Geological and archaeological implications of strontium isotope analysis of exposed bedrock in the Chicxulub crater basin, northwestern Yucatán, Mexico

Adrian Gilli[1,2], David A. Hodell[2,3], George D. Kamenov[2], and Mark Brenner[2]
[1]Geological Institute, ETH Zurich, Sonneggstrasse 5, 8092 Zurich, Switzerland
[2]Department of Geological Sciences & Land Use and Environmental Change Institute (LUECI), University of Florida, 241 Williamson Hall, Gainesville, Florida 32611, USA
[3]Godwin Laboratory for Palaeoclimate Research, Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK

ABSTRACT

The surface geology of the site of the Chicxulub impact crater in northwestern Yucatán, Mexico, has not been studied extensively since the discovery of the crater almost two decades ago. Strontium isotope ($^{87}Sr/^{86}Sr$) measurements in carbonate rock outcrops reveal near-uniform strontium signatures of 0.70905 inside the ring of cenotes (water-filled sinkholes), which represents the rim of the crater basin. Measured strontium isotope ratios were used to infer rock ages, employing the marine Sr isotope curve. We estimate the age of the exposed limestone within the Chicxulub crater basin to be late Miocene to early Pliocene, representing the age of the youngest sediment fill. Discovery of a large terrain of near-uniform strontium isotope ratios in northwestern Yucatán offers new geoarchaeological opportunities to track ancient Maya migration and determine sources of manufactured goods. Our results have implications for applying the Sr isotope method to Maya archaeological sites, such as Mayapán, the last Maya capital, and Chichén Itzá.

INTRODUCTION

Recognition of a large impact structure in the northwestern Yucatán Peninsula, Mexico (Hildebrand et al., 1991; Penfield and Camargo, 1981; Pope et al., 1991), initiated intense research on the buried Chicxulub impact crater. The impact was proposed as the cause of mass extinctions at the Cretaceous-Paleogene boundary, although the exact timing of the impact and its relation to the Cretaceous-Paleogene mass extinction are still debated (e.g., Arenillas et al., 2006; Keller et al., 2007). The giant meteorite impact ca. 65 Ma ago occurred in shallow water, and the site is now deeply buried by sediment (Ward et al., 1995). Removed from erosional forces by this burial, the Chicxulub crater is one of the best-preserved large impact structures on Earth. Previous studies focused on analysis of drill cores and the application of geophysical methods (e.g., seismic, gravity, geomagnetic analyses) (Fig. 1A) to determine the size, and understand the formation, of this large, multiring impact structure. These approaches increased our knowledge about the subsurface structure of the Chicxulub impact crater, but its surface geology has not been reexamined seriously since the discovery of the buried crater almost two decades ago.

A unique surface expression of the buried crater structure is a ring of sinkhole lakes (locally known as cenotes, after the Maya d'zonot), which form a semicircle with a diameter of ~165 km (Hildebrand et al., 1995; Perry et al., 1995; Pope et al., 1991, 1996) (Fig. 1). The ring of cenotes plays a key role in the regional hydrology of the peninsula and was a focus for Maya settlement. Groundwater is channeled along both branches of the cenote ring and discharges into the Gulf of Mexico, where the ring intersects the coast (Perry et al., 1995). Although the cenote ring is clearly associated with the Chicxulub crater basin (Hildebrand et al., 1995), several hypotheses have been proposed to explain the formation of this surface feature by the impact crater, which is covered by several

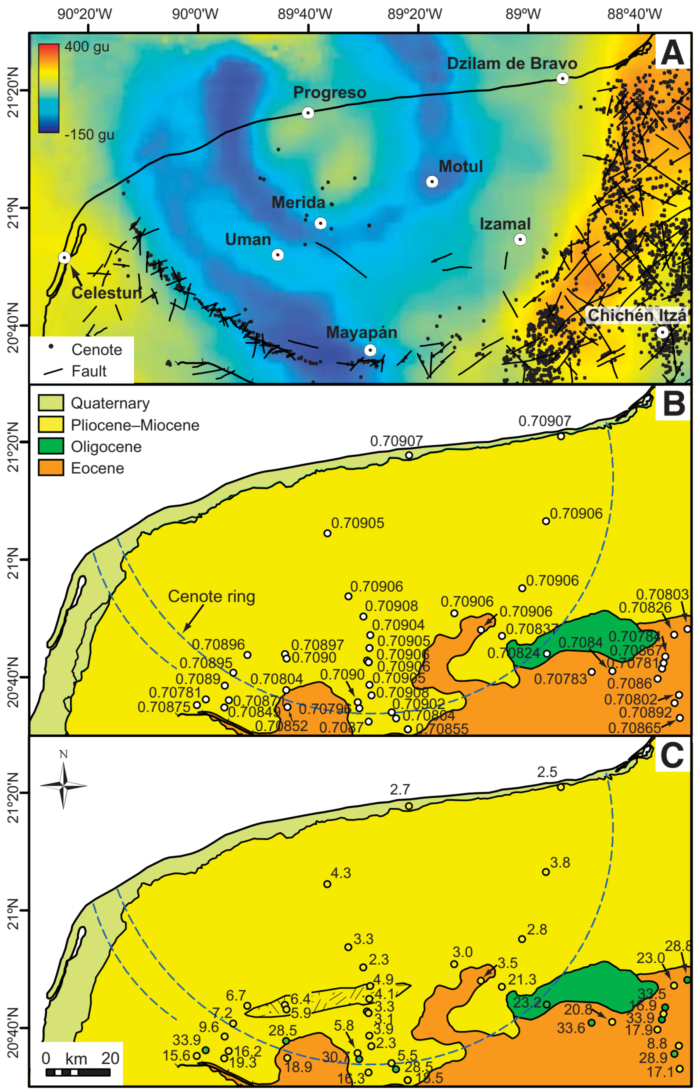

Figure 1. Map of Chicxulub impact basin of northwestern Yucatán, Mexico. A: Bouguer gravity (background color) (Morgan et al., 2007) with location of faults (Instituto Nacional de Estadistica, Geografia, e Informatica, 1984) and cenotes (Connors et al., 1996). B: Geologic map with $^{87}Sr/^{86}Sr$ results of bedrock samples. Geology is according to 1:500,000 geologic map of the Servicio Geológico Mexicano (2007). C: Ages (in Ma) of rock samples based on $^{87}Sr/^{86}Sr$. Sampling locations are color coded according to their ages. Geologic map (Servicio Geológico Mexicano, 2007) is supplemented with Oligocene terrain (hachured) as mapped in older geologic map (Instituto Nacional de Estadistica, Geografia, e Informatica, 1989).

hundred meters of carbonate rock (Perry et al., 1995; Pope et al., 1993; Pope et al., 1996).

Here we present strontium ($^{87}Sr/^{86}Sr$) isotope data from rock and water samples collected inside and outside the cenote ring (see the GSA Data Repository[1]). The $^{87}Sr/^{86}Sr$ values were used to assign ages to the rock samples using the seawater strontium isotope calibration curve, assuming no diagenetic alteration. The data contribute to our understanding of the infilling history of the Chicxulub crater basin on the northern Yucatán Peninsula. These results are also relevant to geoarchaeology, a field in which strontium isotopes are increasingly applied as a provenance indicator to solve problems related to ancient human migration and trade. However, the successful application of the $^{87}Sr/^{86}Sr$ technique depends strongly on knowledge of the spatial variability of strontium isotopes in the surface rocks of the investigated area.

GEOLOGY

The Yucatán Peninsula is a large carbonate platform composed of rocks ranging from Cretaceous to Quaternary age. In general, the age of limestone outcrops is younger toward the northern rim of the peninsula (e.g., Lopez Ramos, 1975) (Fig. 1B). Several factors, however, complicate detailed mapping of the geology of outcrops of the Yucatán Peninsula. Horizontal or near-horizontal layering of geologic units in an almost flat topography causes difficulties in locating contacts. Bushy vegetation, limited outcrops, presence of extensive calcrete crusts (Gerstenhauer, 1987), and generally poor preservation of microfossils and macrofossils further hinder detailed geological mapping. With the exception of a recent geologic map (Servicio Geológico Mexicano, 2007), all geologic mapping studies (see Isphording, 1975, for an overview) were completed before the discovery of the large buried impact crater in the northwestern part of the Yucatán Peninsula. It is therefore not surprising that stratigraphic units crosscut the crater basin (i.e., the cenote ring) (Fig. 1B). According to the geologic maps, Quaternary deposits frame almost the entire Yucatán Peninsula. The northern part of the Chicxulub basin and adjacent area are mapped as late Tertiary (Miocene–Pliocene), whereas the southern part of Mexican Yucatán is early Tertiary (Paleocene–Eocene) (Figs. 1B and 1C). The largest difference between the various geological maps is the extent and location of rock outcrops of Oligocene age. Lopez Ramos (1975) identified Oligocene rocks south of Merida (hachured area in Fig. 1C), whereas the most recent geologic map (Servicio Geológico Mexicano, 2007) indicates Oligocene rock outcrops southeast of Izamal (Fig. 1B).

Several morphological arguments point toward distinct surface lithologies outside and inside the Chicxulub impact basin (i.e., beyond and within the cenote ring), but until this investigation, no study had proven it. Described karst features indicated different landscape evolution between the northwestern part of the Yucatán Peninsula and areas farther east. Ferrer de Mendiolea (1952) discriminated between “carzo evolucionado” (mature karst) in northeastern Yucatán and “carzo menos evolucionado” (undeveloped karst) in the vicinity of the Chicxulub basin. This concept was refined by Isphording (1975), whose “Northwestern coastal plain” district covers exactly the area of the Chicxulub impact basin. Different landscape morphologies are also characterized by the spatial distribution of structural fractures and cenotes. According to the geologic map (Instituto Nacional de Estadistica, Geografia, e Informatica, 1984), structural fractures are almost entirely restricted to the area outside the cenote ring (Fig. 1A), although the Chicxulub crater had not been discovered when this map was published. Likewise, the northeastern part of the Yucatán Peninsula contains numerous cenotes, in contrast to the area inside the cenote ring, where there are few such features (Connors et al., 1996; Pope et al., 1996). In addition, the soil cover is relatively thin within the ring compared to sites elsewhere in Yucatán (Isphording, 1975).

ROCK SURFACE AGE

Spatial $^{87}Sr/^{86}Sr$ distribution shows a clear association of sediments filling the crater, as defined by the ring of cenotes (Figs. 1B and 1C). With a few exceptions just slightly inside the cenote ring, all bedrock samples inside the Chicxulub basin display nearly identical $^{87}Sr/^{86}Sr$ values, ~0.70905. The $^{87}Sr/^{86}Sr$ values of bedrock samples outside the cenote ring are significantly lower. The $^{87}Sr/^{86}Sr$ transition across the cenote ring is sharp in the southern sector (i.e., near Mayapán), where it occurs within a few kilometers. A similar sharp $^{87}Sr/^{86}Sr$ transition is also observed south of Izamal, but there it occurs slightly inward of the cenote ring. The transition southwest of Uman is more gradual.

Strontium isotope values of marine carbonate rock provide independent ages that can be used to verify the inferred biostratigraphic ages used to produce the geologic map. The near-uniform $^{87}Sr/^{86}Sr$ values of rock samples inside the Chicxulub basin indicate that the crater filled between ca. 6 and 2.3 Ma ago (i.e., latest Miocene–Pliocene). This is later than previously suggested, i.e., during the late-middle to early-late Miocene (Galloway et al., 2000), but within the age range proposed by soil analysis (Pope et al., 1996). Extensive Oligocene terrain within the crater basin, as mapped earlier (e.g., Lopez Ramos, 1975; hachured area in Fig. 1C), was not confirmed. The recent geologic map (Servicio Geológico Mexicano, 2007) places Oligocene terrain to the southeast of Izamal, a claim that is supported by our strontium isotopic map. In addition, our data show that the unit southwest of Izamal, mapped entirely as Eocene, contains parts that are considerably younger, as young as 3.5 Ma (Fig. 1C).

The extent of the Chicxulub crater basin was first documented by analysis of boreholes (Ward et al., 1995) and gravity measurements (Hildebrand et al., 1995). Recent seismic data from the offshore part of the impact basin (Gulick et al., 2008) confirmed that the thick Cenozoic infill of the crater is bounded by the inner ring fault, which likely corresponds to the ring of cenotes onshore. The gravity data (Fig. 1A) depict different gradients for the transitions across the cenote ring (Hildebrand et al., 1995). This could explain the center-inward shift of the transition seen in the strontium isotopes along the transect south of Izamal. The presence of cenotes inside the cenote ring in this peripheral sector of the impact basin (Connors et al., 1996) provides additional support for slightly older lithologies in this area. The western part of the Chicxulub basin consists of two cenote rings (Pope et al., 1993), consistent with the more gradual strontium isotope transition southwest of Uman.

Surface rock ages east and south of the cenote ring are within a wide range (Oligocene–Miocene). This greater variability represents a more complex geological structure outside the cenote ring, as expressed by the high abundance of structural fractures (Fig. 1A). Although all geologic maps show lithologies of Eocene age in the south and southeastern part of the investigated area (Fig. 1), no bedrock sample displayed an Eocene age, on the basis of strontium isotopes.

APPLICATIONS TO GEOARCHAEOLOGY

Strontium isotopes are increasingly applied in geoarchaeology to investigate human and animal migration patterns. Through weathering of bedrock, strontium is released into the hydrosphere and pedosphere, where it is incorporated into plants and moves through the food web. Humans and animals incorporate strontium into their teeth and bones without isotopic fractionation. Therefore, the strontium isotope ratio of these mineralized tissues should reflect the $^{87}Sr/^{86}Sr$ of the geological substrate where the organism lived at the time of tissue formation (e.g., Bentley, 2006). Strontium isotope ratios can also be applied to trace the source of food, building materials, or lithic artifacts (e.g., Benson et al.,

[1]GSA Data Repository item 2009174, methods, Table DR1 (bedrock sample Sr isotope values), and Table DR2 (water sample Sr isotope values), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

2003; English et al., 2001). A prerequisite for successful application of this technique is detailed knowledge of the spatial variability of $^{87}Sr/^{86}Sr$ values in the region. A previous strontium isotope mapping study of the Maya area (Hodell et al., 2004) showed sufficiently distinct subregions for the technique to be applied. However, the spatial resolution of strontium measurements in the middle and northern lowlands of the Yucatán Peninsula was too coarse to define the precise extent of these subregions. Our finding of a unique and well-defined terrain within the Chicxulub crater basin offers new possibilities for the application of strontium isotopes in northern Yucatán as a geoarchaeological tracer. Examples are given for two of the most notable Maya sites in northern Yucatán, the Postclassic site of Mayapán and Classic Chichén Itzá.

Mayapán

The archaeological site of Mayapán, the last Maya capital of Yucatán (e.g., Milbrath and Peraza Lope, 2003), is just within the Chicxulub impact basin, only 5 km north of the cenote ring (Fig. 1A). Bedrock samples around Mayapán revealed a clear crater-infill signature, with $^{87}Sr/^{86}Sr$ value between 0.70896 and 0.70908 (Fig. 2). The $^{87}Sr/^{86}Sr$ values are significantly lower south of the cenote ring, with values between 0.7085 and 0.7088. A few isolated $^{87}Sr/^{86}Sr$ measurements close to the cenote ring reveal even lower strontium isotope values (i.e., 0.7078–0.7080). Sr isotopes were also measured on soil, groundwater, and plant samples (banana tree leaf) from Mayapán, and revealed values of 0.70897, 0.70819, and 0.70871, respectively. The $^{87}Sr/^{86}Sr$ value on groundwater is considerably lower (Fig. 2) than the value for surface bedrock, indicating that the groundwater was in contact with older rock strata (Perry et al., 2009). Variability in the $^{87}Sr/^{86}Sr$ ratio of different materials (i.e., soil, plants, water) from Mayapán raises questions about the $^{87}Sr/^{86}Sr$ values that might be expected in the skeletal tissue (i.e., bones and teeth) of local individuals. The geoarchaeological community has adopted the concept of "biologically available" strontium and uses the $^{87}Sr/^{86}Sr$ in animal skeletal tissue to define the local Sr isotope signature (Bentley et al., 2004; Price et al., 2002). Wright (2007) measured five bone samples of white-tailed deer that gave an average local $^{87}Sr/^{86}Sr$ value of 0.70886. This is in general agreement with our $^{87}Sr/^{86}Sr$ measurements from soil and plant samples of Mayapán, which are expected to be close to the biologically available $^{87}Sr/^{86}Sr$ ratios.

The location of Mayapán is near an important geological boundary with contrasting $^{87}Sr/^{86}Sr$ signatures on either side, making it a potentially interesting site to apply this strontium isotopic technique. However, the sharp strontium isotope boundary in close proximity to this archaeological site offers both opportunities and challenges for tracking human migration and the provenance of artifacts. For example, outlier strontium isotope values, recognized on the basis of $^{87}Sr/^{86}Sr$ at Mayapán, may come from only a short distance away, if measurements are within the range of values determined for samples taken south of the cenote ring. Alternatively, the large contrast of $^{87}Sr/^{86}Sr$ over short distances offers new possibilities to track small-scale movements of goods and artifacts, as well as assess the regional influence of this archaeological site.

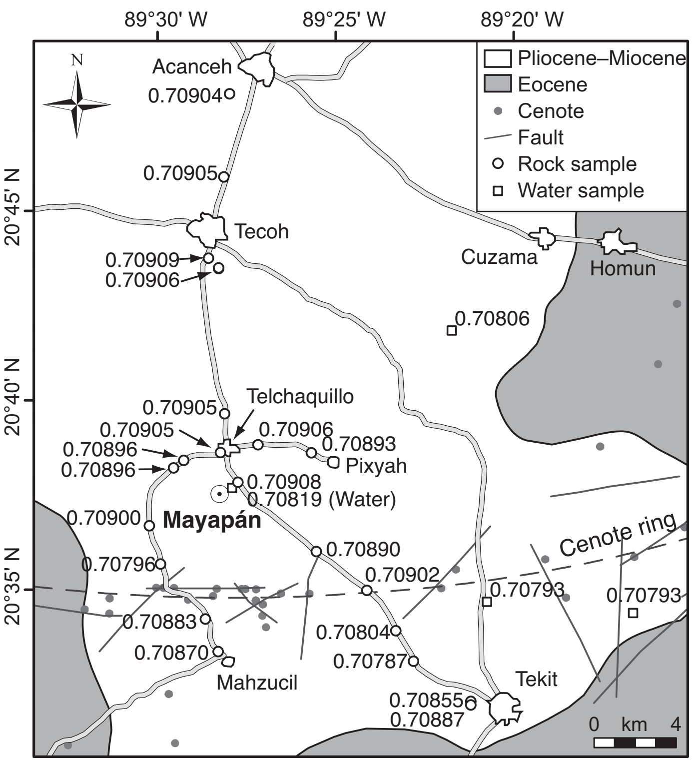

Figure 2. Detailed $^{87}Sr/^{86}Sr$ map with measurements on bedrock and water samples around archaeological site of Mayapán.

Chichén Itzá

Chichén Itzá is the largest archaeological site in northwestern Yucatán that flourished during the Classic and Terminal Classic periods. This site is southeast of the Chicxulub crater basin, ~30 km outside the cenote ring (Fig. 1A). Bedrock samples in the near vicinity of Chichén Itzá revealed lower Sr values with considerably larger variability than around Mayapán (Fig. 3). Values vary between 0.7078 and 0.7089 along a regional trend, although the values cluster around 0.70783, 0.70805, and 0.70864. This indicates a complex geology in the proximity of Chichén Itzá that is currently not represented in the geological maps. Price et al. (2008) reported one local Sr isotope value of 0.7087 for Chichén Itzá, a value probably slightly higher than expected by the Sr analysis of rocks and water (0.70806). Future migration studies should consider the variability in the local biologically available Sr around Chichén Itzá to clearly identify outliers in the ancient population.

CONCLUSIONS

The $^{87}Sr/^{86}Sr$ measurements of exposed limestone in northwest Yucatán delineate an age difference across the ring of cenotes, representing a surficial expression of the buried Chicxulub impact crater. Near-uniform strontium isotope values within the ring indicate a late Miocene–early Pliocene age for the youngest sediment filling the crater basin. Mapping of fine-scale Sr isotope variation in northwest Yucatán has implications for applying Sr isotopes as a geoarchaeological tracer. For example, the last

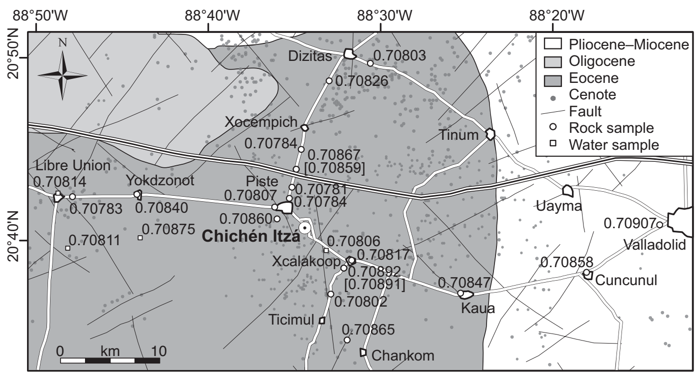

Figure 3. Detailed $^{87}Sr/^{86}Sr$ map with measurements on bedrock and water samples around archaeological site of Chichén Itzá. Sr values in brackets are measurements on weathered limestone (sascab) collected at same location as corresponding bedrock sample.

Maya capital of Mayapán is located inside the cenote ring, where $^{87}Sr/^{86}Sr$ values are uniform, but close to a sharp strontium isotope contact only a few kilometers away. A more complex geology with greater variability in bedrock Sr isotope values is documented for the archaeological site of Chichén Itzá. Although biologically available Sr should be the starting point for ancient migration studies, detailed knowledge of the geology around archaeological sites is important for evaluating the local Sr signature and exploiting the full potential of the strontium isotope method.

ACKNOWLEDGMENTS

We thank Alma Albornaz-Pat, Jason Curtis, and Susan Milbrath for their help with sampling in the field. We also thank Jo Morgan and Martin Connors for sharing the gravity data set and the locations of the cenotes, respectively. Christian Russell was very helpful in the initial phase of geographic information system (GIS) analysis, and Ann Heatherington is acknowledged for her help with the isotope measurements. Adrian Gilli was supported by a fellowship from the Swiss National Science Foundation (PBEZ2—104322). This is a contribution of the University of Florida Land Use and Environmental Change Institute (LUECI).

REFERENCES CITED

Arenillas, I., Arz, J.A., Grajales-Nishimura, J.M., Murillo-Muneton, G., Alvarez, W., Camargo-Zanoguera, A., Molina, E., and Rosales-Dominguez, C., 2006, Chicxulub impact event is Cretaceous/Paleogene boundary in age: New micropaleontological evidence: Earth and Planetary Science Letters, v. 249, p. 241–257, doi: 10.1016/j.epsl.2006.07.020.

Benson, L., Cordell, L., Vincent, K., Taylor, H., Stein, J., Farmer, G.L., and Futa, K., 2003, Ancient maize from Chacoan great houses: Where was it grown?: National Academy of Sciences Proceedings, v. 100, p. 13111–13115, doi: 10.1073/pnas.2135068100.

Bentley, R.A., 2006, Strontium isotopes from the earth to the archaeological skeleton: A review: Journal of Archaeological Method and Theory, v. 13, p. 135–187, doi: 10.1007/s10816-006-9009-x.

Bentley, R.A., Price, T.D., and Stephan, E., 2004, Determining the 'local' $^{87}Sr/^{86}Sr$ range for archaeological skeletons: A case study from Neolithic Europe: Journal of Archaeological Science, v. 31, p. 365–375, doi: 10.1016/j.jas.2003.09.003.

Connors, M., Hildebrand, A.R., Pilkington, M., Ortiz-Aleman, C., Chavez, R.E., Urrutia-Fucugauchi, J., Graniel-Castro, E., Camara-Zi, A., Vasquez, J., and Halpenny, J.F., 1996, Yucatan karst features and the size of Chicxulub crater: Geophysical Journal International, v. 127, p. F11–F14, doi: 10.1111/j.1365-246X.1996.tb04066.x.

English, N.B., Betancourt, J.L., Dean, J.S., and Quade, J., 2001, Strontium isotopes reveal distant sources of architectural timber in Chaco Canyon, New Mexico: National Academy of Sciences Proceedings, v. 98, p. 11891–11896, doi: 10.1073/pnas.211305498.

Ferrer de Mendiolea, G., 1952, Geografía de Yucatán: Boletín de la Sociedad Mexicana de Geografía y Estadística, v. 74, p. 161–238.

Galloway, W.E., Ganey-Curry, P.E., Li, X., and Buffler, R.T., 2000, Cenozoic depositional history of the Gulf of Mexico basin: American Association of Petroleum Geologists Bulletin, v. 84, p. 1743–1774, doi: 10.1306/8626C37F-173B-11D7-8645000102C1865D.

Gerstenhauer, A., 1987, Kalkkrusten und Karstformenschatz auf Yucatan/Mexico: Erdkunde, v. 41, p. 30–37, doi: 10.3112/erdkunde.1987.01.03.

Gulick, S.P.S., Barton, P.J., Christeson, G.L., Morgan, J.V., McDonald, M., Mendoza-Cervantes, K., Pearson, Z.F., Surendra, A., Urrutia-Fucugauchi, J., Vermeesch, P.M., and Warner, M.R., 2008, Importance of pre-impact crustal structure for the asymmetry of the Chicxulub impact crater: Nature Geoscience, v. 1, p. 131–135, doi: 10.1038/ngeo103.

Hildebrand, A.R., Penfield, G.T., Kring, D.A., Pilkington, M., Camargo, A., Jacobsen, S.B., and Boynton, W.V., 1991, Chicxulub Crater—A possible Cretaceous/Tertiary boundary impact crater on the Yucatán Peninsula, Mexico: Geology, v. 19, p. 867–871, doi: 10.1130/0091-7613(1991)019<0867:CCAPCT>2.3.CO;2.

Hildebrand, A.R., Pilkington, M., Connors, M., Ortiz-Aleman, C., and Chavez, R.E., 1995, Size and structure of the Chicxulub crater revealed by horizontal gravity gradients and cenotes: Nature, v. 376, p. 415–417, doi: 10.1038/376415a0.

Hodell, D.A., Quinn, R.L., Brenner, M., and Kamenov, G., 2004, Spatial variation of strontium isotopes (Sr-87/Sr-86) in the Maya region: A tool for tracking ancient human migration: Journal of Archaeological Science, v. 31, p. 585–601, doi: 10.1016/j.jas.2003.10.009.

Instituto Nacional de Estadistica, Geografia, e Informatica [INEGI], 1984, Carta Geologica, sheets Tizimin F16-7, Calcini F15-9-12, Merida F16-10: Ciudad de México, scale 1:250,000.

Instituto Nacional de Estadistica, Geografia, e Informatica [INEGI], 1989, Carta Geologica, sheet Merida: Ciudad de México, scale 1:1,000,000.

Isphording, W.C., 1975, The physical geology of Yucatan: Gulf Coast Association of Geological Societies Transactions, v. 25, p. 231–262, doi: 10.1306/A1ADD8E6-0DFE-11D7-8641000102C1865D.

Keller, G., Adatte, T., Berner, Z., Harting, M., Baum, G., Prauss, M., Tantawy, A., and Stueben, D., 2007, Chicxulub impact predates K-T boundary: New evidence from Brazos, Texas: Earth and Planetary Science Letters, v. 255, p. 339–356, doi: 10.1016/j.epsl.2006.12.026.

Lopez Ramos, E., 1975, Geological summary of the Yucatan Peninsula, the Gulf of Mexico and the Caribbean, *in* Nairn, A.E.M., and Stehli, F.G., eds., The ocean basins and margins, Volume 3: The Gulf of Mexico and the Caribbean: New York, Plenum Press, p. 257–282.

Milbrath, S., and Peraza Lope, C., 2003, Revisiting Mayapan—Mexico's last Maya capital: Ancient Mesoamerica, v. 14, p. 1–46, doi: 10.1017/S0956536103132178.

Morgan, J., Christeson, G., Gulick, S., Grieve, R., Urrutia, J., Barton, P., Rebolledo, M., and Melosh, J., 2007, Joint IODP/ ICDP scientific drilling of the Chicxulub impact crater: Scientific Drilling, v. 4, p. 42–44, doi: 10.2204/iodp.sd.4.11.2007.

Penfield, G.T., and Camargo, Z.A., 1981, Definition of a major igneous zone in the central Yucatan Platform with aeromagnetics and gravity [abs.]: Society of Exploration Geophysicists 51st annual meeting: Tulsa, Oklahoma, Society of Exploration Geophysicists Technical Program, Abstracts and Biographies, v. 51, p. 37.

Perry, E., Marin, L., McClain, J., and Velazquez, G., 1995, Ring of cenotes (sinkholes), northwest Yucatan, Mexico: Its hydrologic characteristics and possible association with the Chicxulub impact crater: Geology, v. 23, p. 17–20, doi: 10.1130/0091-7613(1995)023<0017:ROCSNY>2.3.CO;2.

Perry, E., Paytan, A., Pedersen, B., and Velazquez-Oliman, G., 2009, Groundwater geochemistry of the Yucatan Peninsula, Mexico: Constraints on stratigraphy and hydrogeology: Journal of Hydrology, v. 367, p. 27–40, doi:10.1016/j.jhydrol.2008.12.026.

Pope, K.O., Ocampo, A.C., and Duller, C.E., 1991, Mexican site for K/T impact crater?: Nature, v. 351, p. 105–105, doi: 10.1038/351105a0.

Pope, K.O., Ocampo, A.C., and Duller, C.E., 1993, Surficial geology of the Chicxulub impact crater, Yucatan, Mexico: Earth, Moon, and Planets, v. 63, p. 93–104, doi: 10.1007/BF00575099.

Pope, K.O., Ocampo, S.C., Kinsland, G.L., and Smith, R., 1996, Surface expression of the Chicxulub crater: Geology, v. 24, p. 527–530, doi: 10.1130/0091-7613(1996)024<0527:SEOTCC>2.3.CO;2.

Price, T.D., Burton, J.H., and Bentley, R.A., 2002, The characterization of biologically available strontium isotope ratios for the study of prehistoric migration: Archaeometry, v. 44, p. 117–135, doi: 10.1111/1475-4754.00047.

Price, T.D., Burton, J.H., Fullagar, P.D., Wright, L.E., Buikstra, J.E., and Tiesler, V., 2008, Strontium isotopes and the study of human mobility in ancient Mesoamerica: Latin American Antiquity, v. 19, p. 167–180.

Servicio Geológico Mexicano, 2007, Carta geológico-minera; Estados de Campeche, Quintana Roo y Yucatán, México, scale 1:500,000: http://www.coremisgm.gob.mx (January 2009).

Ward, W.C., Keller, G., Stinnesbeck, W., and Adatte, T., 1995, Yucatan subsurface stratigraphy—Implications and constraints for the Chicxulub impact: Geology, v. 23, p. 873–876, doi: 10.1130/0091-7613(1995)023<0873:YNSSIA>2.3.CO;2.

Wright, L.E., 2007, Ethnicity and isotopes at Mayapán: Grantee Report: Crystal River, Florida, Foundation for the Advancement of Mesoamerican studies, Inc. (FAMSI), 10 p., http://www.famsi.org/reports/05068/05068Wright01.pdf.

Manuscript received 3 February 2009
Revised manuscript received --
Manuscript accepted 31 March 2009

Printed in USA