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Structural evolution of lamprophyric dikes in Lailai, northeastern coast of Taiwan, deduced from mesoscopic structures in dikes and country rocks

[#]Cian-Siang You[1], Wen-Jeng Huang[1,2], Wei Lo[3], Tzu-Bin Wang[2], Chien-Chih Chen[2]

[1] Institute of Applied Geology([#]freedom00_sine@hotmail.com), NCU, Taiwan; [2]Department of Earth Sciences, NCU, Taiwan; [3]Institute of Mineral Resources Engineering, NTUT, Taiwan

Introduction

Lamprophyric dikes are standing in right-stepping en-echelon arrangement up to 2.3 meters high within Lai-Lai marine platform (Fig.1). Folds, faults, joints, and other mesoscopic structures are associated with the dikes.

Fig. 1. En-echelon dikes on platform

Goal

To explain and explore:

- Dikes standing in en-echelon arrangement
- Difference in structural behavior between of dikes and country rocks
- Structural evolution of dikes since the dike intrusion

Method

- UAV photography and orthorectification: mapping dikes and main faults on the ground surface.
- Field work and structural mapping: documenting the structures in dikes in detail.
- Electrical resistivity imaging(ERI): exploring the distribution of the dikes beneath the ground surface.

Conception

Dike intrusion

- **Conditions for dike intrusion (Anderson, 1951; Fig. 2)**
  1. $P_m \geq \sigma_v$ (P_m: magmatic pressure, σ_v:overburden pressure)
  2. The least principal stress, σ_3, is horizontal and perpendicular to orientation of dike.
- **Mechanisms of dike intrusion (Pollard, 1973)**
  1. Forceful injection(Fig. 3a)
  2. Intrusion into pre-existing fissures (Fig. 3b)
  3. Metasomatic replacement (Fig. 3c)
- **Mechanisms of dike propagation on dike tip (Pollard, 1973)**
  1. Extension fracturing (Fig. 4a)
  2. Brittle faulting and stoping (Fig.4b)
  3. Ductile faulting and flow (Fig. 4c)

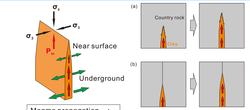


Fig. 2. Conditions for dike intrusion

Fig. 3. Mechanisms of dike intrusion

Scenarios of en-echelon dikes

- Being Faulted after the dike intrudes (Fig. 5a)
- Rotation of the least principal stress field as the surface is approached during dike intrusion (Pollard, 1987; Fig. 5b)

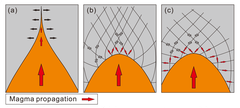


Fig. 4. Mechanisms of dike propagation on dike tips

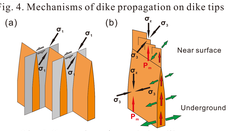


Fig. 5. Formation of en-echelon dikes

Study area

Location and lithology

Lailai wave-cut platform is located at the northeastern coast of Taiwan (Fig. 6). The marine platform composed mainly of argillite within the Oligocene Tatungshan formation is the extension of Hsuehshan range, which has the tallest peak of 3,886 m high in Taiwan.

Structural setting

A series of folds commonly plunging northwards appear on the marine platforms (Fig. 7). The stratified rocks exposed on them mostly incline to north. Lailai is located on the eastern limb of an open syncline (red box in Fig. 7). A set of NNE-SSW strike-slip faults widely distribute on all the platforms.

Geological history

The stratified rocks exposed on the Lailai platform was deposited on continental shelf during late Oligocene. The dike intrusion took place in late Miocene of 9.1±1.1 Ma ago (Chen et al., 1989). According to the stratigraphic analysis, the dikes were likely formed at depth of 2.9 km. Since then, the dikes have experienced tectonic deformation, especially Penglai orogeny beginning in Pliocene.

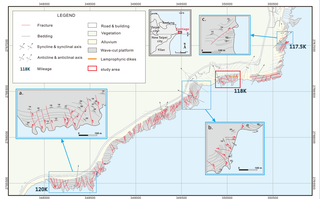
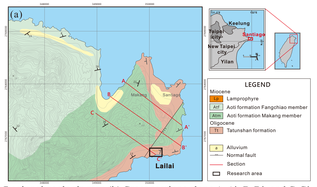


Fig. 7. Structural map



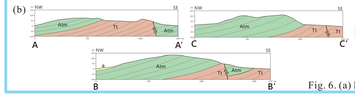


Fig. 6. (a) Regional geologic map (b) Cross sections along A-A', B-B', and C-C'

Result

Orthorectification of aerial photograph

Fig.8. is an aerial photo of Lailai platform taken via unmanned aerial vehicle (UAV). Its orthophotograph is shown in Fig. 9.

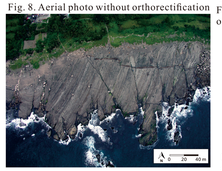


Fig. 8. Aerial photo without orthorectification

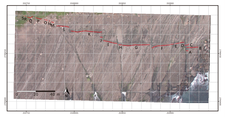


Fig. 9. Orthophotograph. Red lines are the locations of dikes surveyed by total station for comparison.

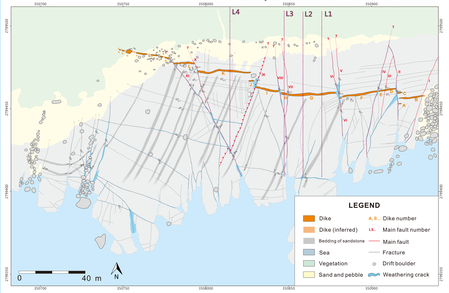


Fig.10. Distribution of dikes, faults, folds, and strata on Lailai platform. Line L1 to L4 are ERI sections.

Field works

- **Main faults**

Most of main faults are high-angle west-dipping right-lateral faults. Most of dikes are cut by faulting at their ends except Dikes B, C, J, and K have intrusive contact with country rocks (Fig. 11 & Table. 1).

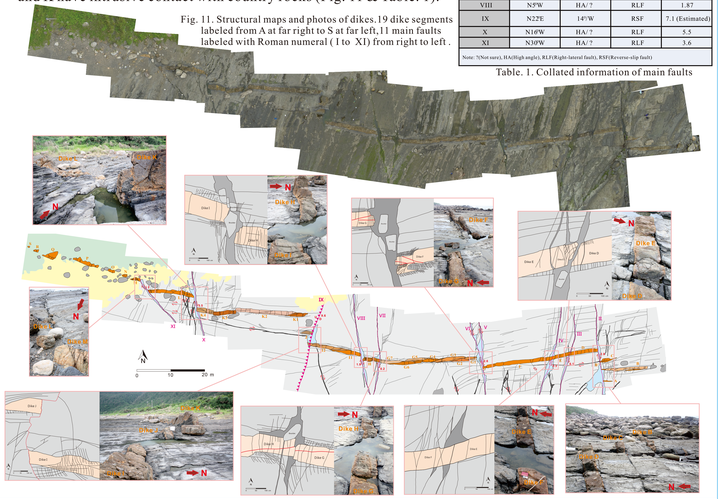


Fig. 11. Structural maps and photos of dikes.19 dike segments labeled from A at far right to S at far left,11 main faults labeled with Roman numeral (I to XI) from right to left .

Fault	Strike (°)	Dip (angle/dip direction)	Type of fault	Separation (m)
I	?	?	?	?
II	N6°W	HA/?	RLF	3.1
III	N10°E	HA/?	RLF	0.1
IV	N6°E	HA/?	RLF	0.3
V	N2°W	HA/?	RLF	2.56 (In total)
VI	N4°W	HA/?	RLF	
VII	N9°E	HA/?	RLF	0.2
VIII	N5°W	HA/?	RLF	1.87
IX	N22°E	14°W	RSF	7.1 (Estimated)
X	N16°W	HA/?	RLF	5.5
XI	N30°W	HA/?	RLF	3.6

Note: ?(Not sure), HA(High angle), RLF(Right-lateral fault), RSF(Reverse-slip fault)

Table. 1. Collated information of main faults

Structures in dikes

1. Ubiquitous in all dikes
   a. Strike-slip faults cutting dikes in a angle of less than 45° (green lines in Fig. 12)
   b. Reverse faults dipping to west (red lines in Fig. 12)
   c. Step-like boundaries on dikes which usually appear together with strike-slip faults.
2. Sequence order of structures in dikes: step-like boundaries=>strike-slip faults => reverse faults (likely formed under same stress status with fault IX)

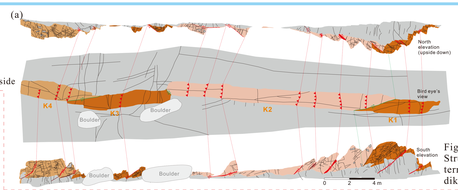


Fig. 12. Structural maps of dikes: (a) Dike K (b) Dike I (c) Dike G. Structures in dikes commonly don't extend into country rocks or they terminate within the country rocks very close to the contact with the dikes.

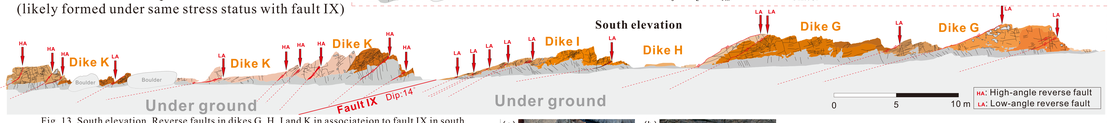


Fig. 13. South elevation. Reverse faults in dikes G, H, I and K in associateion to fault IX in south side of dike mapping.

3. Structural differences between the dikes in the hanging wall of the fault IX (Fig. 13 & Table. 2) and those in the foot wall:
   a. Reverse faults appear more intensively in either side near fault IX
   b. Higher angle (45°) reverse faults only occur in dikes in the hanging wall of fault IX.

Electrical resistivity imaging (ERI)

- Dike G vertically extends downward to 15 meters depth at least (Fig. 14).
- We derive the dip angle, 14°, of thefault IX from information of a shallow drilling. It accords to the vertical extension of dike K, which is only about 4.5 m in depth, in the image of profile L4.

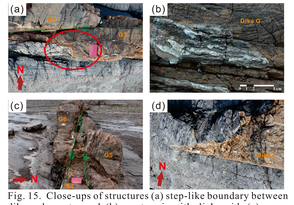


Fig. 15. Close-ups of structures (a) step-like boundary between dike and country rock (b) quartz vein with slickenside (c) duplex structure (d) asymmetric wedge-shaped dike tip

Dikes	Length (m)	Reverse fault (sets/number/angle)	Strik-slip faults (number /duplex /structure)
A	2.57	None	None/None
B	12.55	1/1/LA,2/1/HA	1/d.s.
C	4.97	1/1/LA	None/None
D	12.13	1/1/LA	None/None
E	4.29	None	None/None
F	17.61	1/2/LA	2/d.s.
G	28.58	1/4/LA	6/d.s.
H	3.55	None	1/d.s.
I	15.03	1/6/LA, 2/2/HA	2/d.s.
J	2.7	None	None/None
K	32.95	1/5/LA, 2/8/HA	2/d.s.
L	2.95	None	1/None

Note: HA(High angle, > 45°), LA(Low angle, < 30°)

Table. 2. Length of each dike and information of faults within dikes

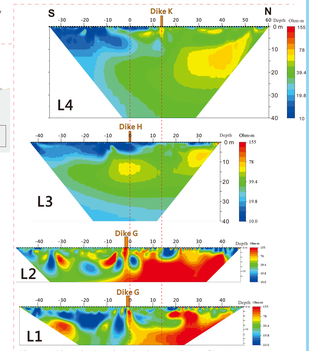


Fig. 14. Electrical resistivity images in profile L1 to L4

Discussion and conclusions

Faulting on LaiLai marine platform

The N-S striking right-lateral faults and fault IX both crosscut other structures and displace dikes. Namely, the faulting took place after dike intrusion and played the main role in arranging the dikes. We restore these displaced dikes accordingly. The dikes remain en-echelon arrangement but reduce to three segments only instead of 19 (Fig. 16).

Formation of en-echelon dikes

Dike-parallel adjacent joints and regional joints are both present in dikes on Lailai platform. The shape of dike tail-ends is not blunt or digital but wedge-shaped. It implies that magma ascended along pre-existing fractures and filled up them (Fig.17).

Thus,we conclude that magma ascended along pre-existing regional joints in en-echelon arrangement, which might merge into one fracture at deeper depth.

Fig. 16. Restoration of displaced and faulted dikes.

Fig. 17. A scenario for the formation of the en-echelon dikes at Lailai marine platform.

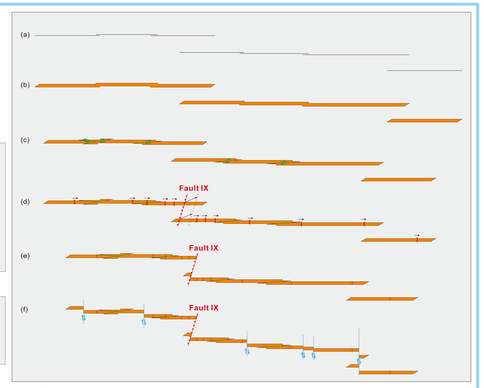


Fig. 18. Structural evolution of dikes

Proposed scenario for the structural evolution of dikes in Lailai

The structural evolution of the dikes in sequence of events: (a) echelon joints formed (b) magma intruded (c) strike-slip faults (most of all are right-lateral) occurred in dikes and fold occurred in country rocks (d,e) reverse faults occurred in both dikes and country rocks (f) N-S right-lateral faults formed (Fig. 18).

Future works

- Estimating the amount of horizontal shortening of dikes in total .
- Determining the dip angle and net slip direction of each main fault by ERI.
- Observing structures in country rocks and comparing structural behavior in dikes with structural behavior in country rocks.

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