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Lahars in and around the Taipei basin: Implications for the activity of the Shanchiao fault

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Abstract

In the last decade, more than 21 deep geological cores have been drilled in the Taipei basin to obtain a firmer grasp of its basic geology and engineering properties prior to the construction of new infrastructure. Thirteen of those cores contain lahar deposits, with the number of layers varying from one to three and the thickness of each layer varying from several to over 100 m. Based on their occurrence, petrology and geochemistry, it has been determined that the deposits originated from the southern slope of the Tatun Volcano Group (TVG). K–Ar age dating has shown that the lower layer of lahars was deposited less than 0.4 Ma, and this is clearly correlated to outcrops in the Kauntu, Chengtzeliao and Shihtzutao areas. These findings may well suggest that the Taipei basin has been formed in last 0.4 Ma and that the Shanchiao normal fault commenced its activity within this period. The surface trace and the activity of the Shanchiao normal fault have also been inferred and subsequently defined from stratigraphic data derived from these cores.

Keywords: Taipei basin; Tatun Volcano Group; Shanchiao normal fault; Lahar; Subsurface geology

1. Introduction

The Taipei basin is widely considered to be an extensional basin formed by subsidence in the hanging wall of the Shanchiao normal fault, which is recognized as the potentially most hazardous fault in this densely urbanized region (Fig. 1) (Lin, 1957; Wu, 1965; Chiu, 1968; Ho, 1969). Although studies on the stratigraphy, sedimentology and tectonics as well as age dating have been undertaken in the basin (Lin, 1957; Wu, 1965; Chiu, 1968; Ho, 1969; Wang Lee et al., 1978; Chen and Lin, 1999, 2000; Lee and Su, 1994; Liew et al., 1997; Lin and Chen, 2001; Liu et al., 1994; Teng et al., 1994, 1996; Wei et al., 1998), the onset of basin subsidence and the activity of the Shanchiao fault have remained subjects of debate (Wei et al., 1998).

Over the past decade, to ensure the sound construction of new infrastructure, a large-scale research project has been undertaken by the Central Geological Survey, Ministry of Economic Affairs (CGS-MOE), Taiwan, ROC to study the sedimentation, petrology, tectonic activity, geological history as well as engineering geology of the Taipei basin. A total of about 21 deep holes, each more than 200 m in depth, have been drilled in the basin, and most have been located in its western and northwestern parts (Fig. 1). In addition, numerous shallow holes were necessitated by the construction of local traffic networks and buildings, e.g. the Mass Rapid Transportation (MRT) and the world's tallest structure, the Taipei 101 Business Building. The combinations of seismic reflection profiles as well as stratigraphic data obtained from the cores provide abundant information with which to better understand the subsurface geology of the Taipei basin and its environs (Wang et al., 1995; Lin et al., 1999).

Huge amounts of volcaniclastic strata, dominated by lahar deposits, are distributed in surface outcrops and

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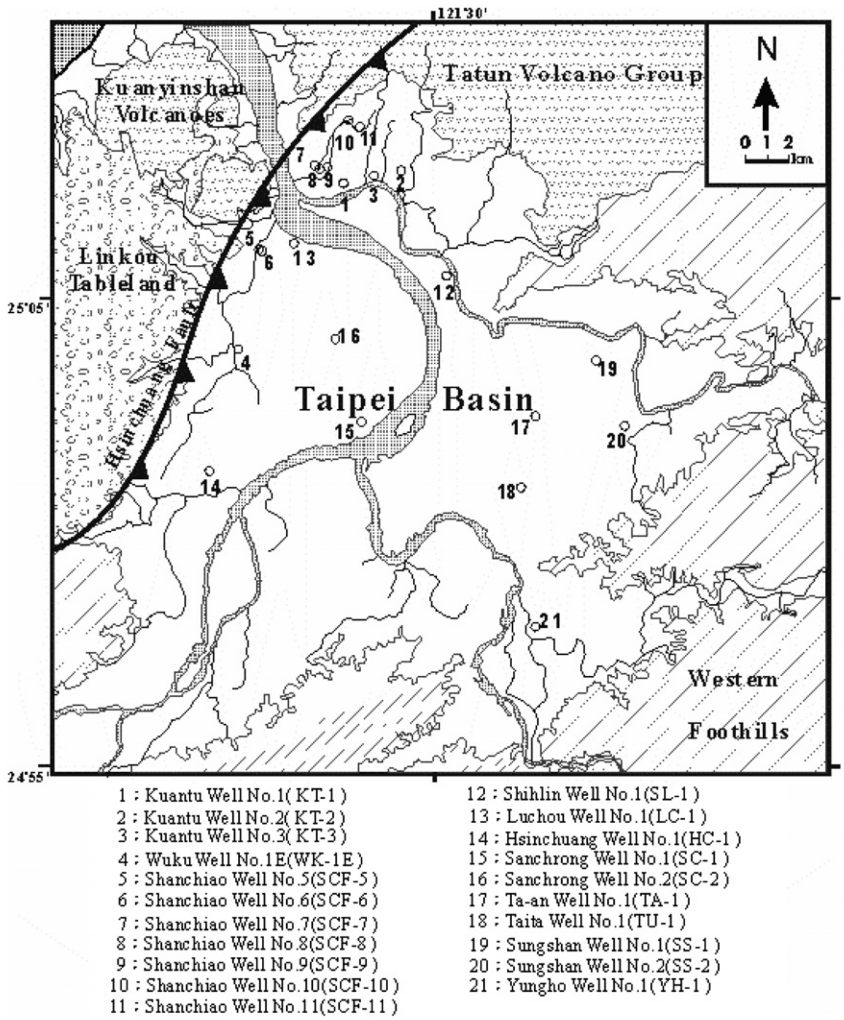

Fig. 1. Simplified geological map around the Taipei basin and the locations of the drilling holes. The numbers represent the well name and site listed below.

defined in subsurface cores in the northwestern portion of the Taipei basin (Song and Lo, 1995; Tsao et al., 2001). With regard to field occurrences, petrology and petrochemistry, the lahar deposits in the surface and subsurface have been identified as being derived from the Tatun Volcano Group (TVG) (Song and Lo, 1995; Tsao et al., 2001). The TVG is located in the northwestern part of the Taipei basin, where it is bounded between the Chinshan and the Kanchiao faults (Fig. 1). Unconformably overlying the Oligocene to Miocene sedimentary rocks (Chen and Wu, 1970; Yen et al., 1984), the volcanic rocks mainly erupted during two periods: one from 2.8 to 2.5 Ma and the other from 0.8 to 0.2 Ma (Jiang and Chen, 1989; Wang and Chen, 1990; Tsao, 1994).

In this paper, our work has focused on studying the lahar deposits found in the drilled cores of the Taipei basin and correlating these to surface outcrops. The purposes are threefold: to (i) unravel the timing of the age of the formation of the Taipei basin; (ii) define the surface trace of the Shanchiao normal fault; and (iii) estimate the past and future activity and seismic hazards of the Shanchiao normal fault.

2. Geological setting

The Taipei basin is a triangular-shaped, tectonically controlled basin (Fig. 1) (Lin, 1957; Wu, 1965; Chiu, 1968; Ho, 1969). Its western border is delimited by the Shanchiao fault, which separates it from the Linkou Tableland. Its southeastern boundary is marked by the Taipei fault, across from which stand the Western Foothills, while its northern rim is bordered by the TVG. More than 600 m of Quaternary sediments, unconformably overlying the Tertiary basement (Wang et al., 1995) have previously been divided, in ascending order, into four stratigraphic units: the Banchiao, Wuku, Chingmei and Sungshan Formations (Teng et al., 1994).

During the Quarternary arc-related volcanism erupted a number of volcanoes in northern Taiwan, including the TVG, the Chilung Volcano Group, the Kuanyinshan volcanoes and the four offshore volcanic islets, of Chilungtao, Huapinghsu, Meinhuahsu and Penghiahsu. The TVG is composed of more than 18 volcanoes, built predominantly from lava flows and pyroclastic and water-laid volcaniclastic strata (Chen and Wu, 1971; Wang and Chen, 1990; Song et al., 2000). Based on the age of these volcanic strata, eruptive histories can be grouped into two periods (Jiang and Chen, 1989; Wang and Chen, 1990; Tsao, 1994). The first period includes small-scale eruptions around 2.8–2.5 Ma, when limited volumes of lava and pyroclastic deposits were produced, whereas the second period occurred around 0.8–0.2 Ma, when a cauldron was formed, followed by outpourings of voluminous lava flows at most of the volcanic centers (Song et al., 2000).

The Linkou Formation in the Linkou Tableland, situated to the west of the Taipei basin (Fig. 1), is dominantly composed of gravels, sands and mud with minor volcaniclastic strata (Ho, 1969; Wang Lee, 1969; Chang, 1971). The volcaniclastic-bearing gravel beds are generally distributed in the northern and northeastern Linkou Tableland around the Kuanyinshan volcanoes in the upper part of the Linkou Formation, suggesting that these volcanoes were the source of volcaniclastic strata emplaced in the gravel beds (Hwang and Lo, 1986; Chen and Teng, 1990). Song and Lo (1995), however, postulated that some of them might have, in fact, been derived from the TVG. In addition, another recent study on the greatly weathered outcrop of andesite in the lower part of the Linkou Formation suggests that these blocks might have been derived from the Chilung Volcano Group (Tien et al., 1994).

3. Lahars in the Taipei basin

Lahars are rapidly emplaced water-supported flows of volcaniclastic deposits (Crandell, 1971; Fisher and Schmincke, 1984) that are similar to debris-flow deposits (Scott, 1988; Smith and Lowe, 1991). A total of 13 of the 21 cores drilled in the Taipei basin, dominantly in the northwestern and western parts were found to have lahar deposits (Fig. 1). The drilled depths range from 94 to 760 m, reaching Tertiary basement rocks at depths between 70 and about 680 m (Fig. 2). One to three lahar units of varying thickness intercalated with fluvial tuffaceous or lacustrine sediments have been identified in the cores (Tsao et al., 2001). The thickness of lahar deposits ranges from a few meters to more than 100 m and decreases from north to south away from the TVG (Fig. 2). Among them, for example, is Shanchiao-Fault Well No. 11 (SCF-11) with two layers of fluvial tuffaceous sediments, 54.9 and 100.5 m thick, that is separated into three lahar units from 73 to 507 m, with a thickness of 49.9, 116.5 and 112.2 m, respectively. Kuantou Well No. 1 (KT-1) has 81.6 m thick sequence of fluvial tuffaceous sediments separated into two lahar deposits from 236 to 488 m in depth, with a thickness of 87.1 and 84.1 m (Tsao et al., 2001). This contrasts with Wuku No.1 (WK-1), which has just one thin lahar layer about 6 m thick.

The lahar deposits are dominantly composed of subangular to subrounded andesite with a few basaltic lapilli and blocks with gravels of sedimentary or metamorphic provenance embedded in a sandy to clayed matrix. Clasts in the lahars range from a few centimeters to a meter in diameter. The longest, intact core of one volcanic block is more than 1 m. Sedimentary features of the lahars include poorly sorted and massive beds that are matrix-supported. Clast-supported and crude-stratified beds do occur, but not uncommon in the deposits. The intercalated fluvial tuffaceous sediments are dominantly composed of unconsolidated, interlayered sand, mud, and minor andesitic cobbles or pebbles. Normal fining upward sequences and facies characteristics indicate the tuffaceous sediments were probably deposited in a braided river system (Tsao et al., 2001), while the presence of the lahar deposits in the boreholes indicates a depositional environment with high-energy flow and a large gradient slope developed on the southern side of the TVG. Interbedded tuffaceous sediments, by contrast, serve as evidence that a low-energy stream was also formed during the interval between the emplacement of two or three lahar units.

Andesitic and basaltic blocks in the lahar deposits are porphyritic in texture with a glassy or microcrystalline matrix. Zoned plagioclase are the most abundant phenocrysts with hornblende and pyroxene (augite and hypersthene) included as the more common mafic phenocrysts in the andesitic blocks. Thus, each andesite is further defined by its predominant mafic phenocrysts. Petrographic examination further reveals that two-pyroxene andesite and two-pyroxene hornblende andesite are the two main rock types among the samples, whereas hypersthene hornblende andesite, hornblende andesite and augite andesite only appear in minor amounts (Tsao et al., 2001). The distribution of andesitic rock types in different lahar layers show that the lower and the upper lahar layers in two of the cores, i.e., KT-1 and SCF-11, are characterized by polymictic volcanic blocks, while the middle layers are mostly monomictic; that is, dominated by two-pyroxene andesite. In this section, it becomes obvious that the andesitic blocks in the lower layer contain more hornblende phenocrysts than those in the middle layer.

Volcanic blocks in lahars have a wider range of SiO_2 content (48.29–66.64%), although most lie between 50% and 56%. Most of the samples are andesitic (52% $< SiO_2 <$ 63%), but a few are basaltic (45% $< SiO_2 <$ 52%) and rhyolitic (>63%). The variation diagram show that TiO_2, Fe_2O_3, MgO and CaO decrease, and Na_2O and K_2O increase with increasing SiO_2. Fig. 3 shows that all the volcanic blocks in the lahars can be classified into both the calc-alkaline rock series and the hypersthene rich rock series of the Hakone area, Japan (Kuno, 1950). It is also worth noting that the MgO/ΣFeO ratio and Sr concentrations can be used to distinguish volcanic rocks of the TVG from those from the Kuanyinshan volcanic center (Fig. 4). The abundance of trace elements in all the volcanic clasts in the lahar deposits are distributed in very narrow ranges. The variation diagrams of SiO_2 versus Sr, Ba, Zr, and La reveal similar results to those of the major elements. The REE patterns and spidergrams show light REE enrichment and slight Eu negative anomaly along with Nb and Ta depletion.

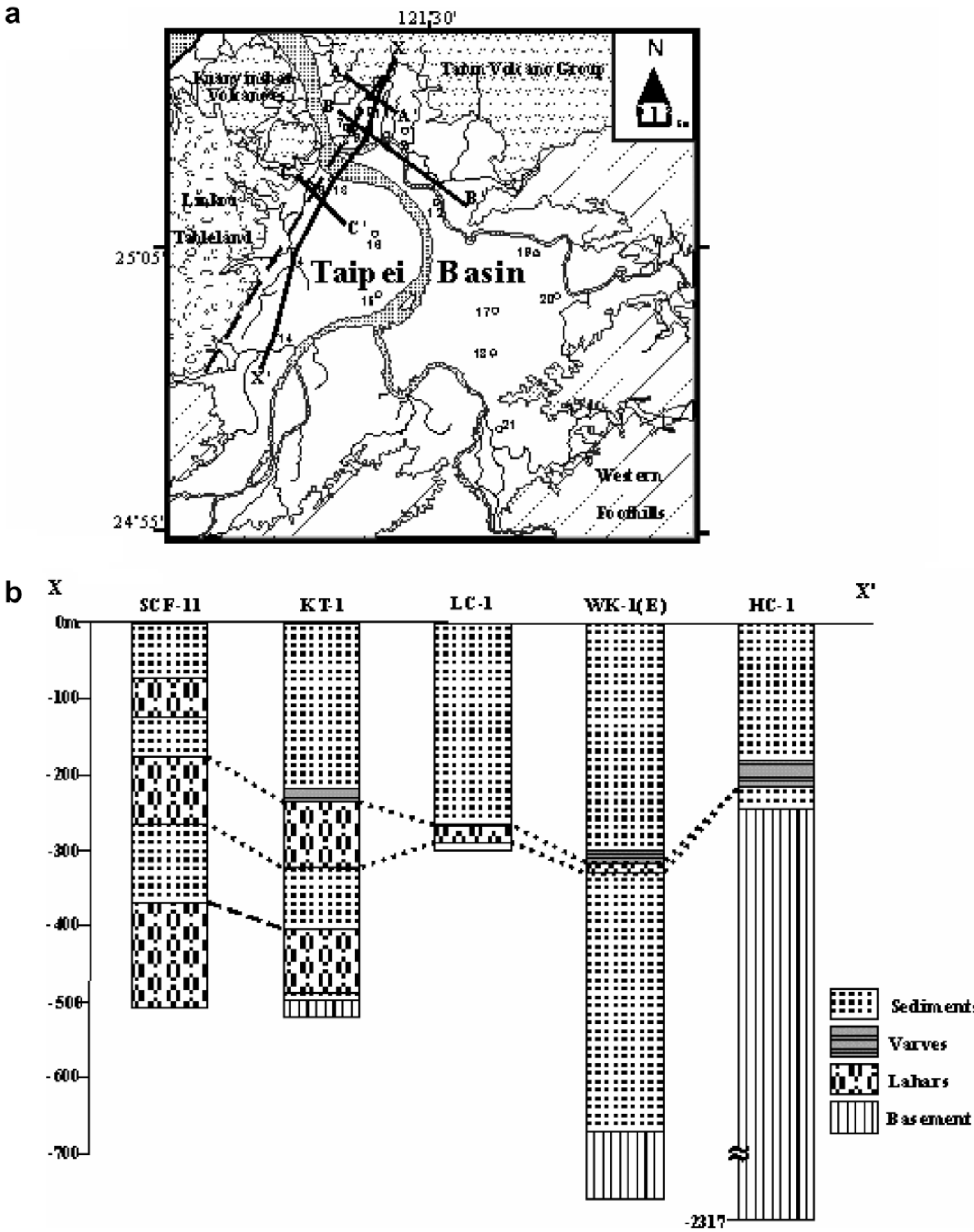

Fig. 2. The locations (a) and the lithological columns (b) of cores distributed from north to south. It shows that the thickness of lahars decrease from the north to the south.

The volcanic blocks in the lahar deposits from the KT-1 core have been dated using the K–Ar radiometric method, and the ages can be categorized into two ranges, i.e. 0.3–0.3 Ma for the lower layer and 0.1–0.4 Ma for the middle layer (Tsao et al., 2001). Since the lahars were emplaced as a result of a number of volcanic eruptions, we argue that these two lahar layers may have come from two different sources: either each was generated by the eruption of different volcanoes or each was produced from the same volcano but in different volcanic periods. Accordingly, in the case of the KT-1 borehole, it is suggested that, with the 2σ error taken into account, the depositional age of the lower and middle layers of the lahars is, respectively, not older than 0.4 and 0.2 Ma (Tsao et al., 2001).

4. Lahars around the Taipei basin

Lahar deposits around the Taipei basin are dominantly distributed in a narrow belt, which pinches out to the south from Kauntu, Chengtzeliao and Shihtzutao in the northwestern and western parts of the basin (Song and Lo, 1995). The thickness of the deposits varies from hundreds of meters at Kauntu, and several tens of meters at Shihtzutao to several meters at Chengtzeliao from north to south; in general lahar thickness decreases from east to west. The

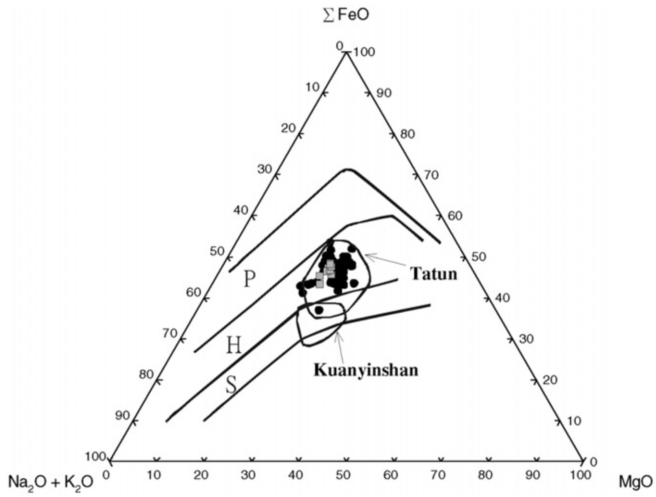

Fig. 3. AFM ($Na_2O + K_2O$, ΣFeO, MgO) diagram illustrating the variation of the volcanics in the surface and subsurface lahar deposits. Squares for the samples of the volcanics in the surface lahars, circles for those of the subsurface lahars. The Tatun and Kuanyinshan representing the distribution fields of the volcanics in the TVG and Kuanyinshan volcano. P and H representing the field of the pigeonitic and hypersthenic rock series in Hakone, Japan (Kuno, 1950), and S denoting that of the shoshonitic series of New Guinea Highlands (Mackenzie and Chappell, 1972).

lahar deposits are massive to faintly laminated and are either matrix-supported or clast-supported. Volcanic blocks make up the major part (over 90%) of the lahar deposits, whereas sedimentary and metamorphic blocks only constitute a minor part. The volcanic blocks are generally angular to subangular and heterolithologic, unlike the sedimentary and metamorphic blocks, which are rounded to subrounded. The volcanic blocks in lahar deposits are also heterolithologic, dark, light grey, yellow or pale red. Plagioclase (about 30–40%) is the most abundant phenocryst. Augite and hypersthene with some hornblende are the principal mafic phenocrysts, which are embedded in the glassy or microcrystalline matrix. The groundmass in these volcanic rocks generally consists of microlithic plagioclase and augite or glass and makes up about 35–45% of the bulk rock volume (Song and Lo, 1995).

Volcanic clasts of the lahar deposits have a narrower range of SiO_2 content (54.48–58.22%). Most of the samples are andesitic. The variation diagrams show that TiO_2, Fe_2O_3, MgO and CaO decrease, and Na_2O and K_2O increase as SiO_2increases (Song and Lo, 1995). Fig. 3 also show that all of volcanic blocks in the lahars can be classified into the calc-alkaline rock series and the hypersthenic rock series of the Hakone area, Japan (Kuno, 1950). It is also apparent that the MgO/ΣFeO ratio and Sr concentrations of clasts in the lahars are similar to rocks from the TVG and can be easily discriminate from Kuanyinshan volcanic strata. The abundance of trace elements in all of the volcanic blocks in the lahar deposits shows the concentrations are distributed in very narrow ranges. The variation diagrams of SiO_2 versus Sr, Ba, Zr, and La yield similar results to those of the major elements. The REE patterns and spidergrams show light REE enrichment and a slight Eu negative anomaly along with Nb and Ta depletion (Song and Lo, 1995).

Two samples collected from the surface outcrops in Kuandu and Chuwei, which were also dated using the K–Ar radiometric method, are 0.55 ± 0.02 Ma and 0.53 ± 0.04 Ma, respectively (Tsao et al., 2001).

5. Discussion

5.1. Formation of the Taipei basin

The lahars in the surface outcrops decrease in thickness from north to south. Volcanic blocks therein are characterized lithologically, as two-pyroxene or two-pyroxene hornblende andesite, and geochemically, by the calc-alkaline and the hypersthenic rock series. The source of the lahar deposits in the Kauntu, Chentzeliao and Shihtzetou areas could, therefore, be determined from the TVG on the basis of field occurrence, lithology, major and trace element chemistry such as Sr, Ba, Ni, Cr, Th, U and light REE of the andesitic blocks (Song and Lo, 1995).

One to three lahar units have been identified in the subsurface cores of the Taipei basin, and these may have been induced by and deposited after major volcanic eruptions. On the basis of their occurrences, the characteristics of intercalated sediments, lithology and major and trace geochemistry, lahars can be well correlated with each other from one borehole to another. The lower and upper layers of the lahars are characterized by polymictic volcanic blocks, which are dominantly composed of two-pyroxene hornblende andesite with minor two-pyroxene and hornblende andesite. Monomictic volcanic blocks, which dominate in the two-pyroxene andesite with minor two-pyroxene hornblende and hornblende andesites, are the major rock types in the middle layer. The source of the lahar deposits is also ascertained from the TVG based on the occurrences, lithology as well as major and trace geochemistry (Tsao et al., 2001). Therefore, with an understanding of the occurrence, rock types, major and trace geochemistry along with the K–Ar ages, the subaerial lahars exposed in the Kauntu, Chentzeliao and Shihtzetou areas can be correlated with those found in the lower layer of the subsurface lahars in the Taipei basin. Given that the lahar deposits in surface outcrops are similar to those of the lower layer of the subsurface we argue they comprise the same flow. We further suggest that they were offset by later normal faulting. Such normal faulting may have been caused by extensional tectonism, which reactivated the pre-existing Chinshan-Hsinchuang thrust fault from as a normal fault (Chu et al., 1998).

The youngest K–Ar age (0.36 ± 0.09 Ma) of all of the lower lahar deposits, suggests the age of this tectonic event could not be older than 0.4 Ma (Tsao et al., 2001), which also indicates that the age of formation of the Taipei basin. This is consistent with thermal luminescence age results on sediments of Wuku Well (Wei et al., 1998). A schematic presentation of

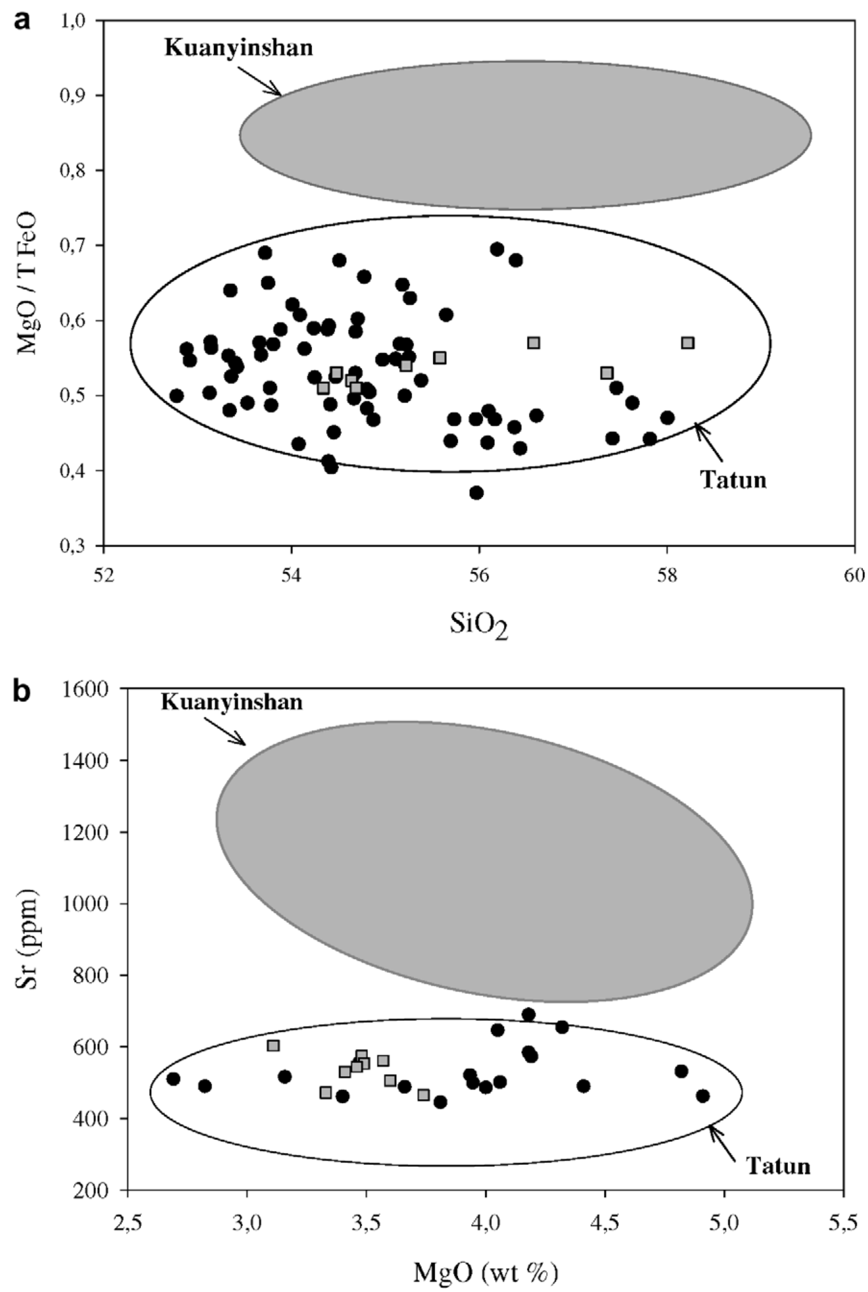

Fig. 4. Variation diagrams of MgO/T FeO versus SiO_2 (a) and Sr versus MgO (b) of the volcanics in the surface and subsurface lahar deposits. Symbols the same as in Fig. 3.

the formation model of the Taipei basin is presented in Fig. 5. Stated briefly, before or around 0.4 Ma, a major eruption occurred in the southern part of the TVG that produced a large amount of pyroclastic flow deposits or lavas. This would have provided source materials for the generation of lahars during heavy rainstorms. Alternatively, the lahars may have originated from the collapse of unconsolidated pyroclastic flow deposits on the steep slopes of a volcano. Such a collapse could be caused by an earthquake or by heavy rains shortly after an eruption, as elaborated by Siebert et al. (1987). The lahar would have then been deposited in the southern part of the TVG or the northwestern corner of the pre-Taipei basin and would have decreased in thickness from north to south. After the lahar was emplaced, the local stress field may have changed from the compressional to the extensional (Hu et al., 1996; Chu et al., 1998; Song et al., 2000). The normal Shanchiao fault that accommodated this extension is now located parallel to the older Chinshan-Hsinchuang thrust fault, separating the Linkou Tableland from the Western Foothills underlain by Tertiary strata (Wang Lee and Lin, 1987; Chen and Teng, 1990).

5.2. Surface trace of the Shanchiao fault

The topography on both sides of the Shanchiao normal fault, the Taipei basin and the Linkou Tableland can also

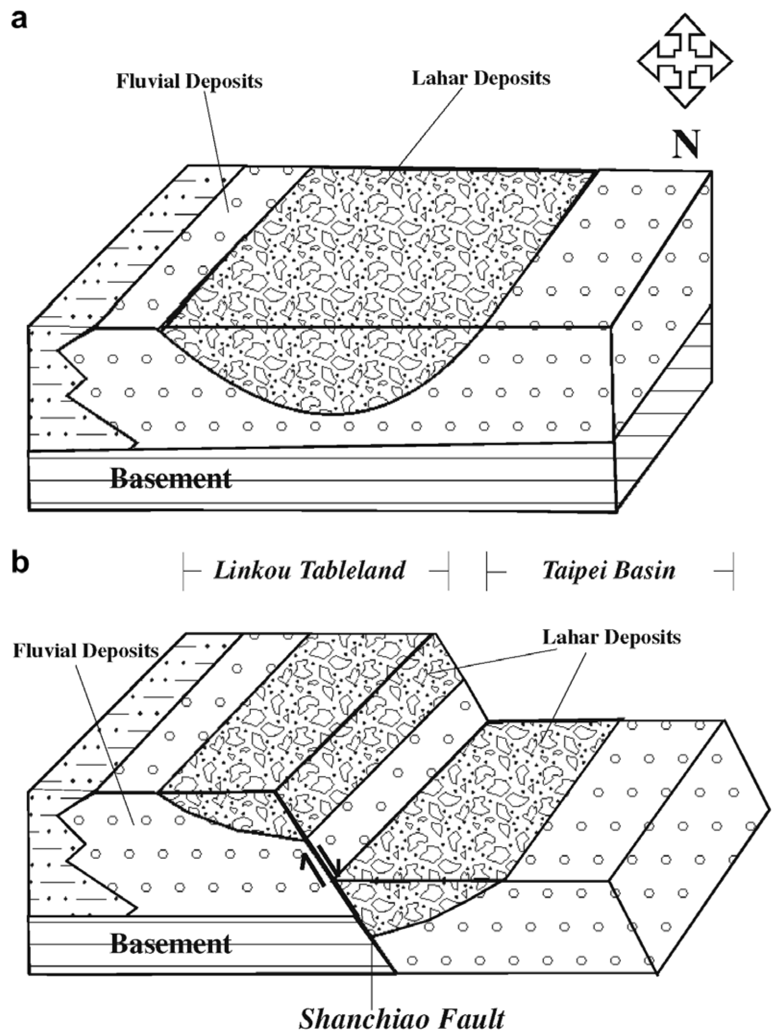

Fig. 5. Schematic maps illustrate the formation model of the Taipei basin. (a) Pre-normal faulting stage and (b) post-normal faulting stage. Details are presented in the text.

be used to map the surface trace of the Shanchiao fault. The basin lies at about 5–10 m a.s.l. in elevation and has flat relief, while the Tableland is higher at about 100–150 m a.s.l. and is dissected by stream networks. The Shanchiao fault, therefore, can be interpreted as bounding the edge of the basin. The exact trace of the fault, however, is hard to find in surface due to erosion and/or the fact they are covered with recent sediments. In an effort to better locate the fault, trenching of the fault zone was conducted by the Central Geological Survey, MOE and a private consulting company prior to the installation of traffic-related infrastructure and construction of buildings in the southern segment of the Shanchiao fault (Lin et al., 1999). In summary, the drilling cores can be used to further pinpoint the fault trace and the amount of displacement across it.

Three E–W boring profiles cut cross the Shanchiao fault, as shown in Figs. 6a–c. The A–A′ profile (Fig. 6a), located in the northernmost part of the fault, cuts through the surface to Cores SCF-10 and SCF-11, where the Tertiary basement rocks are penetrated at depths of 78.0 m and over 507.0 m, respectively. While the profile shows a steady decrease in depth to basement from surface outcrop to Core SCF-10, a rapid drop between Cores SCF-10 and SCF-11 is also revealed. We postulate that the Shanchiao fault cuts through the area between these two cores.

Profile B–B′ (Fig. 6b) extends across Cores SCF-7, SCF-8, SCF-9, KT-1 and KT-3, where Tertiary basement rocks occur at respective depths of 70.8, 139.6, 356.0, 499.3 and 297.75 m. This is indicative of a steady decrease in the basement depth from surface to Core SCF-8 and also of the rapid drop between Cores SCF-8 and SCF-9. We proposed that the major fault zone of the Shanchiao fault is, therefore, located between Cores SCF-8 and SCF-9.

Profile C–C′ (Fig. 6c) is located across Cores SCF-5, SCF-6 and the line connecting Cores LC-1 and WK-1E, where Tertiary basement rocks are met at the depths of 125.0 m, 220.5 m and around 679.0 m, respectively. This also points to a smooth decrease in the basement depth from surface to Core SCF-6 and a rapid drop, which occurs between Cores SCF-6 and the area along the

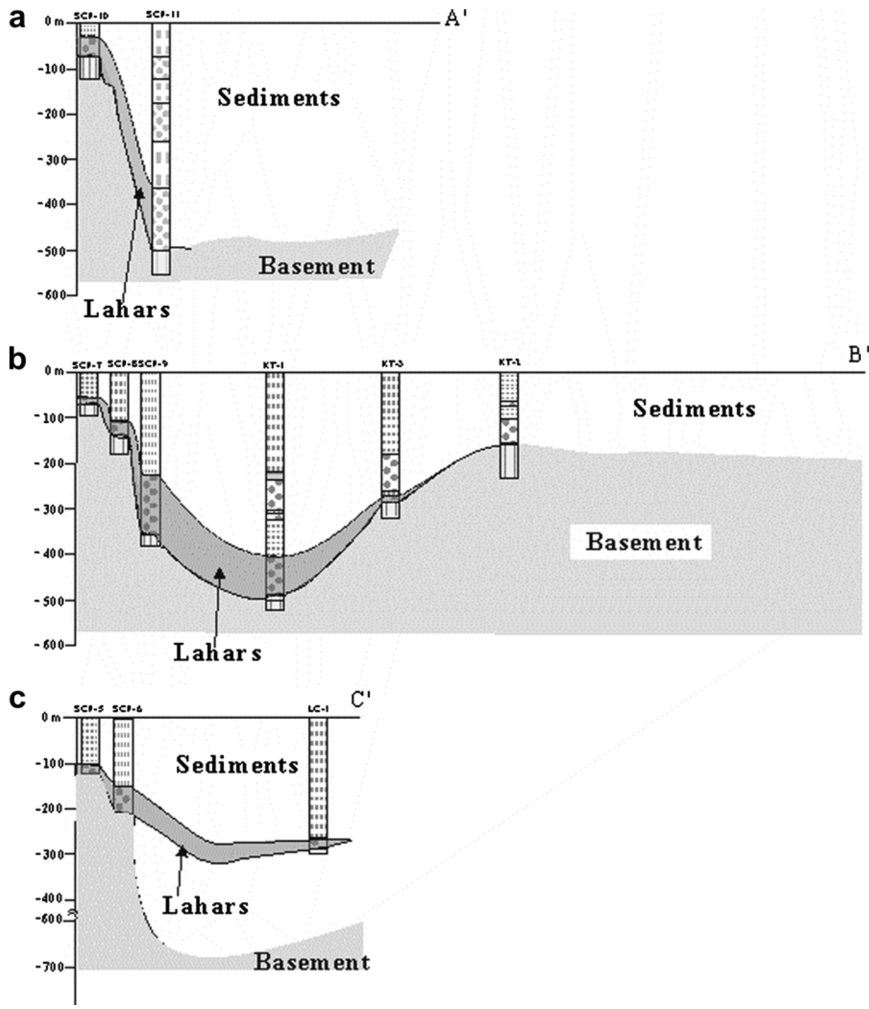

Fig. 6. Three E–W cross-profiles, (a), (b) and (c) show the correlations of depth of basement and lower lahar deposits in different cores. The locations are shown in the Fig. 2.

length of the line connecting Cores LC-1 and WK-1E. Thus, the major fault zone of the Shanchiao fault may be located between Core SCF-8 and the area along the length of the line connecting Cores LC-1 and WK-1E. When these three profiles and the published surface trail in the southern part of the Shanchiao fault are combined, the fault trail of the Shanchiao fault in the surface should be that depicted in Fig. 7.

5.3. Activity of the Shanchiao fault

Earthquakes generated by seismic faulting are generally considered to be the most unpredictable natural hazards in the world that give rise to huge numbers of injuries and casualties. The 1976 Tanshan earthquake in China and the 1999 Chi-Chi earthquake in Taiwan serve as two prime examples, because they caused more than 200,000 and 2400 deaths, respectively. The Taipei basin has been widely accepted as a tectonically controlled basin formed by active extension (Chiu, 1968; Ho, 1969; Lin, 1957; Wu, 1965). A major earthquake, likely with a magnitude greater than 7, might have occurred on the Shanchiao normal fault, which struck the basin in historical time (Lin, 1957), 3–5 m of subsidence in the hanging wall in depth in the footwall then formed a lake, which Lin (1957) refers to as "Taipei Lake". Being a city with a population of about seven million people, Taipei city, is at risk from earthquake on the active Shanchiao fault. It is, thus, imperative that the seismic history of the fault is to be better defined.

Based on the geometry of lahar deposits located in the Kauntu, Chentzeliao and Shihtzetou areas and in the subsurface of the Taipei basin, dip slip across the Shanchiao normal fault was probably about 500 m in the Kauntu area. However, this offset might be as large as about 680 m depending on the differences in the depth of the Tertiary basement rocks in the surface and subsurface in the Wuku area. Presumably, the Shanchiao fault may have commenced its activity after ca. 0.4 Ma. Assuming it commenced at 0.4 Ma and was offset 3–5 m in a major earthquake, there would have been at least 100–166 or 136–226 occurrences of major events. In addition to such recurrence events, the intervals between major earthquakes may have been 2400–4000 or 1800–3000 years. This also

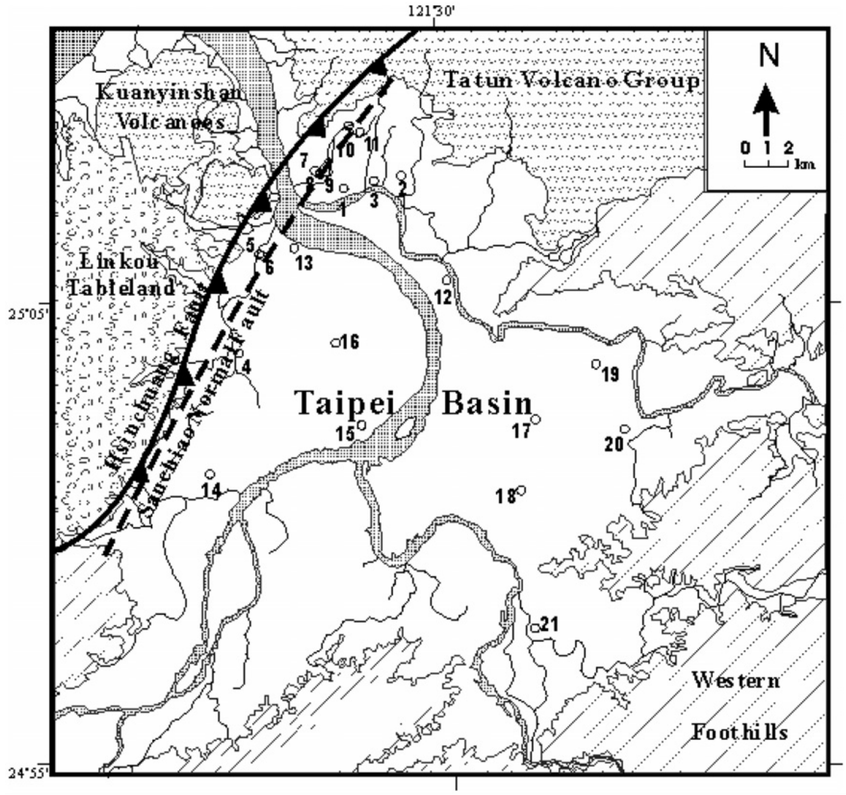

Fig. 7. The dashed line indicates the surface trace of the Shanchiao normal fault. Fault trace data of south segment modified from Lin et al. (2000).

suggests that the long term slip rate on the Shanchiao fault is about 1.3–1.7 mm/year.

6. Conclusions

At least three regional extensive lahar deposits interbedded with volcano-fluvial sediments has been characterized in the subsurface of the Taipei basin using continuously cored boreholes. Given their field occurrence, petrology and major and trace geochemistry, the source of these deposits has been identified as having been in the south of the TVG. The lowermost of the lahars in the subsurface was deposited around or not older than 0.4 Ma and can be correlated with the surface outcrops in the Kauntu, Chentzeliao and Shihtzetou areas, again based on field occurrences, petrology, major and trace geochemistry as well as age dating. This evidence indicates that the age of formation of the Taipei basin was not older than 0.4 Ma. Given a range of 500–680 m of dip slip for the fault, and an onset of slip at 0.4 Ma, we estimate a slip rate for the Shanchiao fault of 1.3–1.7 mm/year.

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