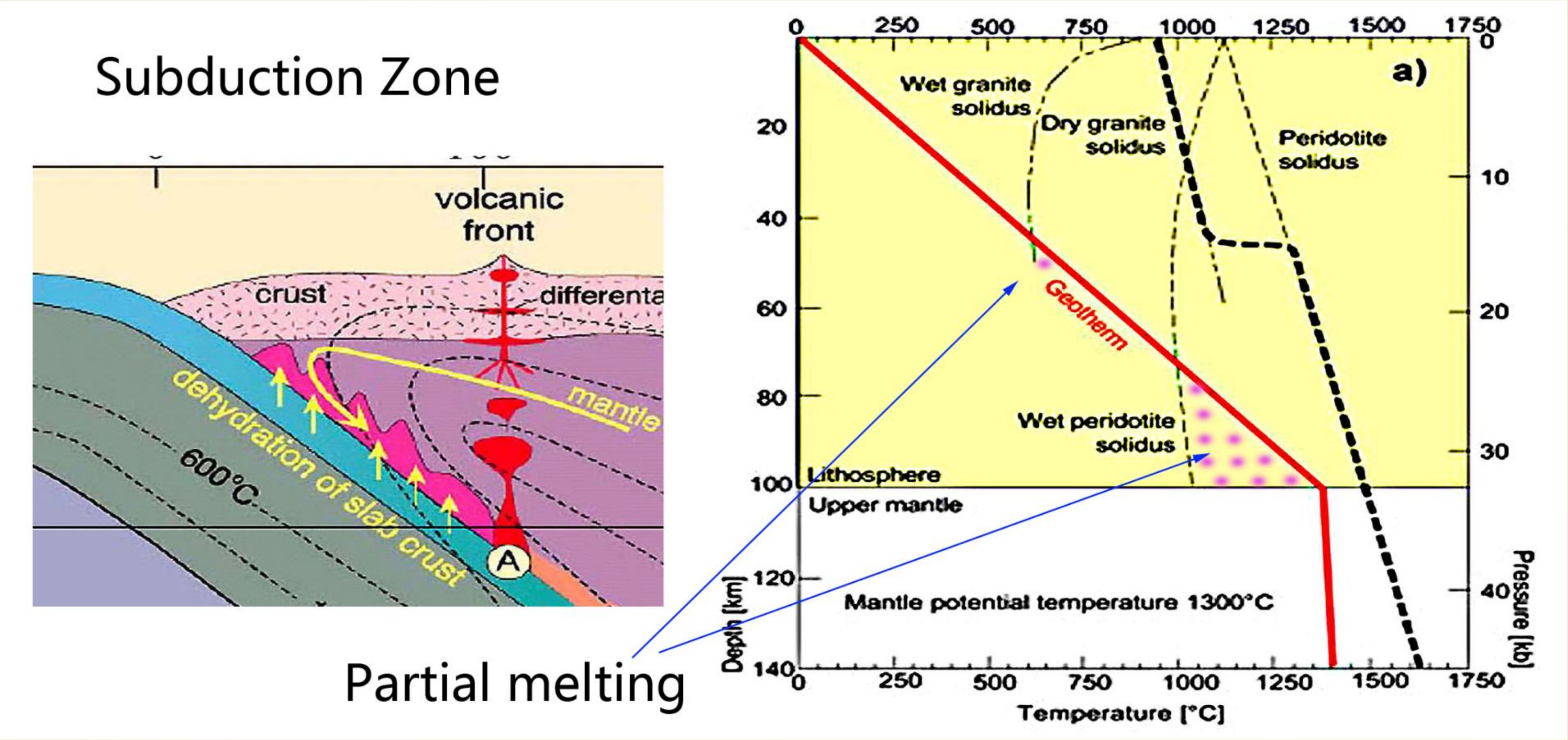
受到冲蚀的地表物质填充了盆地，形成了巨厚的 T_{2-3} 复理石沉积，包括其底部富锂的沉积层。渗入的海水，导致岩石圈部分熔融，形成地壳中的岩浆房，激发了锂辉石的矿化



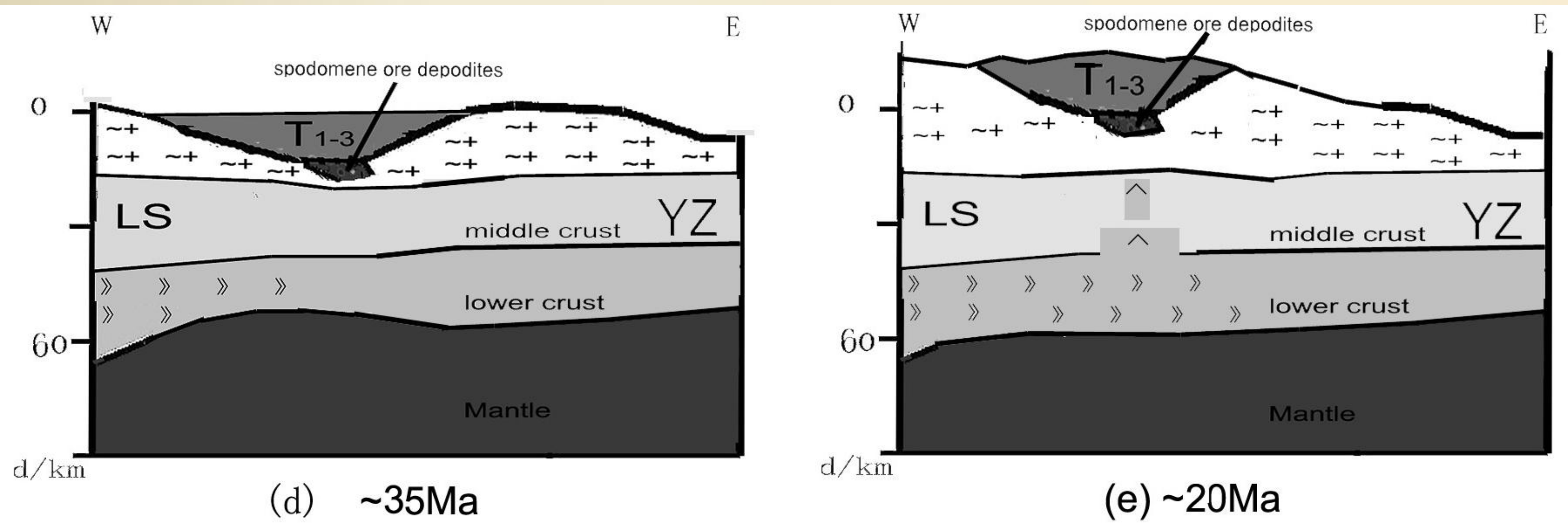
(b) ~225Ma

(c) ~200Ma

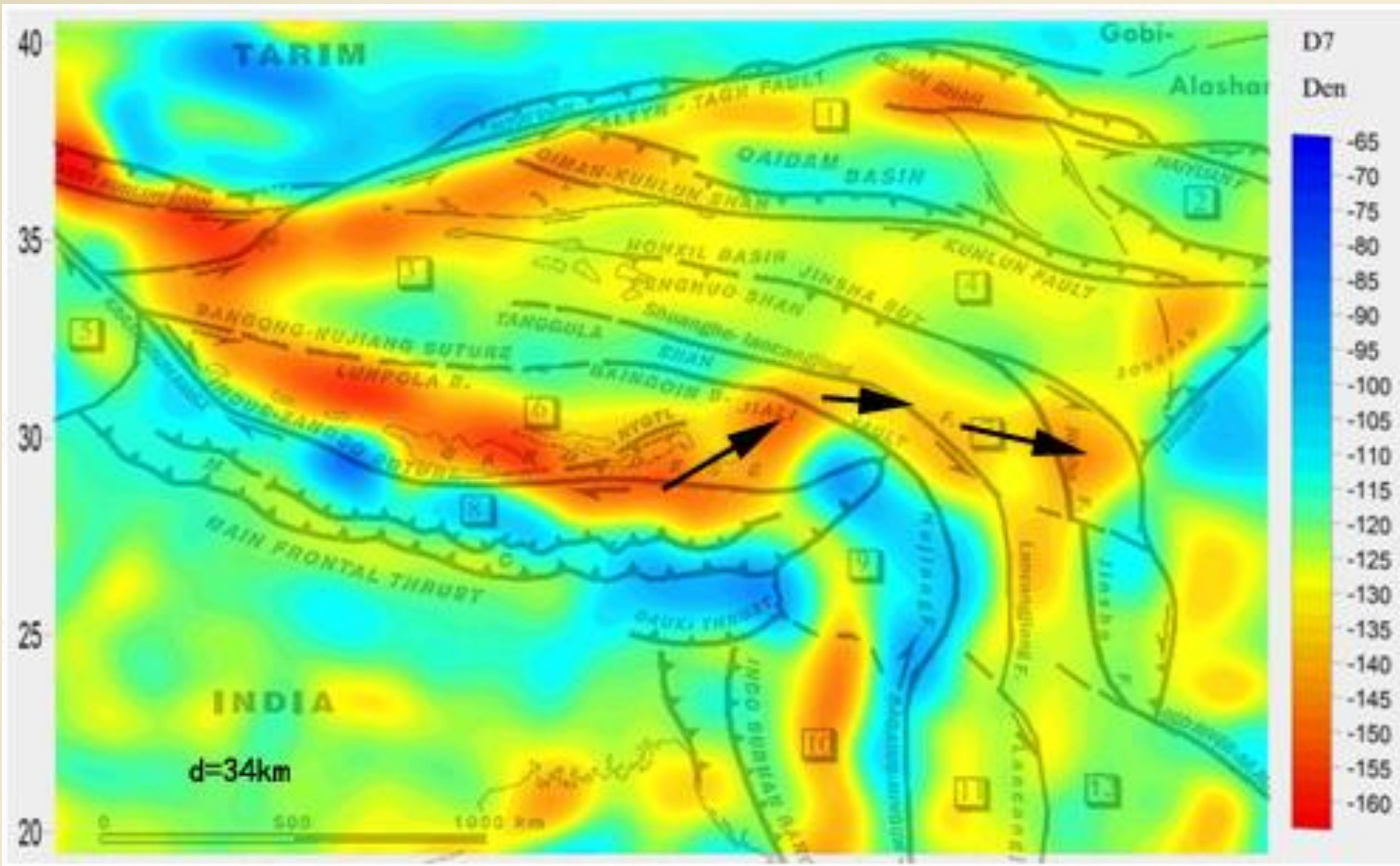
海水，导致岩石圈部分熔融，形成地壳中的岩浆房，



（3） 地壳岩石固结和重结晶变质 (190-60Ma)
（4） 青藏高原的下地壳流东行到雅江复理石盆地(60-20Ma)

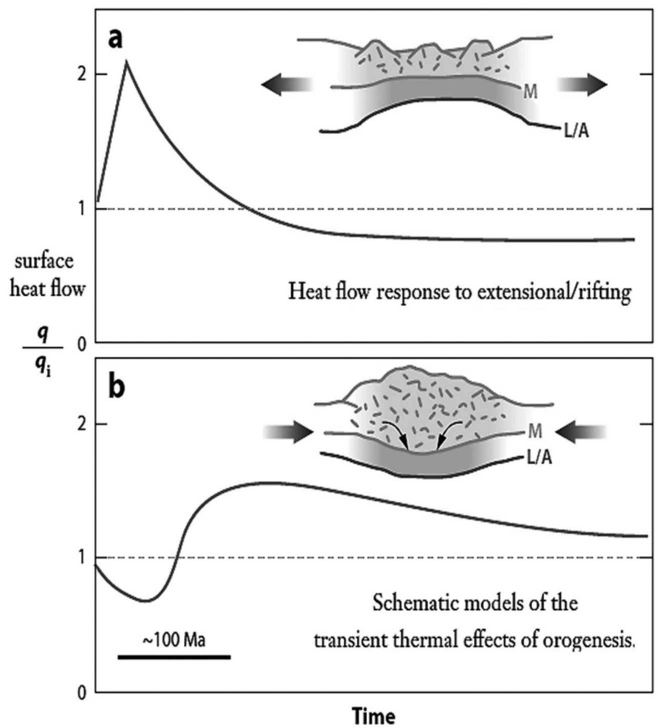


青西藏高原之下的密度扰动图。
最低密度异常反映下地壳流

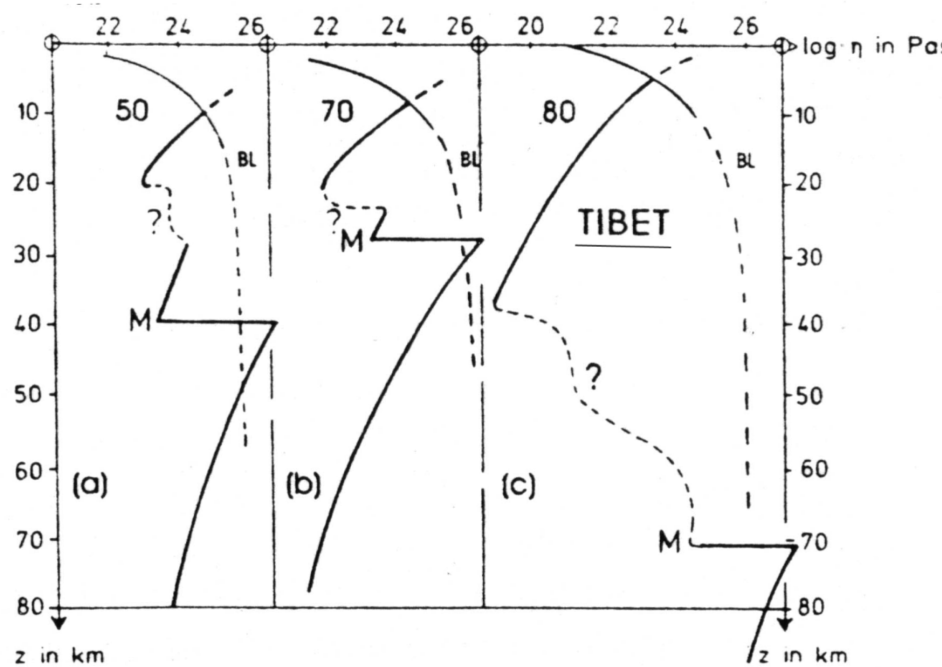


后造山热流上涌产生低粘度下地壳流

Post-collisional heat-flow uprifting causes decreasing viscosity of lower-crust rocks

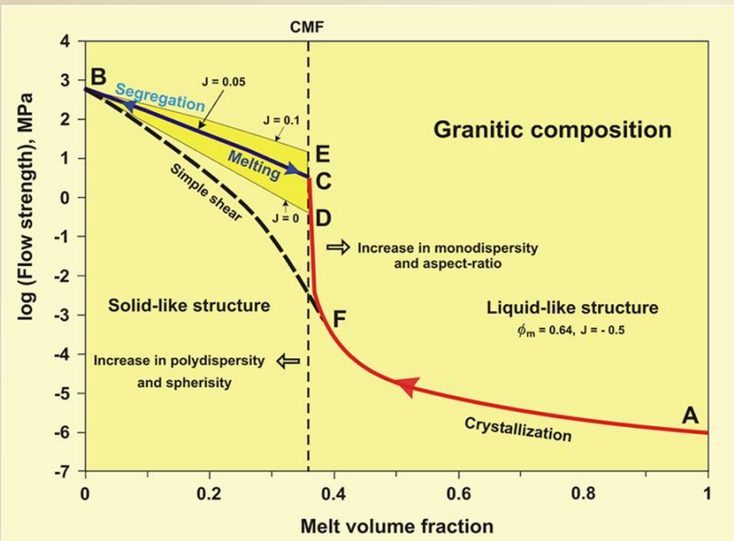


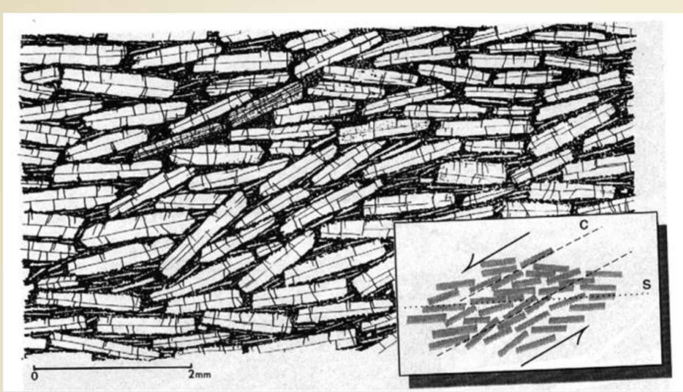
Low viscosity lower crust causes the lower-crust creep flows

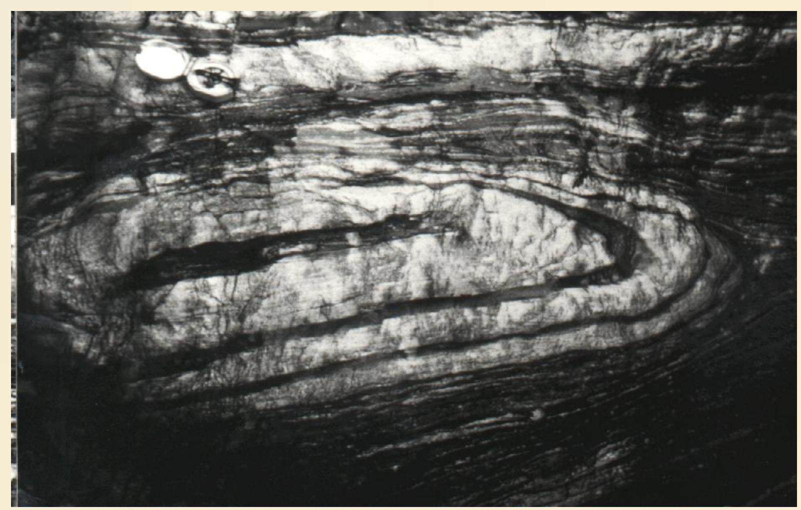


Simple viscosity depth models for southern Tibet, (a) 50 mW/m^2, (b) 70 mW/m^2, (c) 80 mW/m^2: Tibet lower crust flow.

流变的三种相态-韧性剪切、蠕动和熔动

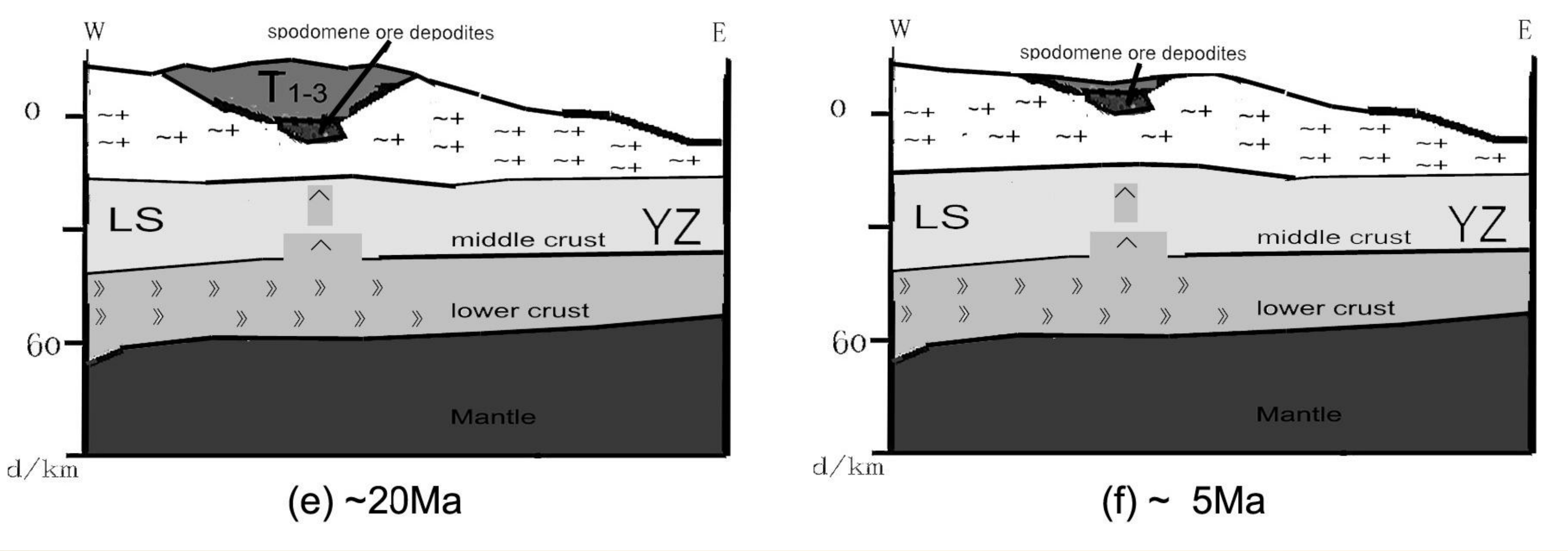




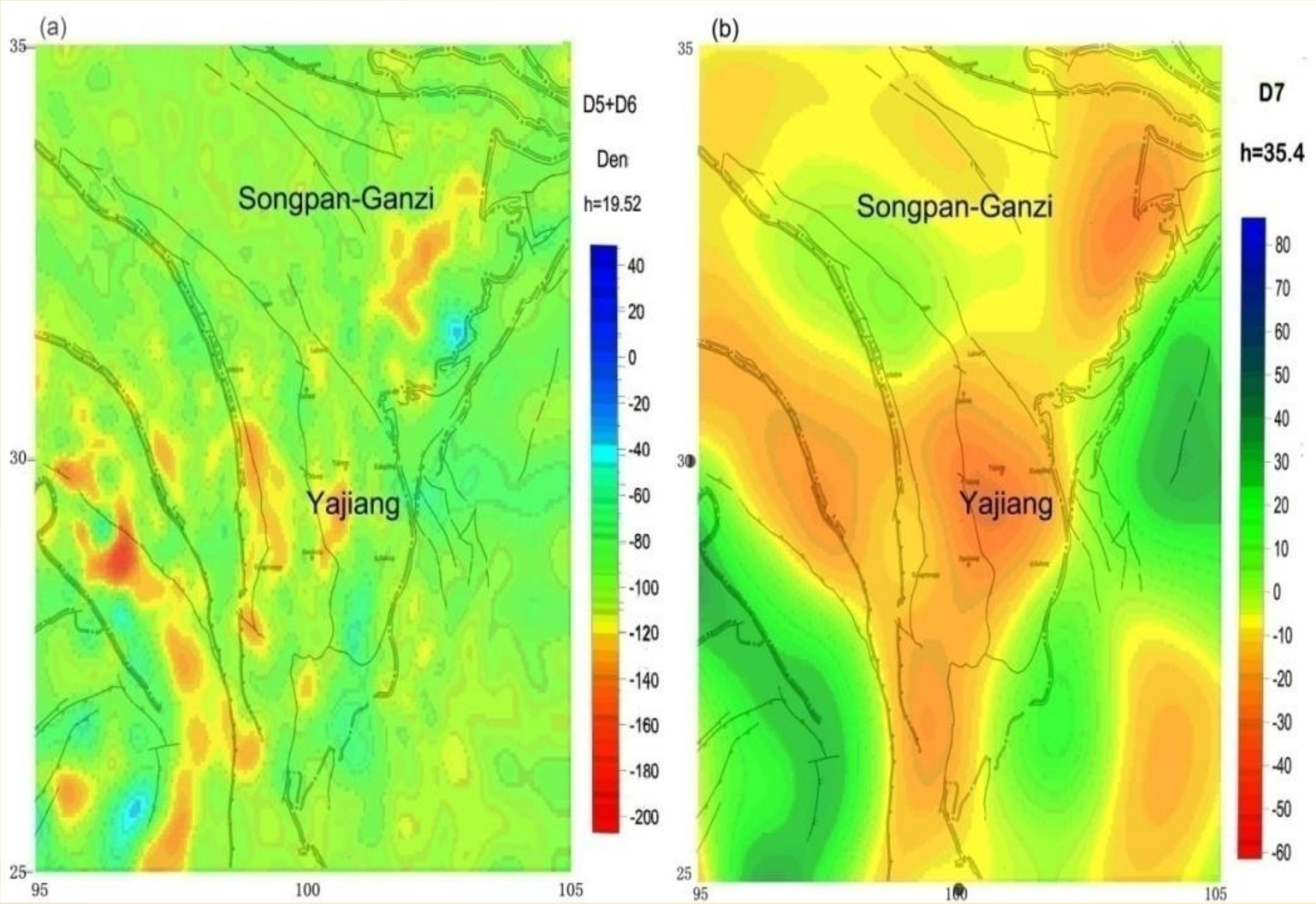


（5）雅江复理石盆地的抬升和冲蚀 (40-15 Ma);

（6）雅江地区变成一个残留复理石盆地；锂辉石沉积在近地表出露

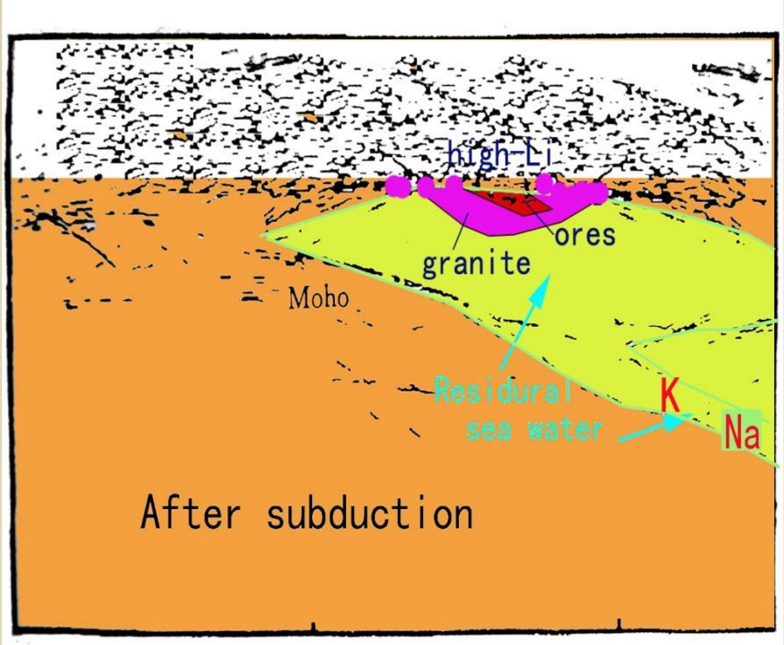


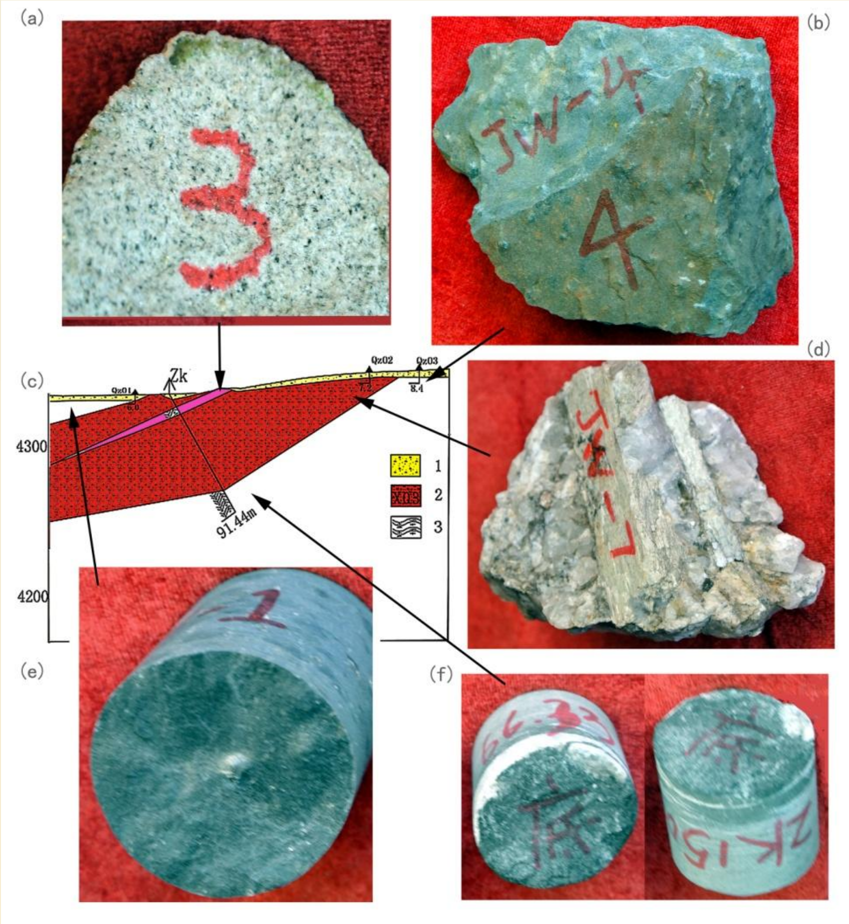
证据: 在中地壳流变物质向上挤出，使中地壳增厚，产生小规模低密度异常



IV.雅江锂矿成矿作用模型的验证

预测锂矿上方围岩必须有较高的锂含量





测试理论

- 我们预测锂辉石矿的上方围岩必须有较高的锂含量
- 样品在国家研究测试中心进行地球化学分析
- 进行了等离子光谱分析（ Perkinelmer 8300 ）
- 相关元素的成分估计

测试结果

Chemical Analysis Report

Testing set No. QT2016028 Reprot No. GDBQT16028

Specimen No.	JW1-B	JW3-J	JW4-A	JW6-D	JW6-C	JW6-E	JW7-K
Analysis No.	QT16028001	QT16028002	QT16028003	QT16028004	QT16028005	QT16028006	QT16028007
SiO_2 (%)	64.33	73.66	61.33	65.34	66.88	65.36	83.61
Al_2O_3 (%)	17.37	14.65	18.24	16.00	16.39	15.99	10.73
CaO (%)	0.73	0.82	1.11	0.91	1.03	0.78	0.13
TFe_2O_3 (%)	6.60	0.93	6.92	6.89	5.94	7.01	0.55
K_2O (%)	3.34	4.94	3.52	3.35	0.05	3.44	0.84
MgO (%)	2.28	0.18	2.53	2.64	2.23	2.68	0.05
MnO (%)	0.09	0.03	0.11	0.09	0.17	0.07	0.20
Na_2O (%)	1.04	3.23	1.56	1.24	1.72	1.15	2.21
P_2O_5 (%)	0.13	0.17	0.14	0.15	0.06	0.16	0.06
TiO_2 (%)	0.74	0.07	0.80	0.68	0.58	0.67	0.01
LOI (%)	3.13	0.79	3.61	2.23	1.34	2.26	0.68
Li (μg/g)	above 1112	granite 319	above 846	242	75.4	beneath 153	ore 5154
Rb (μg/g)	150	306	186	173	2.79	175	270
Cs (μg/g)	131	51.0	138	20.0	1.50	19.9	52.2
Be (μg/g)	2.38	8.65	2.44	4.24	17.6	0.76	4.42
Sr (μg/g)	75.5	38.7	107	82.5	67.3	77.6	4.68
Ba (μg/g)	342	70.8	400	329	11.5	330	8.98
Ga (μg/g)	25.3	20.2	25.1	22.3	19.8	20.9	26.3
As (μg/g)	0.40	0.89	9.38	0.36	0.77	0.23	0.98

结论

- 当海洋中的盐水向下渗透，穿过俯冲带，富锂盐水在浮力影响下集聚在海底
- 之后在雅江复理石盆地底部，岩浆热液作用导致锂矿化，产生最初的锂辉石矿体
- 只有当地壳增厚上升，并风化和冲蚀之后，锂辉石沉积才能抬升到近地表，成为具有开发价值的能源资源
- 对围岩和矿体进行化学分析的测试，获得了预测的证据，验证了锂矿成矿作用模型
- 同样的复理石盆地在全世界广泛分布，它们其中的一些盆地已经抬升，锂辉石有开发潜力

谢谢

- 重建地球动力学过程是理解地球的关键