Research Article

Geochronology and Tectonic Evolution of the Lincang Batholith in Southwestern Yunnan, China

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Geochronological research of the Lincang Batholith is one key scientific problem to discuss the tectonic evolution of the Tethys. Two granitic specimens were selected from the Mengku-Douge area in the Lincang Batholith to perform the LA-ICPMS Zircon U-Pb dating based on thorough review of petrological, geochemical, and geochronological data by the former scientists. Rock-forming age data of biotite granite specimen from Kunsai is about 220 Ma, the Norian age. However, the west sample from Mengku shows 230 Ma, the Carnian age. The later intrusion in Kunsai area located east to the Mengku area shows directly their uneven phenomena in both space and time and may indirectly reflect the space difference of the contraction-extension transformation period of the deep seated faults. Considering the former $^{40}\text{Ar}/^{39}\text{Ar}$ data and the outcrop in Mengku, the Lincang Batholith should have experienced one tectonic exhumation and regional subsidence cycle. The regional subsidence cycle has close relations to the expansion of the Meso Tethys.

1. Introduction

The Sanjiang-Indochina region is one key area to study the evolution of the Tethys [1–10] (Figure 1). The Changning-Menglian zone was considered as the major faunal break between Gondwanan assemblage to the west and Cathaysian to the east [11, 12]. The subduction-related magmatism occurred along the western edge of the Lanping-Simao-Indochina terrane throughout the Triassic and the closure of Palaeo-Tethys [12, 13]. The Lincang Batholith extends ~370 km from north to south, covering the Chiangrai-Chiang Mai region of Thailand, with an area of more than 10000 km² (Figure 2). It has been shown by many authors that there is great mineral potential [14].

The Lincang Batholith was divided into three lithologic intervals by previous authors, the Xiaojie, Lincang, and Menghai intervals (Figure 2) [15–17]. The major intrusion is porphyritic monzonitic granite, which mainly contains quartz, zonal plagioclase, K-feldspar, and biotite. In addition, geochemical studies have shown that the granite mainly has source features of the crust mixing origin [16, 18].

The Lincang Batholith was proposed to form in a passive continental margin according to geochemical research [19]. The intrusive timing spans from late Permian to late Triassic based on whole-rock Rb-Sr, mineral $^{40}\text{Ar}/^{39}\text{Ar}$, whole-rock $^{87}\text{Sr}/^{86}\text{Sr}$, Rb-Sr, Sm-Nd, and some other methods (Table 1).

But there are also some understanding differences on the crystallization period and evolution time of the Lincang Batholith. Many predecessors discussed mineral diagenesis and tectonic evolution through traditional data [16, 20], although, not from the viewpoint of the plate tectonics. On scientific problems of the Lincang Batholith, some solutions were put forward such as single period of mixed granite [16], quasi-situ metasomatic granite [20], or Neoproterozoic type I granite complex batholith with multiperiod transforming events [19].

Therefore, the formation and evolution of the Lincang Batholith is still the key to discuss the regional tectonic evolution of the Baoshan and Lanping-Simao-Indochina block. In this study, we conducted petrographic analysis of the Lincang Batholith and provide new LA-ICP-MS U-Pb data in order to constrain the tectonic evolution of the

FIGURE 1: Map of plate tectonics and ore-forming metals in the southern Sanjiang and Indochina peninsula. (a) Scope of Tethys and zone divisions; (b) research area and distribution of major metals: (1) Changning-Menglian-Chiangmai Paleotethys Suture (time and space after [1, 21, 22]); (2) Ailaoshan-Song Ma Paleotethys Suture (time and space after [2, 6, 8]); (3) Bangong Co-Nujiang Meso-Tethys Suture (time and space after [5]); (4) Yanlung Tsangpo-Naga-Arakan New-Tethys Suture (time and space after [22, 23]); (F1) Nujiang-Saging Fault Zone; (F2) Ranong Fault Zone; (F3) Three Tower Fault Zone; (F4) Tonle Sap Fault Zone; (F5) Đà Lạt-Bianhe Fault Zone; (F6) Điện Biên Phủ Fault Zone; (F7) Changshan-Da Nang Fault Zone; (F8) Lanjiang Fault Zone; (F9) Ailaoshan-Red River Fault Zone; (F10) Xianshuihe-Xiaojiang Fault Zone; (F11) Lancang-Jinghong Fault Zone.

Batholith. We discuss these results of dating in the context of regional tectonic evolution.

2. Dating Methods, Specimens, and Results

2.1. Dating Methods. The U-Pb zircon age dating of monzonitic granite samples selected from the Mengku-Douge research area in Lincang segment (Figures 2 and 3) was

designed and completed in the Institute of Geology and Geophysics, Chinese Academy of Sciences. Jobs of single zircon grain micro-area U-Pb geochronological analysis were taken through Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) of 7500a-type produced by Agilent Co. Ltd., with which the laser beam diameter is $60\ \mu\text{m}$, the erosion frequency is 8 Hz, the energy density is $15\sim 20\ \text{J}\cdot\text{cm}^{-2}$, the erosion time is about 60 s. For detailed

FIGURE 2: Regional map of Indian Period and research locality in western Yunnan. The distribution of metal deposits also indicates that there is an important boundary along the Lincang Granite Batholith. Stereographic maps of lower hemisphere projection indicating the initial occurrence of Lincang granite Batholith are also plotted in the regional map. L, S, Q refer to joints parallel to the initial foliation, parallel to the flow direction but upright to the initial foliation, upright to both the flow direction and initial foliation. Orientation of shear fractures can be generated by local stress system of the Batholith with emplacements [24].

analysis procedures, please see Xu et al. [32]. The Zircon U-Pb isotope and the U, Th data processing are finished by software Glitter4. 0 [33], and computing of U-Pb concordia diagrams, weighted average ages and graphics were completed by software Isoplot3.0 [34].

2.2. Specimens

2.2.1. Specimen from Kunsai Quarries. The biotite monzonitic granite samples were selected from the Kunsai

quarries to the east of Quannei-Douge migmatite rock belt (Figures 3 and 4(a)). The north part of the rock unit is plunged into the Jurassic basin (Figure 3). Field study shows that both the rock unit and the Jurassic basin have experienced a period of ductile transformation events. The microstructure study shows brittle deformed feldspar (Figures 4(b) and 4(c)), dynamically recrystallized quartz (Figure 4(c)), microdeflected biotite (Figure 4(d)), zircon grains with relatively intact crystal, long column, some

TABLE 1: Isotopic age data for the Lincang Batholite in the earlier stage.

Lithologic section	Lithology	Measured objects and methods	Dating results, Ma	Sample positions	Testers and the time
Xiaojie	Granite porphyry	Whole-rock (Rb-Sr)	169 ± 5	Laomaocun	Zhang et al., 2006 [25]
Xiaojie	Monzonitic granite	Whole-rock ($^{87}\text{Sr}/^{86}\text{Sr}$)	279	Yun County	Chen, 1991 [26]
Lincang	Biotite granite	Biotite ($^{40}\text{Ar}/^{39}\text{Ar}$)	201.1 ± 2.7	Near the Lancangjiang River	Dai et al., 1986 [27]
Lincang	Monzonitic granite	Whole-rock (Rb-Sr)	279	Lincang	Chen, 1991 [26]
Lincang	Medium-grained equigranular granodiorite	Whole-rock (Rb-Sr)	263.8	Milestone along Lincang-Mengku road 327–387 km	Zhang et al., 1990 [28]
Lincang	Unequal-sized biotite granite	Whole-rock (Rb-Sr)	193	Shangyun-Xiaotang	Zhang et al., 1990 [28]
Lincang	Monzonitic granite	Whole-rock (Rb-Sr)	275 ± 59	Lincang	Liu et al., 1989 [18]
Menghai	Monzonitic granite	Whole-rock ($^{87}\text{Sr}/^{86}\text{Sr}$)	279	Menghai	Chen, 1991 [26]
Menghai	Monzonitic granite	Biotite (Rb-Sr)	256	Menghai	Wang, 1984 [29]

FIGURE 3: Geological sketch map in Mengku-Douge area (revised after [15–17, 30, 31]) (1) Area of ingress ion sea of the Meso-Tethys; (2) Jurassic terrigenous sediments; (3) Early Jurassic volcanic sedimentary rocks; (4) Lincang Triassic granite rock; (5) deep metamorphic wedge with local granodiorite quality migmatization Late Paleozoic; (6) schistosity occurrence; (7) bedding occurrence.

rounded output and a higher degree of porosity which is symbiotic to microcline grains (Figure 4(b)). The cathode luminescence (CL) images show that the typical magmatic zircon characteristics are colorless and transparent here with oscillatory zoning, the length of about $120\ \mu\text{m}$ – $420\ \mu\text{m}$ and the aspect ratio of 1.2 to 4.1 (Figure 4(e)). Totally, for 22 points of 22 zircon grains of sample biotite granodiorite KS-2 from the Kunsai quarries we performed U-Pb isotope analysis in order to statistically gain a feasible dating result (Figure 4(f)). All points were selected on the edge of long- column euhedral grains where the magmatic zircon oscillatory zoning is clear.

2.2.2. Specimens from Mengku Quarries. The monzonitic granite sample MK-4 is selected from the Mengku East Quarry at the eastern side of the Mengku Town in the Shuangjiang County, which separates Jurassic red clastic rocks with one bedding bottom granitic conglomerate by the paleo-weathering crust in between (Figures 5(a), 5(b), and 5(c)). Figure 5(a) shows the position photo of the biotite monzonitic granite sample in the Mengku East Quarry. From the field outcrop, both granitic intrusion (lower left) and its weathering top can be found to be cleaved which had been covered by the upper Jurassic red detrital sediments with terrigenous origin, namely, the Huakaizuo Formation.

FIGURE 4: Geochronological research of granite sample KS-2. (a) Position photo of the biotite monzonitic granite sample in the field of Kunsai Quarry. (b) The zircon grows together with the microcline CPL. (c) The microstructure of complete recrystallized quartz indicates the rock once experienced high-greenschist facies of deformation, CPL. (d) One biotite crystal is folded, PPL. (e) Magmatic zircon is shown by the SEM cathodoluminescence (CL) image. The circled area is deduced to form during the crystallization of granite and is just the measured area by laser-ICPMS (f) Zircon La-ICPMS U-Pb dating figure, and the average age is about 220 Ma.

The MK-4 zircon grains (Figure 5(d)) change greatly and have different shapes and sizes, such as long column, fan, and irregular granular. However, size of zircon grains is uniform with length between $90\ \mu\text{m}$ and $150\ \mu\text{m}$ and length-width ratio in 1.1:1–1.8:1. Zircon grains develop with quartz, plagioclase in rocks. The rock sample has been affected by weathering, showing retrograde metamorphism (Figure 5(e)). Characteristic oscillatory zoning of typical magmatic zircon is rendered on the cathode CL image. The

idiomorphic degree of zircon is high, but some fragmented. On the sample of MK-4, 18 zircon grains and 18 points were analyzed by ICP-MS. Edge of the long-column idiomorphic or the chipped-hypidiomorphic zircon grains, and the clear zone of magmatic zircon oscillatory were always selected to perform the micro isotope analysis (Figure 5(f)).

2.2.3. Dating Results. As shown in Figure 4(f) and Table 2, the overall harmony values of KS-2 zircon age data range

FIGURE 5: Geochronological research of the granite sample MK-4. (a) Position photo of the biotite monzonitic granite sample in a field Quarry of east Mengku. (b) Granitic intrusion (lower left) and its fossil weathering were cleaved. (c) The red detrital material of terrigenous origin, Huakaizuo Formation in Jurassic, was normal gradational. (d) Granitic intrusions are selected as sample. (e) The micro characteristics of MK-4 and the zircon setting are shown. The zircon grains are associated with quartz and plagioclase and have been degraded by some weathering process, CPL, (f) Magmatic zircon is shown by the SEM cathodoluminescence (CL) image. The circled area is deduced to form during the crystallization of granite and is just the measured area by laser-ICPMS. (g) Zircon La-ICPMS U-Pb dating figure, and the average age is about 245 Ma.

TABLE 2: U-Pb isotopic dating for the single grain Zircon from granite of Kunsai.

No.	$^{207}\text{Pb}/^{206}\text{Pb}$			$^{207}\text{Pb}/^{235}\text{U}$			$^{206}\text{Pb}/^{238}\text{U}$			$^{208}\text{Pb}/^{232}\text{Th}$			$^{207}\text{Pb}/^{206}\text{Pb}$			$^{207}\text{Pb}/^{235}\text{U}$			$^{206}\text{Pb}/^{238}\text{U}$			$^{208}\text{Pb}/^{232}\text{Th}$		
	Ratio	Error (1σ)		Ratio	Error (1σ)		Ratio	Error (1σ)		Ratio	Error (1σ)		Ratio	Error (1σ)		Ratio	Error (1σ)		Ratio	Error (1σ)		Ratio	Error (1σ)	
A77	0.05789	0.00231		0.25961	0.00949		0.03251	0.00089		0.01383	0.00076		526	38		234	8		206	6		278	15	
A78	0.05188	0.00244		0.23562	0.00953		0.03294	0.00079		0.01035	0.00025		280	110		215	8		209	5		208	5	
A79	0.05273	0.00141		0.24329	0.00604		0.03345	0.00081		0.01108	0.00055		317	26		221	5		212	5		223	11	
A80	0.05213	0.00216		0.23471	0.00801		0.03265	0.00077		0.01025	0.00024		291	97		214	7		207	5		206	5	
A81	0.05209	0.00131		0.25938	0.00608		0.0361	0.00086		0.01177	0.00034		289	25		234	5		229	5		237	7	
A82	0.05014	0.00118		0.24192	0.00531		0.03498	0.00082		0.01113	0.00044		201	24		220	4		222	5		224	9	
A83	0.05126	0.00122		0.24287	0.00541		0.03435	0.00081		0.01155	0.0006		253	24		221	4		218	5		232	12	
A84	0.05027	0.00114		0.24534	0.00525		0.03539	0.00083		0.01176	0.00041		207	24		223	4		224	5		236	8	
A89	0.0521	0.00237		0.22575	0.00875		0.03143	0.00075		0.00987	0.00023		290	107		207	7		199	5		199	5	
A90	0.05305	0.00182		0.2649	0.0084		0.03621	0.00094		0.01376	0.00075		331	33		239	7		229	6		276	15	
A91	0.05739	0.00113		0.23972	0.00441		0.03029	0.0007		0.00946	0.00032		507	23		218	4		192	4		190	6	
A92	0.05076	0.00135		0.24604	0.00612		0.03515	0.00085		0.01173	0.00045		230	26		223	5		223	5		236	9	
A93	0.05089	0.00279		0.24455	0.01197		0.03485	0.00086		0.01098	0.00025		236	127		222	10		221	5		221	5	
A94	0.05114	0.00155		0.24377	0.00683		0.03457	0.00087		0.01167	0.00055		247	29		222	6		219	5		235	11	
A95	0.05055	0.00109		0.24175	0.00488		0.03469	0.00081		0.01181	0.00045		220	24		220	4		220	5		237	9	
A96	0.05018	0.00134		0.23857	0.00594		0.03448	0.00084		0.01149	0.00049		203	26		217	5		219	5		231	10	
B02	0.05115	0.00119		0.24774	0.00541		0.03514	0.00084		0.01297	0.00054		248	25		225	4		223	5		260	11	
B03	0.05067	0.00224		0.24165	0.00903		0.03459	0.00082		0.0109	0.00025		226	104		220	7		219	5		219	5	
B04	0.05104	0.00235		0.24163	0.00953		0.03433	0.00082		0.01081	0.00025		243	109		220	8		218	5		217	5	
B05	0.05079	0.00153		0.24968	0.00699		0.03567	0.0009		0.01274	0.00067		231	29		226	6		226	6		256	13	
B06	0.05039	0.00095		0.24525	0.00437		0.03531	0.00082		0.01121	0.00038		213	25		223	4		224	5		225	8	
B07	0.05429	0.00243		0.27463	0.01035		0.03669	0.00089		0.01147	0.00027		383	103		246	8		232	6		230	5	
B08	0.05014	0.00223		0.24399	0.00913		0.0353	0.00085		0.01114	0.00026		201	104		222	7		224	5		224	5	
B09	0.05141	0.00105		0.25807	0.00495		0.03643	0.00086		0.01414	0.00053		259	25		233	4		231	5		284	11

FIGURE 6: Isotopic age histogram showing the major tectonic event in the area east to the Tibet Peateau (after [8]).

from 195 Ma to 245 Ma, but some of them are below the U-Pb harmonic line and deviated from the harmony line. This is probably because the micro region selected is too close to the boundary of the zircon grain. Some zircon grains (Figure 5(f)) also have some cracks in and this may also affect the dating result. From the harmonic visible figure, zircon dating values are focused to a range from 210 Ma to 230 Ma, and the average age is about 220 Ma. This means that the crystallization age of the Kunsai quarries biotite granite is about in the late Triassic Norian period.

As shown in Figure 5(g) and Table 3, the overall harmony values of MK-4 zircon age data range between 190 Ma and 315 Ma. The values are somewhat scattered mainly because the granite of the Mengku quarries has been heavily weathered (Figure 5(d)). During the weathering process, chemical bonds of ZrO_2 in zircon grains of our MK-4 sample would be broken. Therefore, some zircon isotope escaped. The average age of 245 Ma might indicate that the late Permian to early-middle Triassic magmatic event happened in the Mengku Quarries area of the Lincang Batholith.

3. Tectonic Implications

Previous petrological and geochemical studies [18, 26, 28, 35] indicate that the Lincang granite mainly shows two types of granite with an initial strontium isotope ratio ranging from 0.71 to 0.78 and therefore it belongs to S-type granite and once may have been formed in an environment of tectonic collision. Combined with previous chronological data, we propose a three-stage model on the tectonic evolution between late Permian and Jurassic (Figure 6).

(1) *Regional Collision and Contraction before the Formation of the Lincang Batholith.* Before the formation of the Lincang Batholith, the Paleo-Tethys Ocean and many intraoceanic islands distributed between the Baoshan and the Lanping-Simao-Indosinian blocks [36]. In a regional contractional environment of subduction and collision, it is extremely common to find folding, thrusting, and uplifting phenomena (Figure 7(a)).

(2) *Time Heterogeneity of In Situ Hybrid of the Lincang Batholith.* The Lincang Batholith was controlled by one deep-seated fault along the Lancang Jiang River and proposed in situ hybrid origin of the Batholith in the early to middle Triassic collision between the Baoshan-Shantai and Lanping-Simao-Indochina Blocks [16]. Our study shows an ununiform law result in the aspect of mixing time of the Batholith (Figure 7(b)). The intrusion time in the east Qunsai area was later than in the Mengku area, indicating that the regional contraction in Mengku area was weakened or stopped, and triggered magma poured at ~230 Ma, however, the contraction pattern may still remain in the Qunsai area to the east.

(3) *Tectonic Denudation and Regional Exhumation Happened between Late Triassic and Middle Jurassic, Which Is Supported by ~201 Ma Biotite $^{40}Ar/^{39}Ar$ Age from the Lincang Batholith [27].* This paper research shows that the upper part of the Lincang Batholith experienced long-term denudation, resulting in the development of the weathering crust (Figure 7(a)). The upper crust is the Jurassic Huakaizuo Formation, characterized by carbonate rocks of shallow sea facies, together with some volcano clastic rocks (Figure 5(b)).

TABLE 3: U-Pb isotopic dating for the single grain Zircon from granite of Mengku.

Analysis no.	$^{207}\text{Pb}/^{206}\text{Pb}$			$^{207}\text{Pb}/^{235}\text{U}$			$^{206}\text{Pb}/^{238}\text{U}$			$^{208}\text{Pb}/^{232}\text{Th}$			$^{207}\text{Pb}/^{206}\text{Pb}$			$^{207}\text{Pb}/^{235}\text{U}$			$^{206}\text{Pb}/^{238}\text{U}$			$^{208}\text{Pb}/^{232}\text{Th}$		
	Ratio	Error (1 σ)		Ratio	Error (1 σ)		Ratio	Error (1 σ)		Ratio	Error (1 σ)		Ratio	Error (1 σ)		Ratio	Error (1 σ)		Ratio	Error (1 σ)		Ratio	Error (1 σ)	
1	0.05174	0.00244		0.32303	0.0139		0.04528	0.00108		0.01152	0.00053		274	56		284	11		285	7		232	11	
2	0.09115	0.00288		2.96352	0.08448		0.23585	0.0053		0.08061	0.00287		1450	25		1398	22		1365	28		1567	54	
3	0.11509	0.00332		0.50952	0.01225		0.03212	0.00066		0.02102	0.00068		1881	19		418	8		204	4		420	13	
4	0.04837	0.00265		0.22077	0.01108		0.03312	0.00085		0.01153	0.00063		117	69		203	9		210	5		232	13	
5	0.04837	0.0022		0.27295	0.01145		0.04095	0.00092		0.01223	0.0006		117	57		245	9		259	6		246	12	
6	0.05351	0.00279		0.29775	0.01415		0.04038	0.00104		0.01371	0.00078		350	62		265	11		255	6		275	16	
7	0.0806	0.00218		2.27431	0.05585		0.2048	0.00394		0.05968	0.00155		1212	22		1204	17		1201	21		1172	30	
8	0.0802	0.00341		2.36577	0.09085		0.2141	0.00577		0.05352	0.00277		1202	37		1232	27		1251	31		1054	53	
9	0.05928	0.00248		0.29959	0.01132		0.03668	0.00082		0.00966	0.00046		577	45		266	9		232	5		194	9	
10	0.04989	0.00375		0.23793	0.0163		0.03461	0.00119		0.00907	0.00072		190	96		217	13		219	7		182	14	
11	0.07866	0.00333		0.34683	0.01279		0.032	0.00079		0.01233	0.00063		1164	37		302	10		203	5		248	13	
12	0.0406	0.00217		0.22437	0.01119		0.04011	0.00095		0.01052	0.00055		-255	72		206	9		254	6		212	11	
13	0.0639	0.00299		0.31538	0.01317		0.03582	0.00089		0.01126	0.00067		738	48		278	10		227	6		226	13	
14	0.07481	0.00441		0.3517	0.01817		0.03412	0.00108		0.01178	0.00078		1063	56		306	14		216	7		237	16	
15	0.06821	0.00263		0.97745	0.03376		0.10399	0.00236		0.03233	0.00106		875	37		692	17		638	14		643	21	
16	0.05116	0.00255		0.26673	0.01227		0.03784	0.00088		0.01057	0.00052		248	64		240	10		239	5		213	10	
17	0.05025	0.00304		0.25181	0.01395		0.03636	0.00102		0.01037	0.00064		207	77		228	11		230	6		209	13	
18	0.05379	0.003		0.27018	0.01369		0.03645	0.00098		0.00965	0.0006		362	67		243	11		231	6		194	12	
19	0.05083	0.00373		0.26778	0.01802		0.03823	0.00125		0.00987	0.00055		233	96		241	14		242	8		199	11	
20	0.06022	0.00487		0.2998	0.0217		0.03612	0.00142		0.01137	0.00113		611	90		266	17		229	9		229	23	
21	0.0473	0.00214		0.20932	0.0087		0.0321	0.0007		0.00892	0.00038		64	55		193	7		204	4		179	8	
22	0.05405	0.00334		0.28442	0.01602		0.03817	0.00111		0.00858	0.0006		373	75		254	13		241	7		173	12	
23	0.05907	0.0024		0.66212	0.02439		0.08128	0.00181		0.03438	0.00121		570	43		516	15		504	11		683	24	
24	0.05064	0.00245		0.21459	0.00944		0.03072	0.00072		0.00797	0.00046		224	59		197	8		195	5		160	9	
25	0.05594	0.00261		0.26352	0.01113		0.03415	0.0008		0.00964	0.00045		450	53		237	9		216	5		194	9	
26	0.06769	0.00524		0.32217	0.02212		0.0345	0.00134		0.01049	0.0009		859	80		284	17		219	8		211	18	
27	0.06354	0.00206		0.75553	0.02205		0.08618	0.00166		0.02056	0.00084		726	32		571	13		533	10		411	17	
28	0.05014	0.00296		0.33191	0.01801		0.04797	0.00129		0.02068	0.0011		201	77		291	14		302	8		414	22	
29	0.23782	0.00377		6.55914	0.08439		0.19984	0.00325		0.01824	0.00075		3105	12		2054	11		1174	17		365	15

FIGURE 7: Formation and tectonic evolution model for the Lincang Batholith.

Unconformity relationship is shown between the Batholith and the Huakaizuo Formation (Figures 3, 5(a), 5(b), 5(c), and 7(c)). Apparently, the Meso-Tethys expansion also happened in this era and left some effect in the Lincang Area.

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