GSA Data Repository Item **2014123** accompanies Gastil, R.G., Kimbrough, D.L., Kimbrough, J.M., Grove, M., and Shimizu, M., 2014, The Sierra San Pedro Mártir zoned pluton, Baja California, Mexico, *in* Morton, D.M., and Miller, F.K., eds., Peninsular Ranges Batholith, Baja California and Southern California: Geological Society of America Memoir 211, p. 739–758, https://doi.org/10.1130/2014.1211(24).

DATA REPOSITORY - The Sierra San Pedro Mártir Zoned Pluton, Baja California, Mexico

R. Gordon Gastil[1], David L. Kimbrough[2], Joan M. Kimbrough[2], Marty Grove[3], and Masaaki Shimizu[4]

[1]*published posthumously*

[2]*Department of Geological Sciences, San Diego State University, San Diego, CA 921821020*

[3]*Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305*

[4]*Graduate School of Science and Engineering, University of Yoyama, Japan*

INTRODUCTION

The Data Repository includes 1) sample locations and mineral modes determined from stained slabs (Table 1) and thin sections (Table 2), 2) a description of U/Pb geochronology analytical methods and data tables for monazite data (Table 3) and zircon data (Table 4), 3) a database of microprobe mineral analyses from Masaaki Shimizu collected using a Jeol 733 electron microprobe analyzer at the Ocean Research Institute, University of Tokyo. The microprobe data includes ~1637 individual analyses from 63 samples collected from the Sierra San Pedro Mártir (SSPM) pluton, other plutons in the Peninsular Ranges batholith, and ten samples from the Sierra Nevada batholith. The microprobe data includes a summary index table with sample localities (Table 5) and analytical results (Table 6), and 4) a section detailing mineral occurrences and variations within the SSPM that includes 4 Tables (plagioclase, quartz, K-feldspar and biotite).

GEOCHRONOLOGY

Here we present new U/Pb zircon and monazite data for seven samples from the SSPM.

Sample locations and a summary of the U/Pb ages are presented in Table 1 of the paper. The U/Pb data consist of monazite ages determined by conventional thermal ionization mass spectrometry (TIMS) isotope dilution techniques at San Diego State University using a VG Sector 54 multicollector, and zircon ages determined by secondary ion mass spectrometry (SIMS) analyses at the University of California at Los Angeles using a Cameca 1270. The TIMS monazite analyses were conducted on multiple fractions of multigrain highly purified populations. The SIMS data were collected on populations of single hand-picked grains.

Samples averaging c. 25 kg in weight were pulverized using a jaw crusher and roller mill. Heavy minerals were then concentrated using a Wilfley Table, heavy liquids, and a Frantz magnetic separator. Analytical methods employed in TIMS analyses follow Kimbrough et al. (1992; 1994). Monazite separates were split into size fractions and handpicked to remove any contaminating grains. Monazite dissolution and ion exchange chemistry for separation of U and Pb followed procedures modified from Krogh (1973). U and Pb concentrations were determined using a mixed ^{235}U-^{208}Pb tracer. Isotopic ratios were measured with the VG Sector 54 multicollector instrument at San Diego State University. Errors for $^{206}Pb/^{204}Pb$ measurements were minimized by use of an ion counting Daly multiplier. Analytical uncertainties, blanks, and common Pb corrections are outlined in Table 3 below.

For the ion probe samples, suitable zircon grains for analysis grains were individually selected under a binocular microcope. The grains were mounted along with standards in 1" diameter epoxy plugs and polished to expose the interiors of the grains. Mounts were then cleaned with soap and water and immersed in a cleaning solution (2% HNO_3 and 1% 35 HCl) in an ultrasonic cleaner for a few minutes, followed by rinsing with water and final cleaning with isopropyl alcohol using a Kimwipe. The samples were analysed using a Cameca ims 1270 ion microprobe following methods described in Grove et al. (2003). The analytical data are reported in Table 4 below.

Igneous age assignments for the SIMS results are determined from overlapping $^{206*}Pb/^{238}U$ ages. The Th/U ratios for all of the zircons are greater than or equal to 0.1 consistent with the empirically derived cutoff used to identify igneous zircon grains in the Peninsular Ranges batholith (Grove et al., 2008). The total analytical uncertainty for ages reported here represents the quadratic sum of the weighted mean measurement error and systematic error. Systematic error includes contributions from calibration correction, uncertainty in age of the calibration standard, composition of common Pb, and uncertainty in the ^{238}U decay constant and is generally ~1-2% (2σ).

References

Grove, M., Jacobson, C.E., Barth, A., and Vucic, A., 2003, Temporal and spatial trends of Late Cretaceous-Early Tertiary underplating of Pelona and related schist beneath southern California and southwestern Arizona, Geological Society of America Special Paper 374, p. 381-406.

Grove, M., Bebout, G.E., Jacobson, C.E., Barth, A.P., Kimbrough, D.L., King, R.L., Zou, H., Lovera, O.M., Mahoney, J.B., and Gehrels, G.E., 2008, The Catalina Schist: Evidence for mid-Cretaceous subduction erosion of southwestern North America, *in* Draut, A.E., Clift, P.D., and Scholl, D.W., eds., Formation and Applications of the Sedimentary Record in Arc Collision Zones: Geological Society of America Special Paper 436, p. 335–362.

Kimbrough, D.L., Tulloch, A.J., Coombs, D.S., Landis, C.A., Johnston, M.R., and Mattinson, J.M., 1994, Uranium-lead zircon ages from the Median Tectonic Zone, South Island, New Zealand: New Zealand Journal of Geology and Geophysics, v. 37, p. 393-419.

Kimbrough, D.L., Mattinson, J.M., Coombs, D.S., Landis, C.A., and Johnston, M.R., 1992, Uranium-lead ages from the Dun Mountain ophiolite belt and Brook Street Terrane, South Island, New Zealand: Geological Society of America Bulletin, v. 104, p. 429-443.

Krogh, T.E., 1973, A low contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic determination. Geochimica et Cosmochimica Acta, v. 46, p. 631-635.

Ludwig, K.R., 2008, Isoplot 3.60. Berkeley Geochronology Center, Special Publication No. 4, 77p.

Mattinson, J.M., 2005, Zircon U-Pb chemical abrasion ("CA-TIMS") method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages: Chemical Geology, v. 220, p. 47-66.

Stacey, J.S., and Kramers, J.D., 1975, Approximation of terrestrial lead isotope evolution by a two-stage model: Earth and Planetary Science Letters, v. 26, p. 207-221, doi:10.1016/0012-821X(75)90088-6.

DATA REPOSITORY TABLES 1-6

MINERAL OCCURENCE & VARIATION, SIERRA SAN PEDRO MÁRTIR PLUTON

Plagioclase

The abundance of plagioclase ranges from 37% to 59% across the whole rock geochemistry traverse (Table 7). The most calcic plagioclase is found in the outer 1 to 1.5 km of the hornblende zone where the crystals average An 39 in their cores and An 30 at their rims. Within this outer margin of the pluton, the plagioclase content averages 55%.

Plagioclase grains are typically complexly zoned. The size of euhedral to subhedral crystals ranges from 0.5-mm to 7-mm, averaging 3-mm in the hornblende and biotite zone. Smaller, 0.1-mm to 3-mm euhedral to subhedral grains show greater complexity in the compositional zonation. There is an increase in oscillatory zoning and “convolute” zoning (Mackenzie and others, 1982), as well as many intergrown grains. There is no obvious evidence of restite crystals or albitization in plagioclase across the traverse. Sericite occurs locally. Small proportions of plagioclase grains appear to be partially altered to low-birefringence epidote, white mica, and traces of calcite. Accessory minerals within the plagioclase crystals include apatite, zircon, opaque minerals, and allanite.

TABLE 7. PLAGIOCLASE

Mineral Zone	Range % plagioclase in mode	Average % plagioclase	An
Outer 1.0-1.5 km sphene-hornblende biotite tonalite	50-58	55	39-30
Sphene-hornblende-biotite tonalite	46-59	52	33-26
Sphene-biotite tonalite/granodiorite	50-53	51	31-23
Muscovite-biotite granodiorite	39-52	48	29-26
Core muscovite-biotite tonalite/granodiorite	44-52	48	33-26

Notes: Rocks were sawed into slabs and stained. The stained side was point-counted ~600 counts. The unstained side was then counted for opaque minerals. The proportion of those (hornblende, biotite and minor minerals) was obtained by counting under the petrographic microscope.

Quartz

Quartz (Table 8) is the second most abundant mineral in the SSPM pluton. In the western marginal zone of the pluton, quartz grains occur as 0.5 to 2 mm interstitial grains between feldspar and other crystals. Within the sphene-hornblende-biotite zone, quartz crystals range in size from 0.5 to 8 mm, averaging 3 to 4 mm. They are discrete subhedral crystals with few inclusions. At a few locations within the hornblende tonalite zone there are rounded quartz grains of 4 to 9 mm, averaging 6 mm, in addition to smaller subhedral crystals. Many of the rounded grains show undulatory extinction and fracturing.

The muscovite-bearing granodiorite zone also has two quartz populations, the first are clear, anhedral to subhedral, commonly interstitial quartz grains, ranging from 2 to 6 mm and averaging 5 mm. The early populaton is semi-spherical grains, appear more abundant, and have an average diameter of 7 to 8 mm. These large crystals give a knobby appearance to weathered rock exposures and collect on the ground like marbles. Plagioclase, biotite, muscovite, apatite and zircon crystals are present as inclusions within the subspherical quartz crystals. Large (5 to 8 cm) quartz enclaves are distributed widely throughout the muscovite-bearing zones.

TABLE 8. QUARTZ

Zones	Range % quartz	Average % quartz
Outer 1.5-km sphene-hornblende biotite tonalite (marginal zone)	23-25	25
Sphene-hornblende-biotite tonalite	23-31	28
Sphene-biotite tonalite/granodiorite	27-35	31
Muscovite-biotite granodiorite	26-35	31
Core muscovite-biotite tonalite/granodiorite	33-38	35

Potassium Feldspar

Overall, the K-feldspar percentage across the pluton is low (Table 9). The average in the sphene-hornblende-zone is 4%, in the biotite zone 6%, in the muscovite zone 11%, and in the core zone 6%. In the outer marginal zone of the sphene-hornblende-biotite zone, K-feldspar content dips as low as 1 to 2%, and is present as isolated late interstitial crystals. Several outcrops of granodiorite, with an average K-feldspar content of 7 %, and crystals ranging up to 4 mm, occur within this outer margin of the pluton. The exact relationship of the granodiorite to the tonalite is unclear.

Within the main body of the sphene-hornblende-biotite tonalite, K-feldspar occurs mainly as interstitial grains. In a few widely scattered samples, the K-feldspar had begun to organize into sparse irregular oikocrysts with maximum dimensions of 1.5- to 2.0-cm. These oikocrysts are not well enough developed to be visible in hand sample, but are visible in stained slabs. The orientation of the oikocrysts is visible in thin-section. The total K-feldspar content of these oikocrysts of K-feldspar ranges from 20 to 25%.

In the biotite zone the abundance of oikocrysts increases as the K-feldspar content increases. A few oikocrysts are recognizable in hand sample. Their grain boundaries are irregular. They range from 1 cm to 2 cm x 3 cm, with K-feldspar making up 25 to 30% of the oikocryst. There is a tendency toward alignment of these oikocrysts, suggesting that there may be a foliation not readily recognized in the field.

Within the muscovite zone, the microcline occurs as 0.1-mm to 1.5-mm interstitial crystals and as oikocrysts up to 2.5 cm or more in diameter, enclosing all other minerals. The larger oikocrysts contain 30 to 50% K-feldspar. Many smaller oikocrysts (approximately 1 cm) with 80-95% K-feldspar have reasonably well-formed boundaries and are easily recognized in hand sample. In the core zone, microcline tends to be more evenly distributed.

The presence of oikocrysts rather than discrete K-feldspar crystals is not unique to the SSPM pluton, but is observable in stained slabs and hand samples from other La Posta-type plutons.In the Laguna Juarez pluton, where the potassium content is higher, the oikocrysts give way to K-feldspar megacrysts with abundant inclusions (Gunn, 1984).

TABLE 9. POTASSIUM FELDSPAR

Zone	% K-feldspar	Average % K-feldspar
Outer sphene-hornblende-biotite tonalite	1-8	4
Sphene-biotite tonalite/granodiorite	4-7	6
Muscovite-biotite granodiorite	7-14	11
Core muscovite-biotite tonalite/granodiorite	5-7	6

Hornblende

Hornblende occurs only in the sphene-hornblende-biotite tonalite zone with an average content of 0.3%. Hornblende averages 8% in the outer 1.0 to 1.5-km-wide marginal zone and drops off abruptly to 0.3% and ranges inward to 0.5%. The dark green crystals are commonly idiomorphic, embayed, and inclusion-rich. They range in size up to 1 cm in length. Locally, hornblende is partially replaced subsolidus by biotite, epidote, and chlorite. Hornblende crystals commonly enclose crystals of magnetite, apatite, zircon, and lesser amounts of sphene and plagioclase. Yellow to light- or blue-green pleochroism is observed.

Biotite

Biotite is present in every sample, averaging 11% to 13% in the sphene-hornblende zone: 11% in the biotite zone, 7% in the muscovite-biotite zone, and 10% in the core zone (Table 10). Within the hornblende-bearing zone, biotite occurs either as 0.2-mm to 10-mm grains or as 0.5- to 1-cm books. Biotite is also found as pseudomorphs partially or totally replacing hornblende. The abundance of biotite replacement of hornblende, increases inward across the sphene-hornblende-biotite-tonalite zone.

Biotite grains within the biotite zone tend to be smaller, generally less than 0.5 cm. In this zone, biotite pseudomorphs (which completely replace hornblende) range up to 2 cm and mark the transition from the hornblende to the biotite zone. Thin-section examination of samples within the biotite zone reveals that there is commonly some relic hornblende in all the biotite zone samples. The transition between these two zone is gradational.

In the muscovite zone, biotite rarely occurs in books, but rather as individual flakes (commonly 1 to 2 mm), although crystals as large as 4 mm can be found. Within the muscovite-bearing core zone the percentage of biotite increases, although grain size remains small. Magnetite crystals are present as inclusions within the biotite crystals in both the hornblende and biotite zone, though inclusions in biotite are more common in rocks that lack hornblende. Zircon and monazite are also found as inclusions in biotite. There is some subsolidus alteration to epidote, chlorite and sphene.

TABLE 10. BIOTITE

Zone	Range % biotite	Average % biotite
Outer 1.0 to 1.5 km sphene-hornblende-tonalite	11-14	13
Sphene-hornblende-biotite tonalite	8-16	12
Biotite tonalite/granodiorite	10-11	11
Muscovite-biotite granodiorite	6-12	7
Core muscovite-biotite tonalite/granodiorite	8-11	10

Muscovite

The visible presence of muscovite in the field is the criterion used to discriminate the two muscovite-bearing map units. In the muscovite-biotite zone, the abundance of muscovite ranges to 3%, although the average modal percent for the zone is approximately 1.5%. Crystals of muscovite are generally idiomorphic, suggesting primary magmatic occurrence. They rarely exceed 2 mm. A few muscovite grains are crystallized in parallel with biotite.

Muscovite crystals in the core zone are not visible in hand specimen, are generally less than 1 mm, and may be secondary in origin. The modal percent of muscovite in these rocks (seen in thin-section) ranges from 0 to 0.5%.

Sphene

Sphene is easily recognized in hand sample and is a common accessory mineral in La Posta-type plutons (Walawender et al., 1990). Primary sphene crystals, commonly idiomorphic, and up to 0.5 cm in length are present throughout the hornblende and biotite zone (range 0-2.5%, averaging 0.7%). Sphene is also found as mottled or embayed crystals and as inclusions within hornblende. Variation in the color of large sphene crystals is recognizable in the field under a hand lens. Sphene in the more calcium-rich rocks are a pale reddish-brown, whereas those in calcium-poor rocks have a yellowish-green hue. Some samples contain both yellow and green sphene. Primary sphene may contain inclusions of apatite, zircon, and opaque minerals. The color contrast is similar to that seen in bicolor gem sphene.

Selected 45 kg samples from the hornblende-bearing zone yielded sphene concentrations up to 0.6 wt% of the sample. Not recognizable in hand sample is secondary sphene, largely after biotite, which is present throughout the pluton and can be found in mineral concentrate from even the muscovite-bearing rocks. The amount of secondary sphene concentrated from one core zone sample was 0.044 wt%. The secondary sphene differs from the primary sphene in that it is completely nonmagnetic, whereas primary sphene from the hornblende and biotite zone is magnetic.

Sphene also occurs as a distinct phase in dikes found most commonly within the sphene-hornblende-biotite tonalite zone, but also within the biotite tonalite/granodiorite zone. These dikes are commonly a meter wide, with a mineral composition similar to their wall-rock, but containing sphene-rich spots. These "spots" are ovoid, about 1 cm in diameter, and consist mostly of plagioclase and quartz with a poikilitic core of pale sphene. The ovoid spots are commonly flattened parallel to the dike walls, suggesting magmatic flow foliation. Similar sphene "spots" have been reported from other La Posta-type plutons (Hill, 1984; Stensrud, 1978) and are reported from plutons around the world (Lacroix, 1900).

Opaque Minerals

Common opaque minerals within the pluton include magnetite, hematite and ilmenite. Primary magnetite crystals are found as inclusions within hornblende and biotite. Locally, where magnetite is abundant, a rim of green epidote occurs around the magnetite; and may be of secondary origin (Miklic, 1991). The part of the pluton which contains both magnetite-bearing and magnetite-free rocks (Figures 6 and 7), may have resulted from an incomplete alteration of original magnetite (Diamond and Frost, 1990; Diamond, 1989). Small amounts of ilmenite are present throughout the pluton. Ilmenite occurs in both magnetite-bearing rocks and magnetite-free rocks. One grain of titanium oxide (probably rutile) was identified by electron microprobe in the hornblende zone.

In a few localities within the hornblende zone of the pluton, dikes contain not only sphene "spots," but also magnetite "spots." The magnetite-bearing ovoids (typically about 1-cm in diameter) contain a single idiomorphic crystal of magnetite, about 3 mm in diameter. In some localities a small amount of green epidote is present on the outer surface of the magnetite crystal. Magnetite and sphene rarely occur together in a single spot. Magnetite spots have been observed in other La Posta-type plutons and there is at least one report in the literature (Trumbull, 1988).

Allanite

Slender, faceted, dark-gray crystals of an allanite, up to 1 cm in length, have been found in both the inner sphene-hornblende and sphene-biotite zone. Although allanite crystals appear most common in the sphene-biotite zone, they have been identified in thin-section from rocks near the outer margin of the core zone. In mineral concentrates they make up 67-111 ppm of the hornblende and biotite zone, and one gram (20 ppm) or less in the muscovite-bearing zone. Under the microscope, they are idiomorphic and concentrically zoned with brown-orangish hues. Very common is an outer rind of green epidote (colorless in thin-section). A green epidote rind around allanite was also noted by Hill in the Mount San Jacinto pluton (1984). Allanite has been identified in several other La Posta-type plutons, both in the field and under the microscope. A coating of green epidote gives the allanite concentrate a greenish color and makes quantitative identification more difficult.

Zircon

Zircon is present in all parts of the pluton, but is more abundant in the outer sphene-hornblende-biotite tonalite zone and least abundant in the muscovite and core zone, where monazite is also present. Between one and eight grams of zircon (20-180 ppm) were concentrated from each of the 45-kg samples of the hornblende and biotite zone rocks, and less than a gram (20 ppm) from the muscovite-bearing zone.

Monazite

Monazite in the SSPM pluton has been found only in rocks containing muscovite. It is distinguishable in thin-section from zircon by the heavier radiation damage. The crystals are red, idiomorphic, and distinctly larger than zircon crystals.

Apatite

Apatite is observed in every thin-section but is more abundant in the hornblende and biotite zone relative to the muscovite zone.

Epidote and Chlorite

This anomalously birefringent yellow-green epidote, usually accompanied by green chlorite, is common throughout the SSPM pluton. Most of these are clearly replacing preexisting crystals. Epidote also occurs as a thin rind on primary allanite and magnetite crystals. A few crystals of epidote may be primary.

Augite

Trace amounts of green augite have been identified by X-ray diffraction in heavy mineral concentrates from two samples. One is from a road cut at the eastern boundary of the pluton (VO-6, location at intersection Observatory Road and eastern margin of pluton), and the second is from a sphene-spotted dike (locality H 0.9-14.5). Pyroxene has not previously been reported from La Posta-type plutons.

Magnetite

The magnetite content of the pluton was investigated using an Urtec magnetic susceptibility meter. The sphene-hornblende-biotite zone of the SSPM pluton is magnetite-bearing. This is in direct contrast to other La Posta-type plutons which are magnetite-free (Gastil et al., 1990). In SSPM, the greater magnetite content occurs along the western side of the sphene-hornblende-biotite zone, with the exception of the outermost margin, which is essentially magnetite-free. Diamond and others (1989, 1990) concluded that the absence of magnetite in the outer margin of the pluton resulted from subsolidus alteration of magnetite to ilmenite and hematite. Inward along the traverse the next three kilometers of the sphene-hornblende tonalite zone have values that typically fall between 400 and 800 SI units. Inward from km 4 of the traverse, the magnetic susceptibility values vary widely from near 0 to 500 SI units. An abrupt change from magnetite-bearing to magnetite-free rocks occurs within the muscovite-biotite tonalite/granodiorite.

Enclaves relatively rich in mafic minerals, up to a meter in diameter, are locally abundant in the sphene-hornblende-biotite tonalite zone. Where magmatic foliation is pronounced, the enclaves are proportionately flattened. In the more interior portions, mafic enclaves are rare and show little flattening. The magnetite content of the enclaves varies widely: some enclaves have rims 1-3 cm in width, rich in magnetite and green epidote, in which magnetic susceptibility measures as much as 5000 $x10^{-5}$ SI units (Miklic, 1991). Other small enclaves, only a few cm in maximum dimension, measure as much as $10,000x10^{-5}$ SI units.

REFERENCES

Bateman, P.C., 1992, Plutonism in the central part of the Sierra Nevada batholith, California: U.S. Geological Survey Professional Paper 1483, 186 p.

Diamond, J.L., 1989, Mineralogical controls on rock magmatism in the Sierra San Pedro Martir pluton, Baja California, Master of Science thesis, University of Wyoming, Department of Geology and Geophysics, 77 p.

Diamond, J.L., and Frost, B.R., 1990, Mineralogical controls on rock magmatism in the Sierra San Pedro Martir pluton, Baja California, Mexico: EOS, v.69, n. 44, p. 506.

Gastil, R.G., Diamond, J.L., Knaack, D., Walawender, M.J., Marshall, M., Boyles, C., Chadwick, B., Erskin B., Davis T., and Smith, B., 1990, The problem of the magnetite-ilmenite boundary in southern and Baja California, in Anderson, J.L., ed., The Nature and Origin of Cordilleran Magmatism: Geological Society of America Memoir, 174 p., p. 19-32.

Gunn, S.H., 1984, The geology, petrography, and geochemistry of the Laguna Juarez pluton, Baja California, Mexico (Master of Science thesis), San Diego State University, 166p.

Hill, R.I., 1984, Petrology and petrogenesis of batholithic rocks, San Jacinto Mountain southern California (PhD thesis): California Institute of Technology, 660p.

Lacroix, A., 1900, Le granite dwes Pyrenees ut ses phenomenes de contact: Bulletin serv.carte geolgie de la France 11, no.71, p. 36.

Mackenzie, W.S., Donaldson, C.H., and Guilford, C., 1982, Atlas of igneous rocks and their textures: Holstead Press, John Wiley and Sons Inc., New York, 148p.

Miklic, P.A., 1991, A magnetite-enriched enclave rim, Sierra San Pedro Martir, Mexico (Senior Report), Department of Geological Sciences, San Diego State University, 32p.

Stensrud, H.L., 1978, Spotted tonalite dikes from the eastern margin of the southern California batholith: Geological Society of America Abstracts with Program, v. 10, no. 3, p.148.

Trumbull, R.B., 1988, Petrology of flecked gneisses in the northern Wet Mountains, Freemont County Colorado: GSA Bulletin, v. 100, p. 247-256.

Walawender, M.J., Gastil, R.G., Wardlaw, M., Gunn, S.H., Eastman, B.G., McCormick, W.V., and Smith, B.M., 1990, Geochemical, geochronologic, and isotopic constraints on the origin and evolution of the eastern zone of the Peninsular Ranges batholith, in Anderson, J.L. (ed.), The Nature and Origin of Cordilleran Magmatism: Geological Society of America Memoir, 174 p. 1-18.