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Evaluation of terrestrial radiation in the Chengdu Plain using 1/250,000-scale geochemical prospecting data

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Abstract Based on the geochemical prospecting data, we have calculated the gamma absorbed dose rates in air 1 m above the ground surface in the Chengdu Plain, analyzed the relationship between the geological conditions and the distribution of the natural radionuclides, and preliminarily studied the influence of the geological conditions on the terrestrial radiation level in the Chengdu Plain. The result shows that the terrestrial radiation level in the Chengdu Plain is slightly lower than the average values of China and varies greatly according to the complex geological conditions.

Keywords Terrestrial radiation level · Geological condition · Natural radionuclides in soil and rock · External exposures

1 Introduction

The natural radiation exposure on the earth's surface is a key index of the radiation environmental impact assessment. The natural radiation has two principal sources: high-energy cosmic rays coming from the sun and outer space and natural radionuclides, including terrestrial and cosmogenic radionuclides [1, 2]. According to UNSCEAR, irradiation of the human body from external sources is mainly by gamma radiation from radionuclides in the ^{238}U and ^{232}Th series and from ^{40}K [1, 2]. The contributions of these radionuclides to the annual effective dose are listed in Table 1.

The terrestrial radiation level depends mainly on the activity concentration of natural radionuclides in the soils and rocks [4, 5]. When it approximates Clarke values (crustal abundance), about 42% of gamma-ray fluence in air originates from ^{40}K, 25% from the ^{238}U series in equilibrium, and 32% from the ^{232}Th series in equilibrium, respectively [6]. Great interest expressed worldwide for the study of naturally occurring radiation and environmental radioactivity has led to surveys in many countries [7–11]. There are two traditional methods that have been used to evaluate external exposures of gamma radiation. One is based on dose rate monitoring, and the other entails calculating the gamma absorbed dose rate in air using in situ gamma-ray spectrometry [12–14]. However, a different method, based on geochemical prospecting data, can be utilized to evaluate the terrestrial radiation level in the Chengdu Plain.

2 Theory

2.1 Relationship between gamma absorbed dose rate in air and the activity concentration of radionuclides in soil and rock

If the radionuclides are homogeneously distributed in infinite soil or rock, and gamma-ray attenuation can be ignored for 1 m of air (if the gamma-ray energy is

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Table 1 Global average annual effective dose from natural radiation sources [3]

Natural radiation sources	External exposure dose (mSv)	Percentage (%)	Internal exposure dose (mSv)	Percentage (%)	Total exposure dose (mSv)	Percentage (%)
Cosmic rays	0.410	17	–	–	0.410	17
Cosmogenic radionuclides	–	–	0.015	1	0.015	1
Primordial radionuclides						
^{40}K	0.150	6	0.180	7	0.330	13
^{238}U series	0.100	4	1.239	51	1.339	55
^{232}Th series	0.160	7	0.176	7	0.336	14
Total	0.820	34	1.616	66	2.436	100

1.0 MeV, only 0.88% gamma ray is attenuated through 1 m air), the air kerma rate of a monoenergetic gamma ray 1 m above the ground surface is [15]

$$\dot{K}_a = \sum_i \frac{2\pi \cdot \Gamma_{k,i} \cdot \rho}{\mu_i} \cdot c_i, \quad (1)$$

where ρ (g cm^{-3}) is the density of the soil or rock; c_i (Bq g^{-1}) is the activity concentration of the ith radionuclide; μ_i is the linear attenuation coefficient of soil or rock for a gamma ray emitted from the ith radionuclide; and $\Gamma_{k,i}$ is the air kerma rate constant of the ith radionuclide, which is defined as the air kerma rate at 1 cm from a 1 Bq unfiltered point source. In air, the gamma absorbed dose rate is approximately equal to the air kerma rate. About 99% of the gamma absorbed dose in air is from the radionuclides in the soil or rock at depth of <40 cm [6]. Geochemical prospecting data at this depth could represent the activity concentration of radionuclides in the surface soils or rocks. The conversion coefficients between the activity concentration of radionuclides and the natural gamma-ray exposure rate and gamma absorbed dose rate in air are listed in Table 2.

2.2 Uranium–radium equilibrium

The data in Table 2 are based on the assumption that the ^{238}U and ^{232}Th series reach secular decay equilibrium. However, it may not be the case for the ^{238}U series. Some decay products of the ^{238}U series may dissociate from the source material, which facilitates their subsequent environmental transfer. For example, ^{234}U may be somewhat deficient relative to ^{238}U in soils and enhanced in rivers or the sea. ^{226}Ra may also have slightly different activity concentration from ^{238}U because of its greater mobility.

The ^{238}U decay chain can be divided into two groups according to the geochemical behavior and the contributions to the gamma radiation level of the radionuclides: the uranium group and the radium group. The uranium group consists of ^{238}U, ^{234}Th, ^{234}Pa, ^{234}U and ^{230}Th. The gamma-ray energy fluence of this group is about 2% of the total in the equilibrium ^{238}U decay series. The radium group is composed of ^{226}Ra and its progeny. At secular equilibrium, the radium group emits about 98% of gamma-ray energy fluence and the main gamma emitter is ^{214}Bi [6]. Ignoring the emanation in soils or rocks, we find that it takes about one month for ^{226}Ra to reach secular equilibrium with

Table 2 Conversion coefficients between the activity concentration of radionuclides and the natural gamma-ray exposure rate and terrestrial gamma absorbed dose rate 1 m above the ground surface [3]

Radionuclide in soil or rock		Conversion coefficients of activity concentration		Conversion coefficients of exposure rate and gamma absorbed dose rate	
Radioactive element	Concentration (g g^{-1})	Radionuclide	Activity concentration (Bq kg^{-1})	Gamma-ray exposure rate (μR h^{-1})[a]	Absorbed dose rate (nGy h^{-1})
U	1×10^{-6}	^{238}U(^{226}Ra)	12.35	0.653	5.765
Th	1×10^{-6}	^{232}Th	4.06	0.287	2.494
K	1×10^{-2}	^{40}K	313	1.505	13.078

[a] $1R = 2.58 \times 10^{-4}$ C/kg

^{214}Bi. Consequently, we can evaluate the gamma absorbed dose in air of the ^{238}U decay series by measuring the total gamma count rate or gamma spectra.

Before using the concentration of uranium to evaluate the gamma absorbed dose rate of the ^{238}U decay series, we need first to convert the concentration of uranium (C_U) to the concentration of radioactive equivalent uranium (C_{eU}) [3], which is based on the Ra–U equilibrium constant (ξ). The calibration formula is as follows:

$$C_{eU} = \xi \cdot C_U, \tag{2}$$

where C_{eU} is the concentration of radioactive equivalent uranium and ξ is the Ra–U equilibrium constant which can be calculated by using

$$\xi = \frac{C_{Ra}}{C_U} \cdot 2.9 \times 10^6, \tag{3}$$

where C_{Ra} is the concentration of radium, which can be easily obtained by using in situ gamma spectrometry. When the emanation of radon is considered, the concentration of radioactive equivalent uranium (C_{eU}) is given by

$$C_{eU} = \xi \cdot (1 - \eta) \cdot C_U = \beta \cdot C_U, \tag{4}$$

where η is the emanation coefficient of radon, defined as the ratio between the concentration of radon into the atmosphere (C_{Rn}) and that produced by ^{226}Ra (C_{Rn0}). β is defined as the radioactive equivalent uranium ratio:

$$\beta = \xi \cdot (1 - \eta). \tag{5}$$

The ^{232}Th series is a little different from the ^{238}U series. The ^{232}Th series only needs 60 years to reach secular equilibrium. The half-life of ^{220}Rn is 54.5 s; so it may not escape from the soil easily. Therefore, in this paper, a secular equilibrium is assumed for the ^{232}Th series for discussion.

3 Geochemical data and experiments

3.1 Geological condition of the Chengdu Plain

The Chengdu Plain lies in the west of the Sichuan Basin and to the east of the Tibetan Plateau. It is a compound alluvial fan that was washed by natural rivers originated mostly from the Tibetan Plateau (e.g., the Minjiang River, the Tuojiang River, and the Qingbai River). The western portion abuts the edge of the overthrust of the front Longmenshan Mountain, and the eastern portion borders on Longquanshan Mountain [16, 17].

There are three major tectonic units in the Chengdu Plain: the Longquanshan fault zone, the Chengdu Basin, and the Longmenshan fold. These tectonic units are bounded by two NE–SE-trending faults, i.e., the Dayi–Penguan fault and the Pujiang–Xinjing–Deyang hidden fault [18]. The main geological tectonic units of the Chengdu Plain are shown in Fig. 1.

3.2 Geochemical data

The geochemical prospecting data were provided by the Sichuan Geological Survey. The Chengdu Plain was divided into many small quadrate regions of 4 × 4 km, and soil or rock was sampled in each quadrate region.

3.3 Determination of β

To obtain the concentration of radioactive equivalent uranium (C_{eU}), we must determine the radioactive equivalent uranium ratio β in advance. Dozens of soil samples were collected from the Chengdu Plain, the concentration of uranium was determined by laser-induced fluorometry, and that of radium was determined by gamma spectrometry.

Figure 2 shows that there is a linear relationship between the radioactive equivalent uranium ratio and the concentration of uranium in soil or rock, and the adjusted R Square (R^2) is 0.64. When the concentration of uranium falls in the range of $(0-5) \times 10^{-6}$ g/g (representing 99%

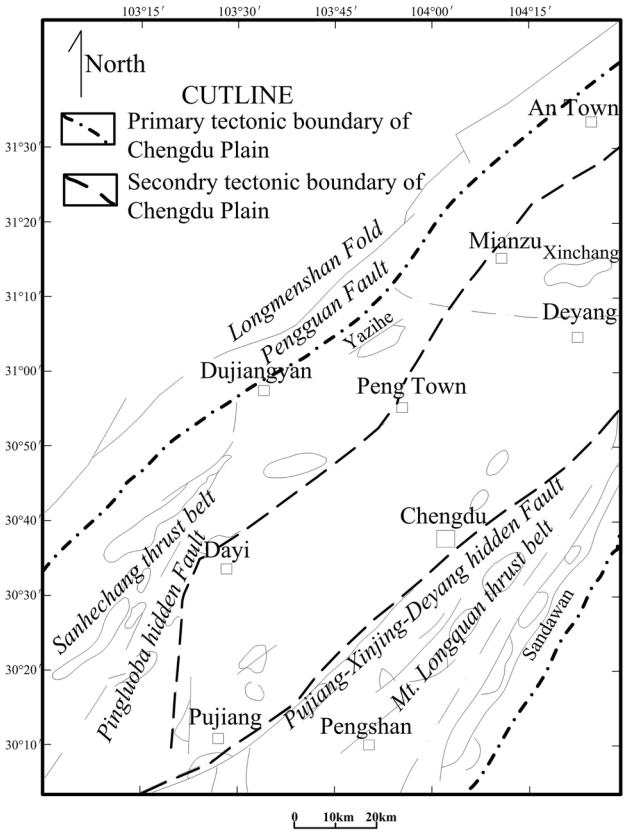

Fig. 1 Geological map of the Chengdu Plain

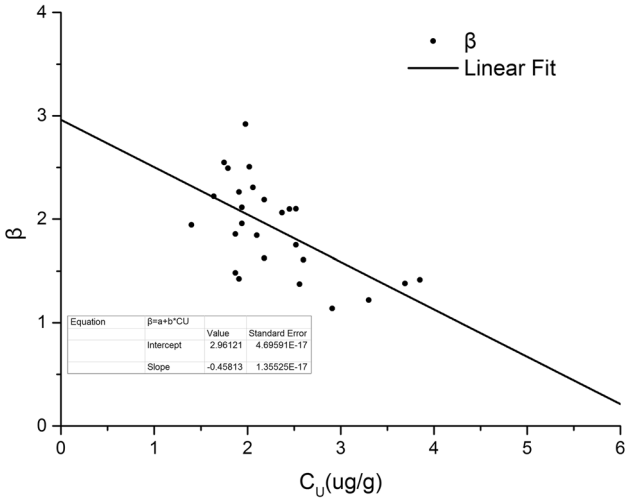

Fig. 2 Relationship between the concentration of uranium and the radioactive equivalent uranium ratio β

of the collected samples), this linear relationship can be written as follows:

$$\beta = 2.961 - 0.458C_{\mathrm{U}}, \tag{6}$$

where β is the radioactive equivalent uranium ratio and C_{U} is the concentration of uranium in soil or rock. The concentration of uranium can be converted to the concentration of equivalent uranium (C_{eu}) as follows:

$$C_{\mathrm{eu}} = \beta \cdot C_{\mathrm{U}} = (2.961 - 0.458 \cdot C_{\mathrm{U}}) \cdot C_{\mathrm{U}}, \tag{7}$$

4 Results

In order to evaluate the gamma absorbed dose rate in air based on geochemical prospecting data, in situ gamma-ray spectrometry was used to measure the gamma absorbed dose rate in air in an area of section in the Chengdu Plain. The conversion coefficients of the gamma absorbed dose rate in Table 2 were used to calculate the gamma absorbed dose rate 1 m above the surface from geochemical prospecting data. The radioactive equivalent uranium (C_{eu}) value was calculated using Eq. (7) and was used as the ^{238}U concentration in Table 2. The results are shown in Fig. 3. The average gamma absorbed dose rate in air using in situ gamma-ray spectrometry is 73.91 nGy/h. The average gamma absorbed dose rate in air using geochemical prospecting data is 80.67 nGy/h. The gamma dose rates obtained by these two methods agree well, indicating that the geochemical prospecting data can be used to evaluate the terrestrial radiation in the Chengdu Plain.

Table 3 lists the activity concentration of ^{40}K, ^{232}Th, and ^{238}U and terrestrial radiation levels in the Chengdu Plain. For comparison, data for China and the earth are also given. As shown in Table 3, the activity concentration of ^{40}K is about one order of magnitude higher than that of ^{238}U or ^{232}Th. For ^{40}K, ^{232}Th, and ^{238}U, the ranges of activity concentration are 179.21–1173.19, 11.78–225.74, and 16.26–224.77 Bq kg^{-1}, respectively. The gamma absorbed dose rate in air using geochemical prospecting data and the conversion coefficients in Table 2 is in the range of 25.53–177.99 nGy h^{-1}, with an average of 74.26 nGy h^{-1} and a standard deviation of 13.36 nGy h^{-1}.

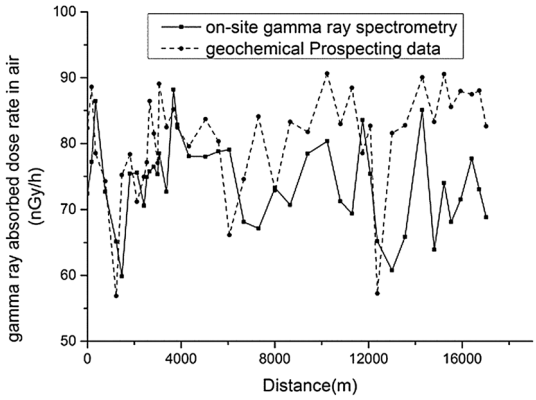

Fig. 3 Gamma absorbed dose rate in air in a section in the Chengdu Plain

The terrestrial radiation level in the Chengdu Plain varies greatly, mainly as a result of the differing geological conditions. To analyze the regional variations, isograms of the terrestrial radiation in the Chengdu Plain are shown in Figs. 4, 5, and 6. The main tectonic units of the Chengdu Plain are also marked on these figures.

5 Discussion

The geological condition of the Chengdu Plain has a great impact on the terrestrial radiation level and distribution. As shown in Fig. 4, in certain areas of the Chengdu Plain, such as the thrust belts and alluvial fan area, the activity concentrations of ^{40}K are higher than elsewhere. There are two reasons for this difference. First, the thrust belts and Longmenshan fold are covered by forest, where the soil is abundant with humus and the concentration of K is enriched. Second, the alluvial fans are mainly conventional paddy fields, and agricultural fertilizers may be a contributor to the elevated ^{40}K concentrations [21]. The distribution of ^{232}Th is shown in Fig. 5 and is more homogeneous. However, because of the enrichment process in the clay, ^{232}Th activity concentration in the alluvial fans is slightly higher than elsewhere. Figure 6 shows the distribution of ^{238}U. The activity concentration of ^{238}U is greatly influenced by the major tectonic units; in regions of

Table 3 Activity concentration of ^{238}U, ^{232}Th, and ^{40}K and terrestrial gamma absorbed dose rate in the Chengdu Plain

Nation or region	Activity concentration of ^{238}U, ^{232}Th, and ^{40}K in soil (Bq kg^{-1})						Gamma absorbed dose rate (nGy h^{-1})	
	^{238}U		^{232}Th		^{40}K			
	Average value	Range	Average value	Range	Average value	Range	Average value	Range
Chengdu Plain	55.6	16.26–224.77	57.6	11.78–225.74	559.1	179.21–1173.19	74.26	25.53–177.99
China[a]	38.5	7.3–449	54.6	10.3–1844	584	ND–1548	81.5	11.6–523
Earth[b]	40	–	40	–	480	–	80	–

[a] Wang [19]

[b] UNSCEAR [20]

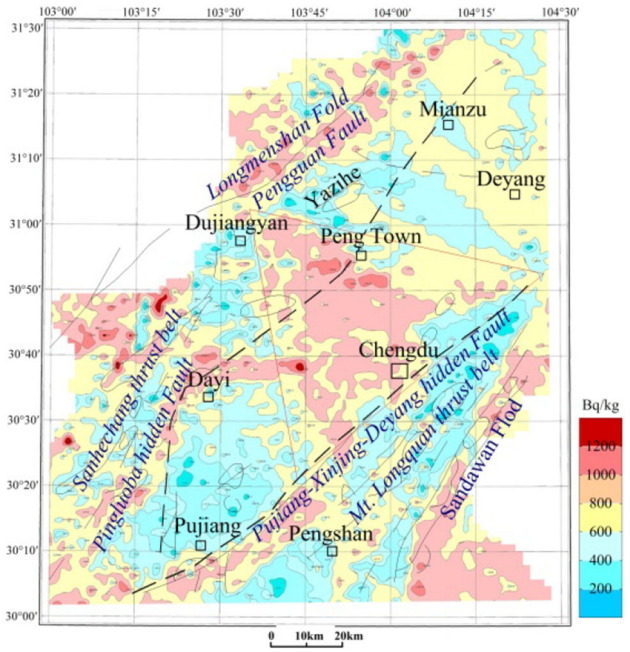

Fig. 4 (Color online) Isograms of the activity concentration of ^{40}K in the Chengdu Plain

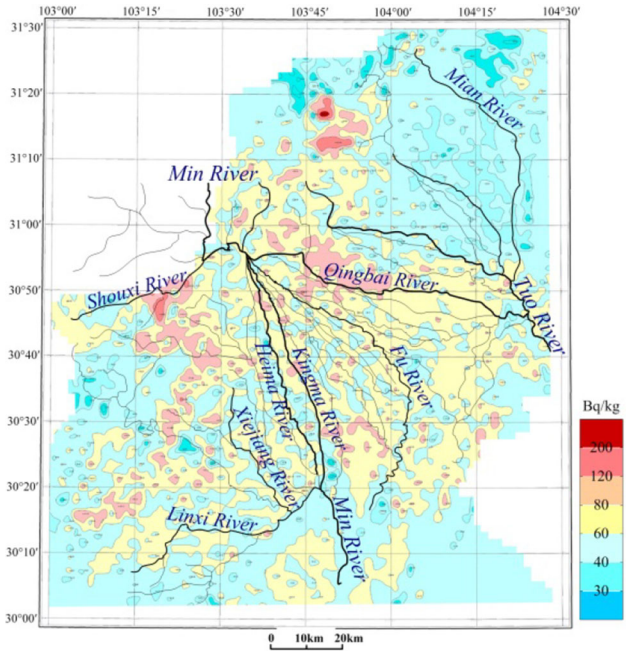

Fig. 5 (Color online) Isograms of the activity concentration of ^{232}Th in the Chengdu Plain

the Longquanshan thrust belt, the Penguan fault, and the Pujiang–Xinjing–Deyang hidden fault, it is >50 Bq kg^{-1}.

Because of the high activity concentrations of ^{238}U and ^{40}K, the gamma absorbed dose rates in air in some regions (e.g., the Longquanshan thrust belt, the Longmenshan fold, and the Pingluoba hidden fault) are higher than elsewhere. The tectonic units with high terrestrial radiation levels are shown in Fig. 7. Moreover, owing to the high activity concentration of ^{232}Th and ^{40}K, the radiation level in the alluvial fans is also higher.

6 Conclusion

Compared with the measured data by in situ gamma-ray spectrometry, using geochemical prospecting data to calculate the terrestrial gamma absorbed dose rate in air is efficient and reliable. However, it is necessary to first derive the radioactive equivalent uranium data from the prospecting data. Our results indicate that the average terrestrial radiation level in the Chengdu Plain is slightly lower than the average value of China and the earth and varies greatly with the complex geological conditions. The gamma absorbed dose rates in air over the fold belts and fault zones are higher than the average, and the activity concentrations of ^{40}K and ^{232}Th in the alluvial sediments of clay are also higher than the averages.

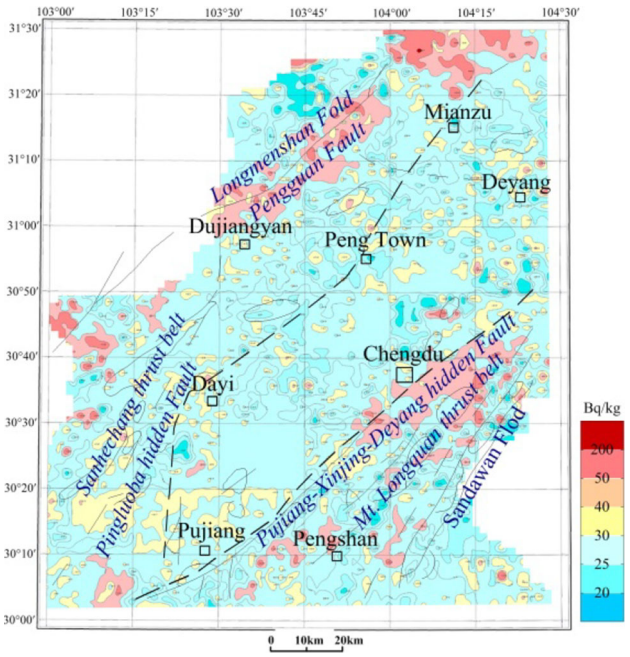

Fig. 6 (Color online) Isograms of the activity concentration of ^{238}U in the Chengdu Plain

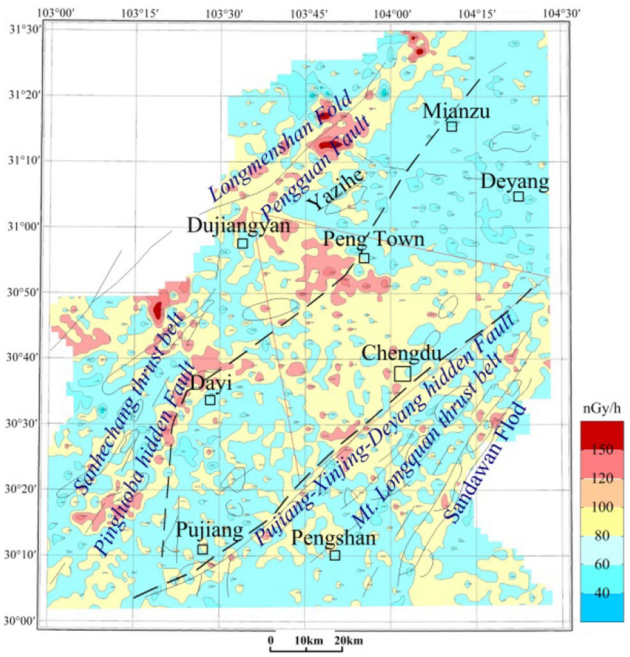

Fig. 7 (Color online) Isograms of gamma absorption dose rates in the Chengdu Plain

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