Abstract

The late Paleozoic tectono-magmatic history and basement of the Maya block are poorly understood due to the lack of exposures of coeval magmatic rocks in the region. Here, we studied recently recovered drill core samples from IODP-ICDP Expedition 364 borehole M0077, located offshore in the Yucatán platform, Gulf of México. The lowermost ~600 m of drill core mainly consists of granitoids, and minor latite dykes and dolerite dykes. Zircon U-Pb dating of granitoids yielded ages around 326±5.3 Ma, representing the first recovery of continuous late Paleozoic magmatic rocks from the Maya block that could be genetically related to the convergence of North America and Gondwana. The granitoids are high-K and show the features of high La<sub>87</sub>/Yb<sub>87</sub>, Sr/Y, but very low Yb and Y contents indicating an adakitic affinity. They are also characterized by slightly positive εNd (t=326Ma) of 0.17–0.68, and intermediate initial 87Sr/86Sr (t=326Ma) of...
0.7036–0.7047, which may indicate a less evolved crustal source. We suggest that the adakitic granitoids were probably generated by partial melting of thickened crust, with source components similar to Neoproterozoic metagrabbro on the Carolina terrane (Pan-African Orogeny materials) along Peri-Gondwana. Latite dykes are shoshonitic with typical continental arc features that they are sourced from slab-fluid metasomatic processes in mantle wedge. Meanwhile, dolerite dykes display OIB-type features such as positive Nb and Ta anomalies, low Th_{NPF}/Nb_{NPF}. We propose that the Chicxulub adakitic granitoids of this study are formed by crustal anatexis due to the asthenosphere upwelling as a result of slab breakoff. Through comparing sources and processes of late Paleozoic magmatism along the Peri-Gondwanan realms, we suggest that a tearing slab breakoff model may explain the discontinuous delamination that appears to have occurred during the convergence of North America and Gondwana. 

**Key Words:** Peri-Gondwanan realms, Chicxulub impact crater, Slab breakoff, Pangea

**Highlights:**

1. First reporting and comprehensive study of continuous drill cores through late Paleozoic granitoids from the Maya block, which were the extension of Alleghanian granite to the west.

2. Chicxulub granitoids with adakitic affinity are attributed to partial melting of thickened crust by upwelling asthenospheric mantle, interpreted as slab breakoff.

3. The basement of Northern Maya block (the site of Chicxulub impact crater) mainly comprise the Pan-African orogeny materials, which was similar to Carolina block.

4. A tearing slab breakoff model along Peri-Gondwanan realms is proposed to explain the late Paleozoic magmatic features.

1. **Introduction**

Peri-Gondwanan areas, such as the Maya block, Oaxaquia block, Suwannee block and Carolina block, are crucial blocks of the assembly of Pangea (Hibbard et al., 2002; Keppie et al., 2012; Mueller et al., 2014; Murphy et al., 2004). With the amalgamation of North America and Gondwana, magmatism is expected to be distributed extensively along Peri-Gondwana, while late Paleozoic magmatism is actually spatially distributed and occur as: (1) pyroclastic rocks in sedimentary formations or intrusions within the Oaxaquia block, (2) tiny intrusions uncovered by boreholes in Suwannee block, and (3) widely dispersed granitoids in Carolina block (Centeno-García, 2016; Lopez and Cameron, 1997; Ortega-Gutiérrez et al., 2018; Poole et al., 2005; Samson et al., 1995a; Speer and Hoff, 1997). The Maya block is located within the central region of Peri-Gondwana, but few outcrops and little is known about the late Paleozoic magmatism (Centeno-García, 2016; Marton and Buffler, 1994). Integrated Ocean Drilling Program – International Continental Scientific Drilling (IODP-ICDP) Expedition 364 borehole M0077, located offshore in the Gulf of México, recovered for the first time, relatively contiguous granitoids and dykes in drill cores (Morgan et al., 2016), which s provide crucial information about the vestige of late Paleozoic magmatism in the Maya block and its relationship with other Paleozoic magmatism along Peri-Gondwana during the assembly of Pangea.

On a regional scale, the late Paleozoic magmatic events, especially in the Carolina and Suwannee blocks, are argued to reflect crustal anataxis related to thickened crust / lithosphere mantle delamination (Heatherington et al., 2010; Sacks and Secor, 1990; Samson et al., 1995a), or coincide with a contemporaneous strike-slip fault (Speer and Hoff, 1997; Speer et al., 1994), whereas on the Oaxaquia block, they are attributed to coeval continental arc magmatism (Dickinson and Lawton, 2001; Lopez and Cameron, 1997; McKee et al., 1988, 1999). Although
these areas are attributed to the Marathon - Ouachita - Alleghanian Orogeny, they might be affected by continuous or discontinuous delamination according to several lines of critical evidence in previous studies (Cameron et al., 1992; Keppie and Dallmeyer, 1995; Nelson, 1992; Sacks and Secor, 1990), here may, thus, be some petrogenetic and tectonic divergences between areas, depending on their original rock compositions and their locations along the Peri-Gondwanan areas during the assembly of Pangea. Alternatively, a transpressional model could explain the lack of continental arc magmatism on Carolina and Suwannee (Mueller et al., 2014), while the coeval continental arc magmatism on Oaxaquia is contradictory to this model.

Since the Maya block is situated between the Oaxaquia and Suwannee blocks according to paleogeographic reconstruction for the late Paleozoic (Ortega-Gutiérrez et al., 2018), Maya block magmatism is critical in helping us unravel whether there is a continuous delamination from east to west along the orogen.

Magmatism can reveal the basement components of blocks such as crust and mantle end-members through analysis of sources and contaminants. Outcrops of high-grade metamorphic rocks to the south of our study area show that the Southern Maya block’s basement is dominated by Grenvillian, Pan-African orogeny, and Acadian materials (Keppie et al., 2012; Kring, 2005; Kring et al., 2004; Schmieder et al., 2017; Steiner and Walker, 1996; Weber and Hecht, 2003; Weber et al., 2008). The Northern Maya block is covered by Mesozoic carbonates and the possible basement samples in this region originate from clasts of Chicxulub impact ejecta, that are mainly composed of Ediacaran arc materials (Keppie et al., 2011). These clasts have only been sampled from a small region of the Northern Maya block. Moreover, the Maya mountain rocks have zircon ages from late Silurian to early Devonian (Weber et al., 2012), which could also be the possible basement in northern Maya block. Therefore, the difference between Southern and Northern Maya basement needs further investigations (Keppie and Keppie, 2013).

In this study, we primarily conducted geochronological and geochemical analyses of late Paleozoic granitoids from the Maya block, and carried out a comparative study of coeval magmatism in the Oaxaquia block (331-270 Ma), the Suwannee terrane (296-294 Ma) and the Carolina terrane (335-285 Ma) (Fig.1). Subsequently an equilibrium melting simulation to assess the possible source of Chicxulub granitoids and performed detailed analyses of the magmatic divergence in the other regions (Oaxaquia, Carolina and Suwannee blocks) to elucidate basement lithological features. Finally, we compared their formation mechanisms and put forward an integrated tearing slab breakoff model for the whole region.
1. Geological setting

The Peri-Gondwanan region is composed of an array of blocks with Gondwana-affinity and separated from Gondwana during the early Paleozoic during the formation of the Rheic Ocean and closure of the Iapetus Ocean. The Peri-Gondwanan region is typically composed of Ediacaran Arc (650–500 Ma) basement (Keppie et al., 2011; Keppie et al., 2012; Pollock et al., 2011). This study mainly focuses on the Late Paleozoic magmatism in Marathon-Ouachita-Alleghany orogeny, located in the Oaxaquia, Maya, Suwannee and Carolina blocks, respectively. Thus, since the basement serves a considerable function on the attributes of these magmatic rocks, we mainly conclude respective basement features of the Oaxaquia, Maya, Suwannee and Carolina blocks.

2.1. Maya block

The Maya block is proximal to the Caribbean plate (Weber et al., 2012) and includes the Yucatán peninsula, coastal plain of the western and northern Gulf of México, eastern part of Isthmus Tehuantepec, Chiapas complex and northern Guatemala. The basement of the Maya block is extensively covered by Mesozoic and Cenozoic carbonates, the pre-Mesozoic materials are identified by high grade metamorphic rocks in the Chiapas and the Cuicateco (Guichicovi) Complexes (Keppie et al., 2012), and rock fragments derived from the end-Cretaceous Chicxulub impact and the K/Pg boundary event. The Chiapas Complex mainly distributes high-grade metamorphic rocks intruded by tiny granitoids (Schaaf et al., 2002; Weber et al., 2008), and the
detrital zircons reveal ages of 500–700 Ma with minor other ages (larger than 0.82 Ga) in the 
Carboniferous sedimentary formations (Weber et al. 2006b). The Nd model ages (T_{DM1}) in this 
area are 1.56–0.94 Ga (Schaaf et al., 2002). In Cuicatéco Complex, parametamorphic rock and 
AMCG suite (anorthosite- mangerite- charnockite- granitoids) aged at 1.2–0.9 Ga reach to 
granulite facies (Fig. 2), their T_{DM1} are 1.63–1.35 Ga (Weber and Köhler, 1999). The fragments 
(Kring, 2005; Kring et al., 2004) excavated by the ~ 66 Ma Chicxulub impact event occur in the 
Yucatán-I borehole as recovered the late Paleozoic sedimentary and volcanic rocks (330–290 Ma) 
(Marton and Buffler, 1994), the Yucatán -6 borehole recovered the target rocks (550 ~ 465Ma, 
418 Ma) (Kamo and Krogh, 1995; Krogh et al., 1993a; Krogh et al., 1993b), and the Yaxcopoil-I 
borehole recovered the Ediacaran volcanic arc rocks (545 Ma) (Keppie et al., 2011) and Paleozoic 
aged clasts (536–395 Ma) (Schmieder et al., 2017; Wittmann et al., 2018), of which Ediacaran 
granitic gneiss clasts reveal a T_{DM1} age of 1.4–1.2 Ga (Kettrup et al., 2000). Therefore, the 
basement of the Maya block may mainly comprise Pan-African and Grenvillian materials.

1.2. Oaxaquia block

Adjacent to the western part of the Maya block lies the Oaxaquia block, which is a 
Mesoproterozoic block consisting of granulite, orthogneisses and paragneisses with 1.1 Ga AMCG 
suites and multiple ages of pegmatites exposed discontinuously along the eastern margin of 
México (Ortega-Gutiérrez et al., 2018; Ortega-Gutierrez et al., 1995). The zircon ages of the 
Oaxaquia block are 1.3–0.92 Ga, and T_{DM1} model ages range from 2.02 to 1.35 Ga, which 
represents a more evolved endmember, the Oaxaquia-type basement (Keppie et al., 2012; 
Ortega-Gutiérrez et al., 2018; Ruiz et al., 1988a; Ruiz et al., 1988b; Weber and Köhler, 1999) (Fig. 
2). McKee et al. (1999) reported the Coahuila arcs magmatisms (331–270 Ma) in the Oaxaquia 
block that also is of Gondwana affinity (Keppie et al., 2012), and their specific chronological and 
geochemical analysis was conducted by Lopez and Cameron (1997), who demonstrated the 
features of continental arc magmatism related to the Ouachita-Marathon orogeny through the 
detrital zircons in foreland basin (Gleason et al., 2007; Shaulis et al., 2012), while some late 
Paleozoic magmatism in the Oaxaquia block could be linked to eastward subduction of the Pacific 
ocean along Pangea (Rosales-Lagarde et al., 2005; Torres et al., 1999) (Fig. 1). Thus, the Oaxaquia 
block appears to be mainly composed of evolved Grenvillian basement with some late Paleozoic 
continental arc materials.

2.3. Suwannee block

Apart from the overlying Mesozoic and younger rocks of the Gulf and Atlantic coastal plains, 
a range of Neoproterozoic to middle Paleozoic rocks comprise the Suwannee block 
(Heatherington et al., 1996) (Fig. 2). Neoproterozoic volcanic and plutonic rocks (~550 Ma) act as 
the basement extending beneath the east and southeast of the Suwannee block (Heatherington et 
al., 1997; Heatherington et al., 2010; Mueller et al., 1994), with the T_{DM1} of 1.58–1.04 Ga (Keppie 
et al., 2012). The minor ~300 Ma post-collisional granitoids from two drill holes in southwestern 
Georgia and northern Florida yielded ages of 294 Ma and 296 Ma respectively, and are related to a 
post-collisional lithospheric collapse (Heatherington et al., 2010; Mueller et al., 2014). Therefore, 
the Suwannee block contains more juvenile materials compared to the Oaxaquia block based on 
the lower T_{DM1}.

2.4. Carolina block

The Carolina block and Inner Piedmont constitute major parts of the Alleghanian terrane (Fig. 
1). The Carolina block is predominantly represented by Neoproterozoic to early Paleozoic
meta-igneous rocks associated metasedimentary rocks extending from central Virginia southwards to Georgia (Samson et al., 1995a), and the Inner Piedmont mainly comprises Mesoproterozoic plutons and high-grade gneisses (Pettingill et al., 1984). Neoproterozoic meta-igneous rocks within the Carolina block represent juvenile crustal materials typified by its higher εNd values (mostly exceeding +3.4) (Samson et al., 1995b) and younger TDM (1.1–0.75 Ga) (Hibbard et al., 2002; Hibbard et al., 2007; Keppie et al., 2012). During the late Paleozoic assembly of Pangea, the Alleghanian terrane hosted extensive magmatic activities (335–285 Ma), of which 75% are metaluminous biotite or amphibole biotite granites and 25% are peraluminous granites. These rocks indicate that the Carolina-type crust is more juvenile than the Grenvillian crust (Inner Piedmont) (Samson et al., 1995a; Speer and Hoff, 1997). Also, Keppie et al. (2012) showed that the Carolina block has a more juvenile basement end-member relative to the Oaxaquia-type basement.

**Fig. 2** Sketched stratigraphic columns for the Oaxaquia (Keppie and Ortega-Gutiérrez, 2010; Lopez and Cameron, 1997; Martens et al., 2010), Southern and Northern Maya (Keppie and Ortega-Gutiérrez, 2010; Kring, 2005; Kring et al., 2004; Martens et al., 2010; Weber et al., 2012), Suwannee (Dallmeyer, 1989; Martens et al., 2010; Mueller et al., 1994) and Carolina blocks (Hibbard et al., 2002; Hibbard et al., 2007; Martens et al., 2010).

### 3. Materials and Methods

#### 3.1 Materials

Samples for this study derive from the IODP-ICDP Expedition 364 drill cores (Site M0077) from the peak ring of the Chicxulub impact structure (21°27.002’N, 89°56.967’W), located at...
about 25 km north-west of the Yucatán Peninsula’s coast line (Fig. 3). The project was designed to
study the formation mechanism of the peak ring of the Chicxulub impact structure and to study the
post impact sedimentary deposits within the crater through multi-disciplinary methods. The
drilling reached to a depth of 1334 meters below sea floor, recovering basement as well as
overlying post-impact sediments and impact melt breccias (Morgan et al., 2016). The drill cores
were divided into three main stratigraphic units from top to bottom: (1) Cenozoic sediments
(505.7–617.33 mbsf); (2) impact breccias or suevites (617.33–747.02 mbsf); (3) granitoids
(747.02–1334.69 mbsf). The sampled granitoids comprise a nearly 600 m contiguous intrusive
body with some intruded dykes such as latite and dolerite (Fig. 3). Latite dykes occur at
1123.71–1125.44 mbsf, 1130.61–1132.05 mbsf, 1136.7–1139.51 mbsf and 1159.72–1162.26 mbsf.
Dolerite dykes (Schmieder, 2017) are at 846.42–850.64 mbsf, 853.42–855.21 mbsf,
855.56–866.45 mbsf, 887.05–887.95 mbsf, 912.49–913.34 mbsf, 933.98–938.22 mbsf,
1015.87–1016.36 mbsf, 1026.92–1027.14 mbsf and 1082.17–1082.95 mbsf.

3.2 Methods for major and trace elements and zircon U-Pb dating

Major elements of granitoids and dykes in this study were ground in an agate mortar to pass a
200 mesh to be examined with a X-ray fluorescence spectrometer (Shimadu xrf-1800, Japan) in
the State Key Laboratory of Geological Processes and Mineral Resources (GPMR), China
University of Geosciences, Wuhan (CUG). Bremen data were acquired at the XRF Core Scanner
Lab at the MARUM Center for Marine Environmental Sciences, University of Bremen, Germany.
Trace elements were analyzed by an Agilent 7500a ICP-MS at GPMR, the detailed
sample-digesting procedures for trace elements analyses are as follows: (1) Samples were ground
in an agate mortar to pass a 200 mesh and placed in an oven at 105 °C for 12 hours, (2) 50mg
sample powders for each sample were weighed and digested by 1ml HNO3 and 1ml HF in a Teflon
bomb, which was put in a stainless steel pressure jacket and heated to 190 °C for over 24 hours,
(3) the Teflon bomb was opened for drying on a hotplate at 140 °C and 1 ml HNO3 was added
and evaporated to dryness again. (4) 1 ml of HNO3, 1 ml of MQ water and 1 ml internal standard
solution of 1 ppm In were added, and the Teflon bomb was placed in an oven at 190 °C for more
12 hours. The final solution was transferred to a polyethylene bottle and diluted to 100g by
the addition of 2% HNO3 for analysis. Relative deviation (RD) calculated from repeated analyses
were lower than 5%. U-Pb isotopes of zircons were analyzed by Agilent 7500a ICP-Ms apparatus
coupled with a GeoLas 2005 laser-ablation system and a DUV 193 nm Arf-eximer laser
(MicroLAS, Germany) (LA-ICP-MS) in GPMR. The Zircon 91500 and glass NIST 610 were used
as external standards for calibrating mass discrimination and U-Pb isotope fractionation. Each
analysis incorporated a background acquisition of approximately 20-30 s followed by 50s of data
acquisition from the sample. In-situ analysis of Hf isotopes and corresponding U-Pb isotopes of
zircons were conducted with spot sizes of 44 μm and 32 μm, respectively by LA-ICP-MS at the
Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China. Operating conditions for
the laser ablation system and the ICP-MS instrument and data reduction were the same as
described by Zong et al. (2017). An excel-based software ICPMSDataCal was used to perform
off-line selection and integration of background and analyzed signals. Time-drift correction and
quantitative calibration for trace element analysis and U-Pb dating followed the protocol outlined
by Liu et al. (2010). Concordia diagrams and weighted mean calculations were generated using
Isoplot/Ex-ver3 (Ludwig, 2003).

3.3 Methods for Sr, Nd and Pb isotopes
Sr, Nd and Pb isotope analyses were conducted on a Neptune MC-ICP-MS operated in the Isotopic Laboratory of GPMR-CUG. Sample digestion followed the same procedures as the trace elements digestion. For Sr isotopes, after the three sample digestion steps mentioned above, we dissolved in 1.5 mL of 2.5 M HCl and conducted centrifugation, the supernatant solution was then loaded into an ion-exchange column packed with AG50W resin. After complete draining of the sample solution, columns were rinsed with 2.5M HCl to remove undesirable matrix elements. Finally, the Sr fraction was eluted using 2.5 M HCl and gently evaporated to dryness prior to mass-spectrometric measurement. The residue was rinsed with 10 ml of 4.0 M HCl and then the REE fraction was eluted using 10 ml of 4.0 M HCl. The REE solution was used to separate the Nd fraction, evaporated to incipient dryness, and taken up with 0.18 M HCl. The converted REE solution was loaded into an ion-exchange column packed with LN resin. After complete draining of the sample solution, columns were rinsed with 0.18 M HCl to remove undesirable matrix elements. Finally, the Nd fraction was eluted using 0.3 M HCl and gently evaporated to dryness prior to mass-spectrometric measurement. The analytical techniques for Sr-Nd isotopes and analytical precision are the same as those of Liu et al. (2004) and Gao et al. (2004). NBS SRM 987 yielded \(^{87}\text{Sr}/^{86}\text{Sr} = 0.710295 \pm 10\) (n=10), La Jolla yielded \(^{143}\text{Nd}/^{144}\text{Nd} = 0.512112 \pm 8\) (n=10). The measured \(^{86}\text{Sr}/^{88}\text{Sr}\) and \(^{146}\text{Nd}/^{144}\text{Nd}\) ratios were normalized to 0.1194 and 0.7219, respectively. For Pb isotope analysis, powder samples also underwent the procedures (1–3) for trace elements digestion, then they were dissolved in 1 ml of 1 M HBr. After centrifugation, the supernatant solution was loaded into an ion-exchange column packed with AG resin. Columns were rinsed with 1.0 M HBr to remove undesirable matrix elements. Finally, the Pb fraction was eluted using 6.0 M HCl and gently evaporated to dryness prior to mass-spectrometric measurement. Instrumental mass discrimination correction was carried out via normalization to a \(^{205}\text{Th}/^{204}\text{Tl}\) ratio of 2.3872, which is the certified value of NBS SRM 997. NBS SRM 981 was used as the Pb isotopic standard and yielded \(^{208}\text{Pb}/^{204}\text{Pb}\) = 36.6853, \(^{207}\text{Pb}/^{204}\text{Pb}\) = 15.4852, and \(^{206}\text{Pb}/^{204}\text{Pb}\) = 16.9325 (n=10). Total procedural Pb blanks were lower than 50 pg. Rb, Sr, Sm, Nd, Th, U, and Pb contents measured by ICP-MS were used to calculate the initial ratios of \(^{87}\text{Rb}/^{86}\text{Sr}\), \(^{147}\text{Sm}/^{144}\text{Nd}\), \(^{208}\text{Pb}/^{204}\text{Pb}\), \(^{207}\text{Pb}/^{204}\text{Pb}\), and \(^{206}\text{Pb}/^{204}\text{Pb}\).
Fig. 3 Map with marked drill site of M0077 and lithostratigraphic context of samples in this borehole. The seismic profile is modified from Morgan et al. (2016) and Gulick et al. (2008).

4. Results

4.1. Petrography

(1) Granitoids

The granitoids in this study exhibit porphyric texture with 10–20% of the volume represented by coarse phenocryst K-feldspar (1–2 cm) and 80–90% matrix in volume. The matrix comprises medium granular (0.2–0.5 cm) K-feldspar (10–20%), coarse granular (0.5–1 cm) quartz (20–40%), medium granular (0.2–0.5 cm) plagioclase (10–20%) and fine granular (0.02–0.2 cm) biotite (5–10%). Accessory minerals include zircon, titanite, apatite and magnetite, all of them are below 1% in volume. Therefore, these rocks plot mostly in field of syenite granites, but a few are monzonitic granites and quartz alkali feldspar syenites (Fig. 4a).
Alteration of granitoids tends to occur more pronounced close to impact melts. Biotite transformed into chlorite partially or completely. Meanwhile, plagioclase underwent sericitization or local epidotization. Albite and feldspathization occurred along fractures closed to impact melt intrusions.

(2) Intermediate dykes

The intermediate dykes in this study are mainly represented by latite dykes with a porphyritic texture. The latite is composed of 5–10% K-feldspar (0.02–0.05 cm), 10–20% biotite (0.02–0.2 cm) and 5–10% quartz (0.02–0.05 cm) phenocrysts and 70–80% matrix, additionally, there are some xenoliths from wall rock such as gneiss and granitoids. Alteration of these dykes is evident with the chloritization of biotite and the occurrence of hydrothermal calcite veins that formed in the late
processes, possibly in connection with hydrothermal activities triggered by Chicxulub impact (Abramov and Kringle, 2007; Hecht et al., 2004).

(3) Mafic dykes

The Mafic dykes are dolerite with a sub-ophitic to ophitic texture, featuring 30~40% plagioclase (0.2~1 cm) and 10~20% pyroxene (0.2~0.5 cm) phenocryst and matrix (40~60%). Some plagioclase is altered to epidote and pyroxene are altered to serpentine or chlorite.

4.2. U-Pb zircon geochronology

Zircons of granitic rocks were selected from five different depths in the drill core: 829.73 mbsf, 927.31 mbsf, 1076.1 mbsf, 1200.26 mbsf and 1328.63 mbsf (Fig. 3). These euhedral to sub-euhedral zircons were mechanically broken with regular to irregular fractures, while oscillatory zoning and in zircons are clearly recognized in cathodoluminescence images. We chose highly concordant zircon ages (Concordance ≈ 95%) to obtain the weighted mean age. The results of LA-ICP-MS are reported in Supplement 1 and illustrated in Fig. 5. The weighted mean age of these zircons is 326±5.3 Ma. Inherited zircons are relatively scarce but one with an age of 589 Ma is shown in Fig. 5 a, 176Hf/177Hf and 176Lu/177Hf ratios of magma zircons are 0.282687~0.282747 and 0.00681~0.001382, εHf (t=326 Ma) ranges from 3.8 to 6.0, and TDM2 are 952~1078 Ma. The inherited zircon has 176Hf/177Hf and 176Lu/177Hf ratios of 0.282672 and 0.001968 with εHf (t=326 Ma) =8.7 and TDM2=984 Ma (Fig. 5 b).

![Fig. 5 Aages and εHf (t) of magma and inherited zircons. Crust and mantle Lu-Hf isotopic parameters from Condie (1993). The present-day CHUR values for 176Hf/177Hf=0.282772 and 176Lu/177Hf=0.0332 (Vervoort and Blichert-Toft, 1999). The dotted lines (176Lu/177Hf=0) demonstrate that there is no significant radiogenic growth of 176Hf in zircon grains through time.]

4.3. Major and trace element geochemistry

(1) Granitoids

The analysed granitoids in our nine samples contain SiO₂ contents of 68.65~73.76%, MgO content of 0.36~0.98% and K₂O contents of 2.45~5.30%, they are medium potassium calc-alkaline series (Fig. 6 e), and most of them are metaluminous (Fig. 6). The K₂O/Na₂O ratios of granitoids range from 0.5 to 1.21. Major and trace elements concentrations are shown in Supplement 2. Hereafter, we refer to these granitoids as Chicxulub granitoids. Trace elements of Chicxulub granitoids have features of negative anomalies in Ba, positive anomalies in Sr (361.88~538.78) (Fig 6 b), and depletions in Nb and Ta compared to N-MORB (Fig. 8 a). The total REE (rare earth elements) content of Chicxulub granitoids range from 44.42 to 81.13 ppm and Eu reveals slightly positive or negative anomalies (δEu are 0.97~1.04, δEu=2*[^Eu]/([Sm]+[^Gd]), normalized to
chondritic values of Sun and McDonough (1989) (Fig. 8 a). Additionally, the Sr/Y ratios of the Chixculub granitoids are higher than 40 ppm (55.63–129.77) and La/Yb ratios are over 20 ppm (21.07–44.61). The Y and Yb contents are less than 18 ppm (3.54–7.24) and 1.9 ppm (0.32–0.7) (Fig. 7 f). Thus they are similar to adakitic rocks as defined by Chung et al. (2003) and Defant and Drummond (1990).

As for Bremen data of Chixculub granitoids, they show a large range of major element concentrations especially Al₂O₃, K₂O, Na₂O, TiO₂ and P₂O₅ contents (Fig. 6 a, e, f, g, h). The trace elements concentrations such as Rb and Ba also demonstrate these large variations (Fig. 7 a, c). All these features indicate that Chixculub granitoids to some extent underwent hydrothermal alteration such as feldspathization, albitization and sericitization after and presumably also prior to the formation of Chixculub impact crater (Abramov and Kring, 2007; Schmieder M, 2019). In order to distinguish the altered and unaltered granitoids, we use the K/Rb ratios to divide Bremen data into two parts (Fig. 4 b): (1) altered (K/Rb >300) and (2) unaltered (K/Rb <300) because the K/Rb ratios in normal crust rock is about 250, and always higher than 400 in altered rocks (Helvacı and Griffin, 1983). Thus, the alteration processes caused the increase of Na₂O and K₂O content, imparting a peralkaline character to these rocks in Fig. 4 c. Theoretically, Sr content is always co-varient with CaO for isomorphism. Hence, Sr and CaO concentrations are expected to decrease during feldspathization or other alterations (Saunders and Tuach, 1988). However, their range did not change compared to unaltered samples (Fig. 4 d, e, f and Fig. 7 b). Therefore, there is no obvious trend of the leaching of Sr and CaO during alteration.

(2) Intermediate dykes

Six latite samples have SiO₂ and K₂O contents of 56.37–59.18% and 3.59–4.61% and plot in shoshonitic series (Fig. 6 e). Mg# (100*Mg²⁺/Mg²⁺+Fe²⁺) of latite are 59–63. Their MgO and CaO contents are 5–6% and 4.89–6.27% (Fig. 6 b, f), and their Ni contents are 96.89–109.81 ppm (Fig. 7 d). The shoshonitic latite has typical features as high K, Ni, Mg#, enriched LILE (large ion lithophile elements) and depleted HREE (high field strength elements) compared to N-MORB (Fig. 8 b). The total REE of latite are 387.41–516.65 ppm, higher than those in the Chixculub granitoid host rocks.

(3) Mafic dykes

The dolerite samples are divided into medium potassium series (Fig. 6 e) with SiO₂ contents of 45.45–48.26%, and low K₂O and Na₂O content of 0.4–0.72% and 2.00–2.8%, respectively. They display high MgO and Fe₂O₃ content of 10.78–13.4% and 11.6–14.72%, respectively. And Mg# are 62–67. In a trace element spider diagram (Fig. 8 a), the dolerite reveals negative anomalies of Th and U, and positive anomalies of Nb, Ta and Sr. Their REE patterns indicate slightly enriched LREE and depleted HREE compared to N-MORB.

4.4. Sr - Nd - Pb isotope characteristics

Chixculub granitoid samples have variable present-day ⁸⁷Sr/⁸⁶Sr (0.706726–0.709886) and ⁸⁷Rb/⁸⁶Rb (0.14938–0.468469), their initial ⁸⁷Sr/⁸⁶Sr (t=326Ma) are 0.7036–0.7047, εNd (t=326Ma) are 0.17–0.68 and T⁰DM2 (t=326Ma) are 1027–1069Ma, Sr and Nd isotopes typically show that our granitoids represent the magmatic features without obvious alteration. Five latite samples have the Rb/Sr ratios of 0.07–0.13 and Sm/Nd ratios of 0.16–0.17, their ⁸⁷Sr/⁸⁶Sr (t=326Ma) and εNd (t=326Ma) are 0.7045–0.7046 and 1.04–1.22, respectively. Because their fSm/Nd values are -0.48–0.50, T⁰DM1 (873–915Ma) are more suitable. Rb/Sr and Sm/Nd ratios in five dolerite samples are 0.05–0.07 and 0.3–0.34, the initial ⁸⁷Sr/⁸⁶Sr (t=326Ma) and εNd (t=326Ma) are 0.7048–0.7053 and 5.4–7.7. In
addition, the dolerite samples have $T_{\text{DM1}}$ and $T_{\text{DM2}}(t=326\text{Ma})$ modeling ages of 908–1771Ma and 459–644Ma in Supplement 3.

Five granitoid samples have $^{206}\text{Pb}/^{204}\text{Pb} (t=326\text{Ma}) = 18.034–18.725$, $^{207}\text{Pb}/^{204}\text{Pb} (t=326\text{Ma}) = 15.718–15.774$, $^{208}\text{Pb}/^{204}\text{Pb} (t=326\text{Ma}) = 38.162–38.692$. Three latite samples have $^{206}\text{Pb}/^{204}\text{Pb} (t=326\text{Ma}) = 18.416–18.769$, $^{207}\text{Pb}/^{204}\text{Pb} (t=326\text{Ma}) = 15.681–15.693$, and $^{208}\text{Pb}/^{204}\text{Pb} (t=326\text{Ma}) = 38.414–38.77$.

The two dolerite samples have $^{206}\text{Pb}/^{204}\text{Pb} (t=326\text{Ma}) = 18.78–18.816$, $^{207}\text{Pb}/^{204}\text{Pb} (t=326\text{Ma}) = 15.72–15.865$, and $^{208}\text{Pb}/^{204}\text{Pb} (t=326\text{Ma}) = 38.71–38.904$. 

![Graphs showing mineralogical and geochemical data](image-url)
Fig. 6 Harker diagrams showing major element variations of the granitoids, latite dykes and dolerite dykes and coeval magmatism. Data sources: Alleghanian granites from Samson et al. (1995a); Speer and Hoff (1997), Suwannee granites from Heatherington et al. (2010), Oaxaquia magmatic rocks from Lopez and Cameron (1997). Metabasaltic and eclogite melts (dehydration melting: 1-4.0 GPa) region (dotted line) after Wang et al. (2007a).

Fig. 7. Harker diagrams on trace element variations of granitoids, latite dykes and dolerite dykes and coeval magmatism, intermediate and mafic dykes. Data sources and symbols are the same as Fig. 6.
5. Discussion

5.1 Ages of Chicxulub granitoids and regional coeval magmatism

According to paleogeographic reconstructions, the Maya block was situated at the convergent margin of Gondwana and North America (Ortega-Gutiérrez et al., 2018), adjacent to the Ouachita Orogen (Poole et al., 2005) (Fig. 1), and is believed to have detached from this orogeny during the Mesozoic breakup of Pangea and the opening of the Gulf of México (Marton and Buffler, 1994) (Fig. 1). Chicxulub granitoids aged at 326 Ma reveal a distinct magmatic event in Ouachita Orogen during the late Paleozoic (Fig 3). These zircon ages were reported in Xiao et al. (2017), which included a summary of all data used in the present study. The 341±6 Ma titanite age of Schmieder et al. (2017), allanite results of Wittmann et al. (2018), and zircon ages from Yax-1 impact breccias in Schmieder et al. (2017) also have the late Paleozoic ages. Although there are
some arc-related materials (such as meta-andesite and dacite with similar ages in borehole Yucatan 1 but lack of geochemistry analyses) (Marton and Buffler, 1994) and tuffs with similar ages
2 (Shaulis et al., 2012) mentioned in previous studies, this is the first report of these ages from a
3 relatively continuous section of Chicxulub granitoids. Centeno-García (2016) summarized the
4 Mesozoic magmatism in México and the magmatic events are spatially and temporally divergent
5 from this late Paleozoic magmatism on the Maya block. Thus, these late Paleozoic magmatic
6 rocks are related to the Marathon - Ouachita orogeny during the assembly of Pangea.
7
8 Magmatism also occurs along the collective orogen such as the Las Delicias arc within the
9 Oaxaquia block (331–270 Ma); granites in the Suwannee block (296–295 Ma) and Alleghanian
10 granites in the Carolina block (335–285 Ma) (see in Fig 1), illustrating the spatial distribution of
11 orogenic products along the Pangea convergent margin from the late Mississippian to the early
12 Permian (Heatherington et al., 2010; Lopez and Cameron, 1997; Samson et al., 1995a). Since the
13 ages of these magmatic events coincide with that of the Chicxulub granitoids, this finding suggests
14 that they may have a similar petrogenesis. Their magma sources, processes or even tectonic
15 models will be further analyzed below.
16
17 5.2. Magma sources of Chicxulub granitoids and dykes
18
19 5.2.1 Granitoids
20
21 The granitoids in this study are conspicuously similar to typical adakitic rocks shown in Sr/Y
22 versus Y and (La/Yb)N versus YbN diagram (Fig. 9). These features are attributed to the melting
23 conditions when the source is melted with amphibolite or eclogite residues (Moyen, 2009).
24 Equilibrium melting modeling is a simple and ideal way to ascertain the possible source and
25 magma melting conditions. According to the results of equilibrium melting of source A
26 (meta-basaltic rock) and source B (MORB) from (Defant and Drummond, 1990), the granitoids
27 might be sourced from metabasaltic rocks which are melted with garnet-bearing amphibolite to
28 eclogite residues. Here, we examine in detail the four possible origins for the granitoids: (1)
29 Typical adakitic rocks formed by melting of young oceanic slab in a subduction zone (Defant and
30 Drummond, 1990; Martin et al., 2005; Moyen, 2009; Thorkelson and Breitsprecher, 2005); (2)
31 Metasomatic mantle melts that underwent a series of high-pressure AFC (assimilation and
32 fractional crystallization) (Castillo et al., 1999; Manikyamba et al., 2009); (3) Thickened
33 continental crust melted by heating from upwelling deep mantle during delamination (Chung et al.,
34 2003; Lee et al., 2009; Wang et al., 2007b; Xiao and Clemens, 2007; Xiao et al., 2007); (4) Partial
35 melting of lower crust in an intraplate setting caused by heating from upwelling mantle (Ma et al.,
36 2015; Qian and Hermann, 2013).
Fig. 9 Sr/Y versus Y and (La/Yb)\textsubscript{N} versus Yb\textsubscript{N} diagram, curves (1, 2, 3, 4) are from Defant and Drummond (1990), MORB refers to Mid-ocean ridge basalt, AFC refers to assimilation and crystallization processes. La/Yb and Yb are normalized by CI chondrite from (Sun and McDonough, 1989) in this paper.

Chicxulub granitoids reveal high K\textsubscript{2}O content and K\textsubscript{2}O/Na\textsubscript{2}O ratios Fig 3, which represent a K-rich metabasaltic source (~1%) (Rapp and Shimizu, 2002; Xiao and Clemens, 2007). Also, high Rb/Sr ratios (>0.05) indicate an evolved source such as continental crust (Fig. 11 b, d). These features are paradoxical to melts sourced from oceanic crust slab, which are lower in K content.
Typical high pressure differentiated adakitic rocks are sourced from metasomatic mantle, they feature adequate intermediate or mafic arc rocks to support differentiation processes (Castillo et al., 1999). Theoretically, intermediate or mafic rocks should be more voluminous than highly differentiated felsic rocks. Thus, they are quite distinct to the dykes in this study for their lower volume and different evolution trends in a Harker diagram (Fig. 6). Also, high pressure differentiated adakitic rocks have similar low K$_2$O/Na$_2$O ratios and large SiO$_2$ content range (Castillo et al., 1999; Macpherson et al., 2006). However, despite the high variation of SiO$_2$ content of 65–80% in Chicxulub granitoids, there is no obvious covariant relationship between Y, Sr and SiO$_2$ content (Fig. 7). Consequently, Chicxulub granitoids are not formed from high pressure differenntiation.

Adakitic melts from intra-continent setting are always indiscernible because they contain the same geochemical features as melts from thickened crust and hinge on ancient crustal source with the diagnostic features of lower (Sm/Yb)$_{SN}$ and higher Y$_{BSN}$ than typical adakitic rocks from oceanic slabs (Ma et al., 2015; Qian and Hermann, 2013). These features are not evident in granitoids in this study. More importantly, regional tectonic setting should be taken into consideration to verify this mechanism.

As to adakitic melts from thickened crust, they have typical features like high K$_2$O content and high K$_2$O/Na$_2$O ratios (Chung et al., 2003; Lee et al., 2009; Wang et al., 2006; Wang et al., 2007a). In addition, relatively higher Rb/Sr, $^{87}$Sr/$^{86}$Sr$_{initial}$, and lower εNd (t) are also distinct from adakitic rocks sourced from oceanic slabs (Wang et al., 2007a). These kinds of K-rich adakitic rocks tend to have a larger range of Al$_2$O$_3$ contents (Lee et al., 2009; Wang et al., 2007a), which are in accordance with results of Chicxulub granitoids in this study. However, there are two types of melting mechanisms for thickened crust, i.e. slab break off and thickened crust delamination. These melting scenarios are discussed in section 5.4.

5.2.2 Latite dykes

The shoshonitic latite dykes exhibit remarkable enrichments in LILE and LREE coupled with depletions in HFSE such as Nb, Ta, and Ti, which are typical features of continental arc rocks (McCulloch and Gamble, 1991). Additionally, high K$_2$O content, enriched LREE and other incompatible elements demonstrate that the source of the latite dykes are slab-fluids metasomatic mantle containing K-rich minerals such as amphibole or phlogopite (Petford and Gallagher, 2001; Rapp et al., 1999). Slightly positive εNd (t=326Ma) = 1.04–1.2 indicate a less evolved metasomatic mantle source. In addition, latite dykes may be contaminated with crustal materials as evidenced by wall rock xenoliths from wall rock within dykes and Pb isotopic features in Fig. 12. Also, based on their REE patterns, the latite dykes are similar to shoshonitic rocks related to slab breakoff reported in the Tibet plateau (Lee et al., 2009) and the Alps (Davies and Blanckenburg, 1995).

5.2.3 Dolerite dykes

The dolerite dykes have high Nb and Ta contents, La/Ba and La/Nb ratios similar to OIB, and (Th/Nb)$_{NRM}$ lower than 1, which means the dolerite dykes have little contamination with crust and lithospheric mantle. The Ce/Y versus Zr/Nb diagram (Supplement 7), suggests that dolerite dykes in this study were possibly derived from spinel peridotite (Hardarson and Fitton, 1991; Xia et al., 2004), which could be the deep mantle (e.g. asthenosphere mantle) consistent with petrology results of Schmieder (2017).
5.2.4 Constituents of the Northern Maya basement and possible sources for Chicxulub granitoids

Unlike the Southern Maya block, there are no high-grade metamorphic rocks outcropping on the Northern Maya block. The basement of the Northern Maya block is mainly composed of Pan-African materials such as mafic tholeiitic dolerite (546 Ma) in the Gd. Victoria area, Grenvillian low-grade metasedimentary rocks and granodiorite clasts from the Chicxulub impact crater, and Acadian granodiorite in the Altos Cuchumatanes region (480–400 Ma). All these features were presented in Ortega-Gutiérrez et al. (2018).

On the other hand, zircons are blended and uncovered in impact breccias from different depths in the Chicxulub impact structure or impact ejecta layers in the K/Pg boundary (Kring and Durda, 2002). Three groups of zircon ages reported in previous studies are categorized according to abundance distribution: (1) 545 Ma (2) 418 Ma (3) 320Ma (Kamo and Krogh, 1995; Kamo et al., 2011; Krogh et al., 1993a; Krogh et al., 1993b); Schmieder et al. (2017). The 545 Ma zircon ages represent Ediacaran arc materials formed in the Pan-African orogeny, which constitutes the major part of the basement of the Yucatán Peninsula/ Northern Maya block (Keppie et al., 2011), while Keppie and Keppie (2013) support most of Yucatán Peninsula/ Northern Maya block is Grenvillian affinity. Zircon ages of granitoids in this study (326 Ma) coincide with the aforementioned juvenile ages of zircons in impact breccias. Meanwhile, ages of andesite or dacite in borehole Yucatán-1 are 330–290 Ma (Marton and Buffler, 1994), these represent the continental arc magmatic rocks that are similar to latite in this study, indicating that there have been young compositions in Northern Maya block (Kring et al., 2004; Marton and Buffler, 1994). The inherited zircon ages of 1210 Ma from Maya mountain (Steiner and Walker, 1996) and 1100Ma from Chicxulub granitoids (Catherine et al, 2019) implies that the Northern Maya block also have Grenvillian materials.

As for Nd and Hf model ages (Fig. 5 b and Fig. 12 b), granitoids in this study range from 1.1 to 0.9 Ga and the majority of the impact breccias in the Chicxulub impact structure show T\textsubscript{DM1} of 1.45–1.2 Ga, while the T\textsubscript{DM1} of impact melt rock are 1.2–1.1 Ga (Keppie et al., 2011; Keppie et al., 2012; Kettrup et al., 2000). These features also imply that both Pan-African basement and more juvenile materials such as late Paleozoic orogeny materials were target rock components for Chicxulub impact melt. The major basement of Northern Maya appears to be Pan-African and a minor proportion of younger materials.

Considering the possible source of the Chicxulub granitoids, several types of Grenvillian sources such as the high-grade metamorphic rocks outcropping in Southern Maya region and the low-grade metasedimentary clasts in the Chicxulub impactites are not alternatives as their trace elements and Sr-Nd isotope characteristics are contradictory to those of the Chicxulub granitoids in this study (Keppie et al., 2012). Instead, the Pan-African materials are the most probable sources for the Chicxulub granitoids, considering its distribution, chronological and isotopic features. However, there are no continuous Pan-African materials have been recovered from the Chicxulub impact structure so far which prevents comparison of geochemical analysis data. Thus, we chose three Pan-African sources for the Northern Maya block and the Carolina terrane to ascertain the possible starting materials and residues by equilibrium melting in Supplement 4 and 5.

Table 1 Possible sources chosen as starting materials for equilibrium melting, their detailed information from Dennis et al. (2004); Keppie et al. (2006); Pollock and Hibbard (2010), and their sites are marked in Fig. 1.

<table>
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<tr>
<th>Source</th>
<th>Location</th>
<th>Age</th>
<th>εNd(t)</th>
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Dennis et al. (2004); Keppie et al. (2006); Pollock and Hibbard (2010), and their sites are marked in Fig. 1.
Mafic metavolcanic arc rocks from Southern Carolina are 540–626 Ma (2.0–3.5 Ga), representing volcanic arc.

Stony Mountain gabbro from Northern Carolina is 530–540 Ma (2.6–3.4 Ga), indicating an arc rift-back arc.

Mafic diabase dykes from the Northern Maya block are 546 Ma, formed by plume-related magmatism during the Pan-African period. These dykes feature high TiO₂ content and relatively enriched trace elements compared to the Chicxulub granitoids (Fig 9 e, f). Therefore, we exclude this type of rock as the possible source.

Moreover, according to the fact that Pan-African materials are dominant in the basement of the Maya block mentioned above (Keppie et al., 2011; Kettrup and Deutsch, 2003), the proximal Carolina region also distributes Pan-African metabasaltic rocks representing a possible juvenile source along the Peri-Gondwanan terrane (Keppie et al., 2011; Samson et al., 1995b), and the ages of Pan-African materials are accessible to that of inherited zircons (589 Ma) in Chicxulub granitoids (Fig. 5 a, b). Thus, we chose two kinds of Pan-African materials from the Carolina terrane mentioned in Table 1 to ascertain possible or analogous sources for the Chicxulub granitoids. Mafic meta-volcanic arc constitutes the basement in South Carolina (Dennis et al., 2004) and Stony Mountain gabbro formed from early Paleozoic arc rift magmatism in Northern Carolina (Pollock and Hibbard, 2010). They are both metabasaltic rocks with less evolved Nd isotope values (εNd(t)=2.6–3.4, 2.0–3.5) (Dennis et al., 2004; Pollock and Hibbard, 2010), theoretically coinciding with the source of Chicxulub granitoids. The geochemical features of source 1 (metavolcanic arc) and 3 (diabase dykes) are enriched in LILE (Rb, Ba), HFSE (Nb, Ta) and HREE (Gd, Y, Lu), but modelling results cannot completely match the features of Chicxulub granitoids (Fig. 10 a, b, e, f). Source 2 (Stony Mountain gabbro) is less rich in Rb, Ba, Nb and Ta and obviously more abundant in U and Sr (Fig. 10 c, d), which is quite identical with that of Chicxulub granitoids. 1%~60% degrees of partial melting results with their starting materials are shown in Fig 10, which indicates that source 2 (Stony Mountain gabbro) may approximate the source of Chicxulub granitoids.
Fig. 10 Primitive-mantle (PM from Sun and McDonough 1989) normalized Spidergrams of equilibrium melting results: melting sources are average compositions of metamorphic Neoproterozoic volcanic arc basements in South Carolina (Dennis et al., 2004) (Source 1) and Stony Mountain metagabbro in North Carolina (Pollock and Hibbard, 2010) (Source 2). The equilibrium melting models are under the circumstance of six types of residues: 1) 10% garnet Amphibolite (Rutile free): 0.1Grt+0.75Amp+0.15Pl; 2) Amphibolite: 100% Amp; 3) 10% garnet Amphibolite (0.5% Rutile): 0.1Grt+0.75Cpx+0.145Pl+0.005Rt; 4) Eclogite (1% Rutile): 0.3Grt+0.69Cpx+0.01Rt, 5) Pyroxenite (2% Ilmenite): 0.08Grt+0.6Cpx+0.25Opx+0.05Pl+0.02IIm, 6) Garnet-bearing Granulite: 0.1Grt+0.3Amp+0.3Cpx+0.2Opx+0.1Pl. Partition coefficients data: D for garnet, amphibole and clinopyroxene from Severs et al. (2009); Xiong (2006), D for rutile from Xiong et al. (2005), D for plagioclase from Severs et al. (2009), more detailed modelling results are in Supplement 5.

5.3 Magma processes of Chicxulub granitoids

Chicxulub granitoids in this study are simulated by melting the source 1 to 3 with six types of residues mentioned in Fig. 10, of which source 2 has a wide range of SiO$_2$ (36.74–53.23%), Al$_2$O$_3$ (9.63–16.1%), MgO (2.13–23.65%), K$_2$O (0.04–1.46%), Mg# (36–89), Sr contents (79.49–382.88 ppm) and Y contents (7.33–64.59 ppm), and the results of melting are compatible with a source melted with garnet in residues, specifically, the residues are possibly garnet-bearing amphibolite.
(residue 1 and 3) or garnet-bearing granulite (residue 5 and 6) (Fig 10 b, d, e, f). Moreover, the
Nb/Ta ratio is low in the Chicxulub granitoids (Fig. 11 a), which means that rutile does not
dominate in melting residues because it would have led to higher Nb/Ta ratios. The partitioning
coefficients and 1~60% modelling data are shown in Supplement 1 and Fig. 10. Sr positive
anomalies and the absence of Eu positive or negative anomalies in Chicxulub granitoids reveal
that plagioclase is either not dominant in residue or plagioclase fractional crystallization is
negligible, or possibly, that the high Sr positive anomalies were inherited from the features of
starting sources. All three explanations are consistent with modelling results (Fig. 10 c, d).
Additionally, some low Nb/Ta ratios in Chicxulub granitoids illustrate that the magma is
contaminated by upper crustal materials or the Nb/Ta of source should be lower (for the simulation,
we use the average Nb/Ta values) (Fig. 8 a and Fig. 11 a).
According to Rb/Ba versus Rb/Sr diagram (Sylvester, 1998) (Fig 10 d), not much sedimentary
material (e.g. pelite) is incorporated into the source of Chicxulub granitoids. Likewise, such
contamination does not affect the Sr-Nd isotopic features (Fig. 12 a, b), but the Pb isotope features
indicate that Chicxulub granitoids are contaminated by more evolved regional upper crustal
materials (Fig. 12 c, d), it also may refer to late alteration. Additionally, Chicxulub granitoids have
relatively low MgO (<3%), Ni, Y and Nb content as a whole (Fig. 7 d, e, f), therefore, the
involvement of mantle materials into Chicxulub granitoids is not significant. Thus, all these
features indicate that Chicxulub granitoids are sourced from a less evolved lower crustal source
(Fig. 12 a, b).
Fig. 11 Equilibrium melting of possible sources from Carolina terrane. The data source and symbols are the same as Fig. 9. Upper crustal (UC) composition from Shaw et al. (1976), Ocean island basalt composition (OIB) comes from Sun and McDonough (1989). The hollow circles on every equilibrium melting curve represent partial melting degree from 10% to 60%. Data sources and symbols are the same as Fig. 6. The vertical dot lines separate the adakitic rocks (right) and continental arc rocks (left). The horizontal dot line separates the melting results of eclogite (up) and amphibolite (down) after Martin et al. (2005).

5.4. Geodynamic models for K-rich adakitic Chicxulub granitoids

K-rich adakitic rocks sourced from thickened continental crust are mainly caused by two mechanisms: slab breakoff (Davies and Blanckenburg, 1995; Lee et al., 2009; Sacks and Secor, 1990) and thickened crust or mantle delamination (Chung et al., 2003; Nelson, 1992; Sacks and Secor, 1990; Wang et al., 2006; Wang et al., 2007a). In both of these models, asthenosphere upwelling is the cause of heating and melting of the upper mantle and/or lower crust, which leads to crustal thickening. However, the type and volume of magma, timing of magmatism, and induced regional topography are quite different in these two models.

5.4.1 Slab breakoff


Slab breakoff can occur after the collision of two continental lithospheres, when continental lithosphere starts subducting with the oceanic slab during the initial stage of collision, which may account for much syn-orogenic magmatism and metamorphism in orogenic belts (Davies and Blanckenburg, 1995; Sacks and Secor, 1990). The sources of magmatic rocks in this model mainly originate within the lower crust, metasomatic lithospheric mantle and even the asthenospheric mantle, generating granitic or rhyolitic, alkaline to ultrapotassic basaltic and MORB-like or OIB-like rocks, respectively (Davies and Blanckenburg, 1995; Kay and Kay, 1993). This type of magmatism tends to produce a linear magmatic zone because of rapid lateral slab breakoff, and relatively small volumes of melt (Davies and Blanckenburg, 1995; Samson et al., 1995a). When the slab breaks off, the relatively light subducted continent becomes buoyant, making the topography rise in a short time. Consequently, there is an increase in the rate of deposition of clastic sediments especially on the foreland. A series of sedimentary records reveal that voluminous sediments deposited in the Ouachita foreland drastically increased (maximum thickness of ~16000 m) during the late Mississippian through Middle Pennsylvanian (Shaulis et al., 2012), which is thicker than that in the Marathon and Sonora region (Morris, 1989; Poole et al., 2005). This deposit may be derived from Alleghanian region (Shaulis et al., 2012), indicating that there exists a trend of rapid uplift, which was a knock-on effect coeval with the formation of Chixculub granitoids of this study. Although there is no late Paleozoic aged detrital zircons in Ouachita foreland (Gleason et al., 2007), this verify the fact that there were little continental arc in Carolina (Alleghanian) and Suwannee regions (Mueller et al., 2014). The late Paleozoic zircons (~320 Ma) in Marathon foreland may be derived from Las Delicias arc or Yucatan regions (Gleason et al., 2007), and the detrital mica (40Ar/39Ar age of ~310Ma) in San Cayetano Formation in western Cuba may also be sourced from Yucatan region (Hutson et al., 1998), however, the Northern Maya block is more proximal to Carolina (Alleghanian) and Suwannee regions according to model a from Keppie and Keppie (2013) and Seton et al. (2012) and the similar basement attributes discussed in section 5.5. Furthermore, the remnant of oceanic slab or crust is revealed by the geophysical profile (Mickus and Keller, 1992), supporting the existence of slab breakoff.

Slab breakoff often precedes the main phase of collision-driven compression. Its corresponding magmas are earlier than the termination of compressive deformation. Deformation in the Ouachita belt begins in mid-Mississippian time and ends in the late Pennsylvanian (Poole et al., 2005). Therefore, this timing supports the slab breakoff model rather than the thickened crust or mantle delamination model. The issue of whether it is possible that the overriding continental crust thickens during this process has been verified by similar K-rich adakitic rocks in Tibet (Lee et al., 2007). The high Sr/Y and La/YbN ratios suggest that the lower crust on the Maya block underwent a crustal thickening. However, the low content of garnet and very low content of rutile in residues do not favor a huge degree of crustal thickening (>60 km or even more), which more likely occurs in a post-collisional period. Thus, the slab breakoff model is more suitable to explain the relatively low degree of crustal thickening that happened in the pre-collision and syn-collision period, when the Rheic ocean subducted beneath the North America.

The lattite dykes in this study are concomitant magma derived from metasomatic mantle according to the aforementioned trace elements features. Their slightly positive εNd and low 87Sr/86Sr initial illustrate a less enriched metasomatic mantle source (Lee et al., 2009). Thus they may have formed by the heating from upwelling asthenosphere materials. The dolerite dykes are
equipped with features of the deep mantle. Generally, they collectively support the slab breakoff model.

5.4.2 Delamination of thickened crust and mantle

This kind of model occurs after collision or during the post collision period due to the collapse of the thickened orogenic root by its high weight (Nelson, 1992). The thickened crust or lithospheric mantle is removed by the divergence of density or mantle convection (Kay and Kay, 1993). K-rich adakitic rocks sourced from thickened lower crust and potassic magmatism are derived from lithospheric mantle and are typical of magmatism due to the upwelling asthenosphere (Chung et al., 2003). The key problem is that the onset time of thickened crust or mantle delamination is contradictory to regional metamorphism and sedimentary records because the formation of Chicxulub granitoids precedes the main compressional setting. Although geochemical features of K-rich adakitic rocks in thickened orogenic crust such as the Tibetan Plateau and the Dabie orogenies quite resemble Chicxulub granitoids, it’s unlikely that Chicxulub granitoids formed by post-collisional magmatism without a period of significant crustal thickening.

5.5. Comparisons of late Paleozoic magmatism on Maya, Oaxaquia, Suwannee and Carolina terrane

5.5.1 The similarities and differences of magma sources and processes

The Maya, Oaxaquia, Carolina and Suwannee blocks are significant constituents of Peri-Gondwanan, where late Paleozoic magmatism mainly occurred during the assembly of Pangaea. The coeval magmatism in these blocks can unravel basement attributes and tectonic evolution. The coeval magmatism on Maya, Suwannee and Carolina blocks resulted in overlapping isotopic features according to Fig. 12 c, which suggests a collective juvenile source of Pan-African materials (not Grevillian materials). We chose the least evolved Oaxaquia and Alleghanian granites as parental magma endmembers and the most evolved foreland sediments from the Marathon and Ouachita Orogeny as evolved endmembers to ascertain the AFC processes by Sr - Nd isotopes. The modelling results are shown in Supplement 6.

(1) Oaxaquia block

The Las Delicias region in Coahuila has outcrops of peperite, granites and dacite ash. Their lower Rb/Sr ratios (most < 0.05), and typical arc features, such as negative anomalies in Nb and Ti, enrichments in LILE, and depletion in HREE (Fig. 8 b), point to a link with continental arc magmatism (Lopez and Cameron, 1997). The lower Rb/Sr and La/Yb ratios represent the absence of crust contamination processes, which may imply a thin crust (Lopez and Cameron, 1997). Their positive range of εNd (t) values (2.7–5.45, -2.17) and higher 87Sr/86Sr (t) ratios (0.7050–0.7070, 0.71) collectively indicate that their sources are slab-fluid metasomatic mantle materials, and AFC processes mainly appear as plagioclase fractional crystallization and less contamination with upper crustal materials. As the west part of the Marathon-Ouachita-Alleghanian orogeny, Oaxaquia block just distributed the continental arc magmatic rocks during the convergence of Pangaea (McKee et al., 1988, 1999; Ortega-Gutiérrez et al., 2018). These features suggest a continuous continental arc setting for the Oaxaquia block during the assembly of Pangaea.

(2) Suwannee block

Late Paleozoic magmatism is scarce on the Suwannee terrane, because it is possibly concealed by Mesozoic cover similar to the Maya block (Mueller et al., 2014). However, A-type granites related to post-collisional, lithospheric delamination events (Heatherington et al., 2010) are
recovered by drill cores. They display the features of high K2O contents, high Rb/Sr ratios (Fig. 11 b, d), intermediate 87Sr/86Sr(t=100Ma)=0.70377 (Fig. 12 a), young TDM1 of 1.1~0.7 Ga and inherited zircon ages of 560 Ma and 1.2~1.0 Ga (Table 2). All these features reveal that these granites were sourced from less evolved Pan-African crust. Moreover, high Y (22.8~46.8 ppm) and Nb (22.3~68.9 ppm) are indicators for the involvement of deep mantle materials (e.g. asthenosphere mantle) (Fig. 11 c, e, f), suggesting the granites are contaminated by the deep mantle (Heatherington et al., 2010). According to AFC processes modelled by Sr - Nd isotopes, Suwannee granites have a high 87Sr/86Sr(t=100Ma) showing contamination with upper crustal materials (Heatherington et al., 2010) (Fig. 12 a), meanwhile, they do show obvious contamination with upper crustal materials according to the Rb/Sr versus Rb/Ba diagram (Fig. 11 d).

Fig. 12 Diagram of Sr-Nd-Pb isotopic features. Regional Sr-Nd isotope data are from Heatherington et al. (2010); Keppie et al. (2012); (Lopez and Cameron, 1997); Ruiz et al. (1988b); (Samson et al., 1995a) and (Ruiz et al., 1988a), Pb isotope data are from Keppie and Dallmeyer (1995) and Ruiz et al. (1999), Sr-Nd isotopes of foreland sediments and tuffs from Marathon and Ouachita Orogeny come from Gleason et al. (1995), Marathon, Ouachita and Appalachian foreland sediments are similar in Nd isotopes (εNd(t) = -7~ -10) (Gleason et al., 1995), partition coefficients of Sr and Nd from DePaolo (1981). MORB (Mid-Ocean ridge basalt) region is from Zindler and Hart (1986), the evolution curves of upper crust, lower crust, orogeny and mantle are from Zartman and Doe (1981).

The NHRL (Northern Hemisphere reference line) is from Hart (1984).

(3) Carolina block

The Carolina terrane hosts extensive late Paleozoic magmatic rocks, especially Alleghanian granites, that are attributed to post-collisional, strike-slip tectonic environments. Some granites are divided into A-type granites for their high Ga/Al ratios, most of them are not related to continental arc rocks (Samson et al., 1995a; Speer and Hoff, 1997; Speer et al., 1994), but Alleghanian granites in the East Blue Ridge reveal an continental arc setting due to older zircon ages (335 Ma) and a relative lack of upper crustal elements (Winchester, 2013). Most of the Alleghanian granites are K-rich show higher Rb/Sr ratios and Nb+Y contents, which demonstrates more involvement of
upper crustal and deep mantle materials (e.g. asthenosphere mantle). The Rb/Ba versus Rb/Sr diagram (Fig. 11 d), indicates that the parental magma of the Alleghanian granites involving more upper crustal materials (clay-rich sources) than the parental magma for Chicxulub granitoids in this study. The negative Sr anomalies (Fig. 8 b) reveal that the parental magma of Alleghanian granites may have been affected by the fractional crystallization of plagioclase (Fig. 11 e, f).

However, some Alleghanian granites show a trend of amphibolite fractional crystallization through low D_{Sr} and high D_{Nd} (DePaolo, 1981) (Fig. 11a), which may explain some positive Sr anomalies in Alleghanian granites, another explanation is that amphibolite acts as residue when the source is melted. As for the source of Alleghanian granites, they are more similar to source 1 (mafic metavolcanic arc rocks) because of their high contents of LILE.

Table 2. Comparisons of late Paleozoic magmatic rocks in the Carolina, Suwannee, Maya and Oaxaquia blocks. These features are summarized from Heatherington et al. (2010); Lopez and Cameron (1997); Speer and Hoff (1997)

<table>
<thead>
<tr>
<th>Magmatism</th>
<th>Age</th>
<th>Inherited zircons</th>
<th>Possible basement</th>
<th>εNd(t)</th>
<th>Tectonic setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carolina</td>
<td>285--326Ma</td>
<td>---</td>
<td>Pan-African</td>
<td>-6.2--2.67</td>
<td>Post-collisional</td>
</tr>
<tr>
<td>Suwannee</td>
<td>294--296Ma</td>
<td>560Ma/1100</td>
<td>Pan-African/</td>
<td>-1--1.6</td>
<td>Post - collisional</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-1200Ma</td>
<td>Grenvillian</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maya</td>
<td>326±5.3Ma</td>
<td>589Ma/1100</td>
<td>Pan-African/</td>
<td>0.17--0.68</td>
<td>Pre- or syn-collisional</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ma</td>
<td>Grenvillian</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oaxaquia</td>
<td>270--331Ma</td>
<td>---</td>
<td>Grenvillian</td>
<td>-2.17--5.45</td>
<td>Continental arc</td>
</tr>
</tbody>
</table>

In summary, the coeval granitoids in the Maya, Suwannee and Carolina terranes display coincident features such as similar mineral assemblages, high K, Rb/Sr and juvenile isotopic characteristics, which suggest that they may have been sourced from a similar juvenile lower crust basement (Pan-African materials) (Heatherington et al., 1997; Keppie et al., 2011; Keppie et al., 2012; Samson et al., 1995a), plausibly, the Chicxulub granitoids are the extension of Alleghanian granites to the west. The major divergences on trace elements such as Rb, Sr, Ba and Nb, Y are caused by different AFC processes such as involvements of upper crustal or deep mantle materials and plagioclase or amphibolite fractional crystallization. Magmatism in the Oaxaquia block, appears to have been sourced from less enriched continental lithosphere mantle (Lopez and Cameron, 1997).

5.5.2 The asynchronous magmatism along the convergent margin of Pangea

The supercontinent Pangea formed by asynchronous collision between Gondwana and North America (Poole et al., 2005) with the Marathon- Ouachita- Alleghanian orogeny. Deformation in three segments of the Marathon- Ouachita- Alleghanian orogen begins approximately in the middle to late Mississippian, and ends diachronously in the early Permian in the Marathon region, the late Pennsylvania in the Ouachita Mountains, and the middle Pennsylvanian in Alleghanian region (Dallmeyer et al., 1986; Poole et al., 2005; Sacks and Secor, 1990). Therefore, the convergence between Peri-Gondwanan and North America commences simultaneously while it ends early in the east and late in the west (Poole et al., 2005). The late Paleozoic magmatism in the Oaxaquia, Maya, Suwannee, and Carolina terranes occurred from west to east at 331–270 Ma (Lopez and Cameron, 1997), 326±5.3 Ma, 296–295 Ma (Heatherington et al., 2010), and 335–285 Ma (Samson et al., 1995a; Winchester, 2013), respectively (Table 2). Magmatism roughly coincided with orogenic deformation periods, which hints at their evolutionary relationship in
space and time. It is plausible that magmatism ended earlier in the east and later in the west in the Marathon-Ouachita-Alleghanian orogeny.

To ascertain the continuity of delamination through the related magmatism in the Marathon-Ouachita-Alleghanian orogen, the ending time of a continental arc magmatism in this orogeny is a key evidence. As discussed above, although Alleghanian granites may have formed due to some early continental arc magmatism (East Blue Ridge) (Winchester, 2013), the major granites are from crustal sources which indicates that continental arc setting ended early in the Alleghanian region. Meanwhile, there are some continental arc rocks in the Maya block (such as tuffs and andesite) (Marton and Buffler, 1994), but synchronous Chicxulub granitoids represent the products of lower crust melting. Thus, transformation from pre-collisional or syn-collisional to post-collisional magmatism and a continuous delamination in the Marathon-Ouachita-Alleghanian orogeny from the Carolina terrane to the Maya block is indicated. The continuous continental arc magmatism on the Oaxaquia block suggests it did not undergo the delamination process; this finding may imply that there is an interruption of delamination between the Maya and Oaxaquia block.

5.5.3 The comparisons of geodynamic mechanisms

With the closing of the Rhei ocean, heat from the upwelling asthenosphere by delamination may have acted as a driving force to generate Alleghanian granites by melting Pan-African lower crust in the Carolina and Suwannee terranes (Heatherington et al., 2010; Sacks and Secor, 1990; Speer and Hoff, 1997). Compared with Chicxulub granitoids, there is no obvious evidence of crustal thickening in the Carolina and Suwannee terranes according to Sr/Y and La/Yb ratios of Alleghanian granites or these features may be hidden by the contamination of deep mantle materials. Additionally, in the Oaxaquia block, the late Paleozoic magmatism shows a continental arc setting from beginning to end, which were all derived from less evolved continental lithospheric mantle with weak crustal contamination (Lopez and Cameron, 1997). Thus, this finding does not completely support a crustal thickening and delamination model. Because there are tiny arc-type magmatism along Peri-Gondwanan, especially in the Carolina and Suwannee terranes, this implies that dextral transpressional convergence impedes the generation of continental arc-type magma (Mueller et al., 2014). However, the discovery of Chicxulub granitoids (non-continental arc rocks) in this study, the occurrence of some coeval continental arc rocks in boreholes on Maya block (Marton and Buffler, 1994) and the tuffs (continental arc type) in Ouachita foreland with the nearly similar ages (Loomis et al., 1994; Poole et al., 2005; Shaulis et al., 2012) are not consistent with transpressional model because of the occurrence of crustal thickening and coeval continental arc magmatism. Therefore, the crust thickening model and strike slip model seems unable to explain this phenomenon across the whole region. A different mechanism is required to explain the transformation mechanism from continental arc to syn-collisional or post-collisional magmatism. The nearly coeval latite dykes in this study and some other continental arc tuffs in the Sabine block are crucial indicators of remnant metasomatic mantle materials, they indicate that the Maya block underwent an early subduction period, then evolved into a delamination or slab break-off model.

Considering the approximate simultaneity of magmatism and metamorphism on these three blocks, and the effects of slab breakoff model in Alleghanian regions reported in previous studies (Nelson, 1992; Sacks and Secor, 1990; Samson et al., 1995a), we put forward a tearing slab breakoff model (Fig 12) to explain the divergences and similarities of magmatism and tectonism.
over the whole regions undergoing the Marathon-Ouachita-Alleghanian orogeny. Slab breakoff
would commence in a certain place and propagate along the strike (Yoshioka and Wortel, 1995).
The detached slab would give an additional drag force on the proximity of the undetached slab,
then this will enhance the lateral propagation (Wortel and Spakman, 1992). Plausibly, the depth of
detachment will migrate into a deeper level owing to the resultant force of both the lower slab and
the neighboring detached slab. This model can explain some major questions about magmatism
along the Marathon-Ouachita-Alleghanian orogeny (Fig. 1 and Fig. 13 a, b):

(1) Syn-collisional or post-collisional magmatism and very minor pre-collisional magmatism
occurred in the east of the Marathon-Ouachita-Alleghanian orogen (Carolina terrane), in contrast,
Abundant continental arc magmatic rocks were emplaced in the west (Oaxaquia block) (Dickinson,
2009; Dickinson and Lawton, 2001). This style of magmatism can be attributed to the depth of the
breakoff site. According to the timing of magmatism, slab breakoff commences in Carolina at a
relatively shallow depth so that there are no metasomatic mantle materials to facilitate the
formation of continental arc magmatism (Fig. 12 c, d). The slab gradually detaches deeper in the
Maya region, affecting the metasomatic mantle materials above the detaching site (Fig. 13 c, e).
Due to a deeper breakoff site or no slab break off in the west, negligible effect on the overlying
metasomatic mantle to generate continental arc magmatism in the Oaxaquia block (Fig. 13 c, e).

(2) All the late Paleozoic magmatism in three blocks (Carolina, Suwannee and Maya) is dispersed
along the Marathon-Ouachita-Alleghanian orogeny. The volume, east-to-west along strike and
gradual age changes of late Paleozoic magmatism along the Peri-Gondwanan region resemble
magmatism caused by the tearing slab breakoff model in Tibet and the Alps (Davies and
Blanckenburg, 1995; Zhang et al., 2014) because slab breakoff always leads to magmatism
distributed linearly with relatively smaller volumes than those generated by thickened crust
delamination.

(3) The upper crustal and deep mantle contamination are divergent in granitoids in the Maya block
and Carolina terrane, which could also relate to the depth of the slab breakoff site. We can observe
different contributing portions from mantle and upper crustal materials to magmatism in these
three blocks. Deep mantle upwelling at a shallow site, will cause the assimilation of a higher
proportion of crustal material and impart more characteristics of deep mantle because of the high
geothermal gradient. If such asthenospheric materials upwelled at a deeper site such as the Maya
block, their heat and volume would decrease when they ascend. Therefore, less crustal melting and
less deep mantle materials would become involved in the resulting magmatism.
Fig. 13 Schematic models for late Paleozoic magmatic activities on Carolina, Suwannee, Maya and Oaxaquia block., diagram a, b are modified from Mueller et al. (2014), Weber et al. (2008) and Dickinson (2009), diagram d is modified from Sacks and Secor (1990)

6. Conclusions

(1) The first reported 326±5.3 Ma Chicxulub granitoids excavated by the Chicxulub impact crater are in accordance with the previous zircon ages found in impact breccias from Chicxulub impact crater. Meanwhile, they represent the extensional magmatic expressions of Alleghanian granite during the assembly of Pangea.

(2) Late Paleozoic Chicxulub granitoids are K-rich adakitic rocks derived from the melting of thickened crust with the residue of garnet-bearing amphibolite or garnet-bearing granulite. Thickened crust had been heated by upwelling asthenospheric mantle which resulted from slab breakoff. These processes also caused metasomatic mantle melting, which generated the intrusions of shoshonitic latite. Dolerite dykes represent the asthenosphere derived melts that may be related to this geodynamic process or formed in the Mesozoic.

(3) Hf model ages in zircons, Nd model ages and equilibrium melting models of trace elements reveal that Chicxulub granitoids were sourced from a juvenile lower crust (Pan-African Orogeny materials) especially similar to Carolina basement and the Northern Maya block (The site of Chicxulub impact crater) is proximal to Carolina block and Suwannee block during the assembly of Pangea. Coeval magmatic rocks on Suwannee and Carolina terranes also have similar sources while they involve more upper crustal and deep mantle materials.

(4) The similarities and divergences of magmatic expressions on Oaxaquia, Maya, Suwannee and Carolina terranes elucidate the asynchronous convergence from west to east and a tearing slab breakoff during the formation of Pangea. The depth of the slab breakoff is the driving force to generate the divergent magma types during the assembly of Pangea.

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