Polymorphic authigenic carbonates and foraminifera taphonomical characteristics of a paleoseep, Southwestern Taiwan

C.-W. Chien (1), C.-Y. Huang (2), H.-C. Lee (3), S.-D. Luo (1), S.-Y. Jiang (4), and C.-H. Liu (4)

(1) Department of Earth Sciences, National Cheng Kung University, Tainan, Taiwan.

(2) Key Laboratory of Marginal Sea Geology, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, China.

(3) Department of Geosciences, National Taiwan University, Taipei, Taiwan

(4) State Key Laboratory for Mineral DepositsResearch, School of Earth Sciences and Engineering, Nanjing University, China

Several polymorphic authigenic carbonate concretions (ACCs) were preserved in the Pliocene Yenshuiken Shale of SW Taiwan foreland sequence (Fig. 1, 2, 3). Carbon isotopic signatures and morphology of these carbonates (Fig. 3) and associated chemosymbiotic bivalve fossils (Figs. 4, 5) indicated their methane seep origin. Foraminiferal fossil assemblages in host rocks represented distinctive differentiation in short distance (~40 cm) away from some large ACCs (Fig.6a, b), revealed that the taphonomic characteristics of foraminiferal assemblages were directly influenced by methane emission intensity within the paleoseep.

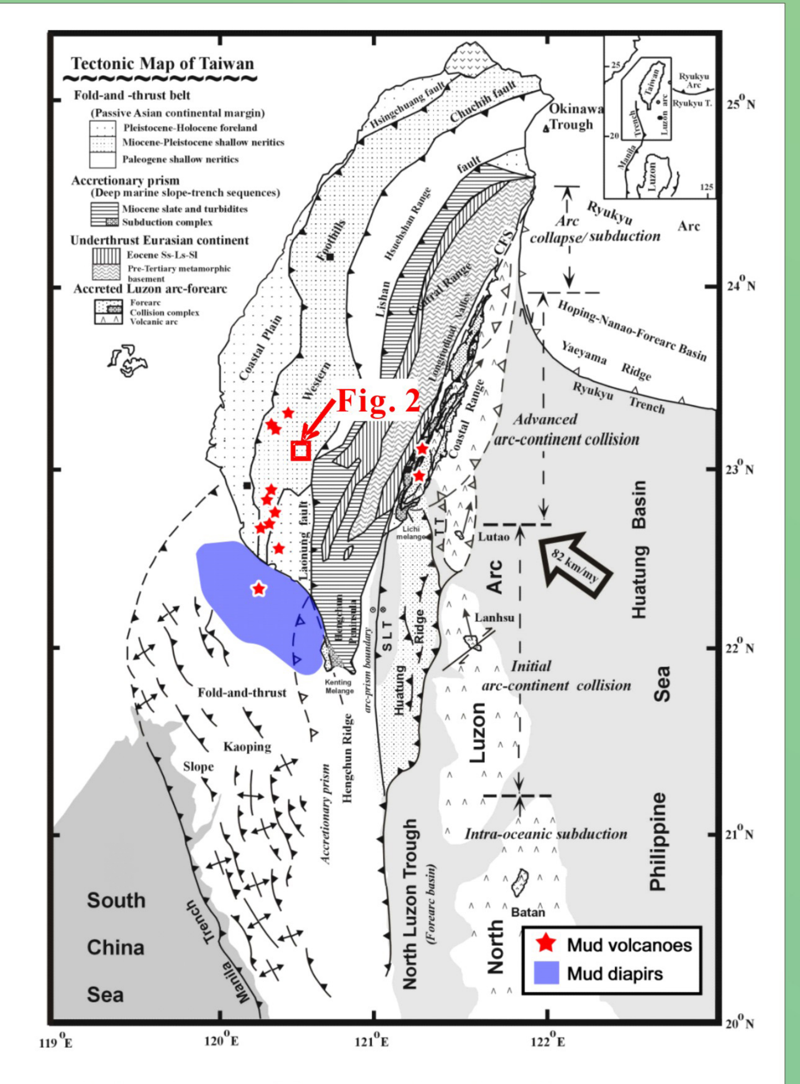


Fig. 1: Geological Map and distribution of mud volcanoes and mud diapirs of Taiwan

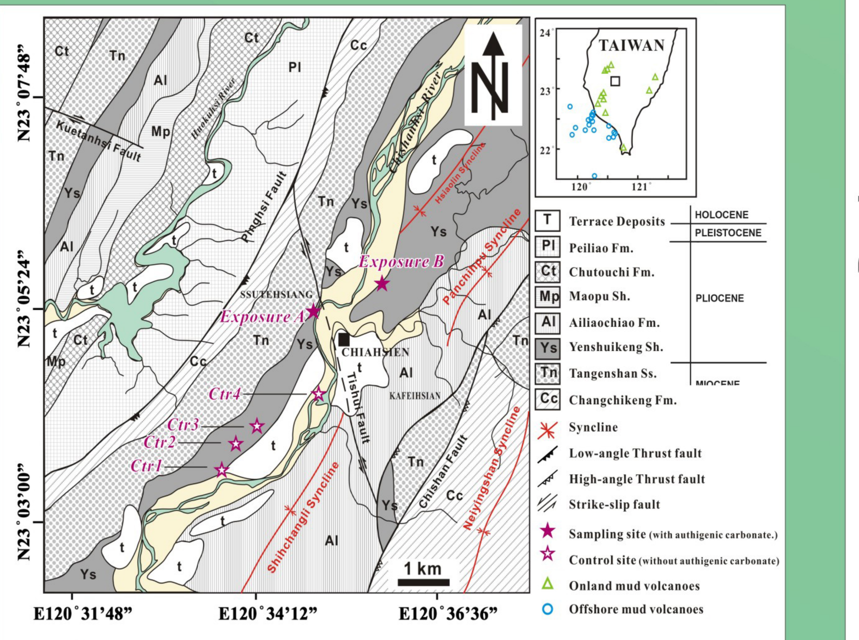


Fig. 2: Geological Map of research area. Outcrops of the Chiahsien Paleoseep mainly expose at Exposure A and B (solid purple stars).

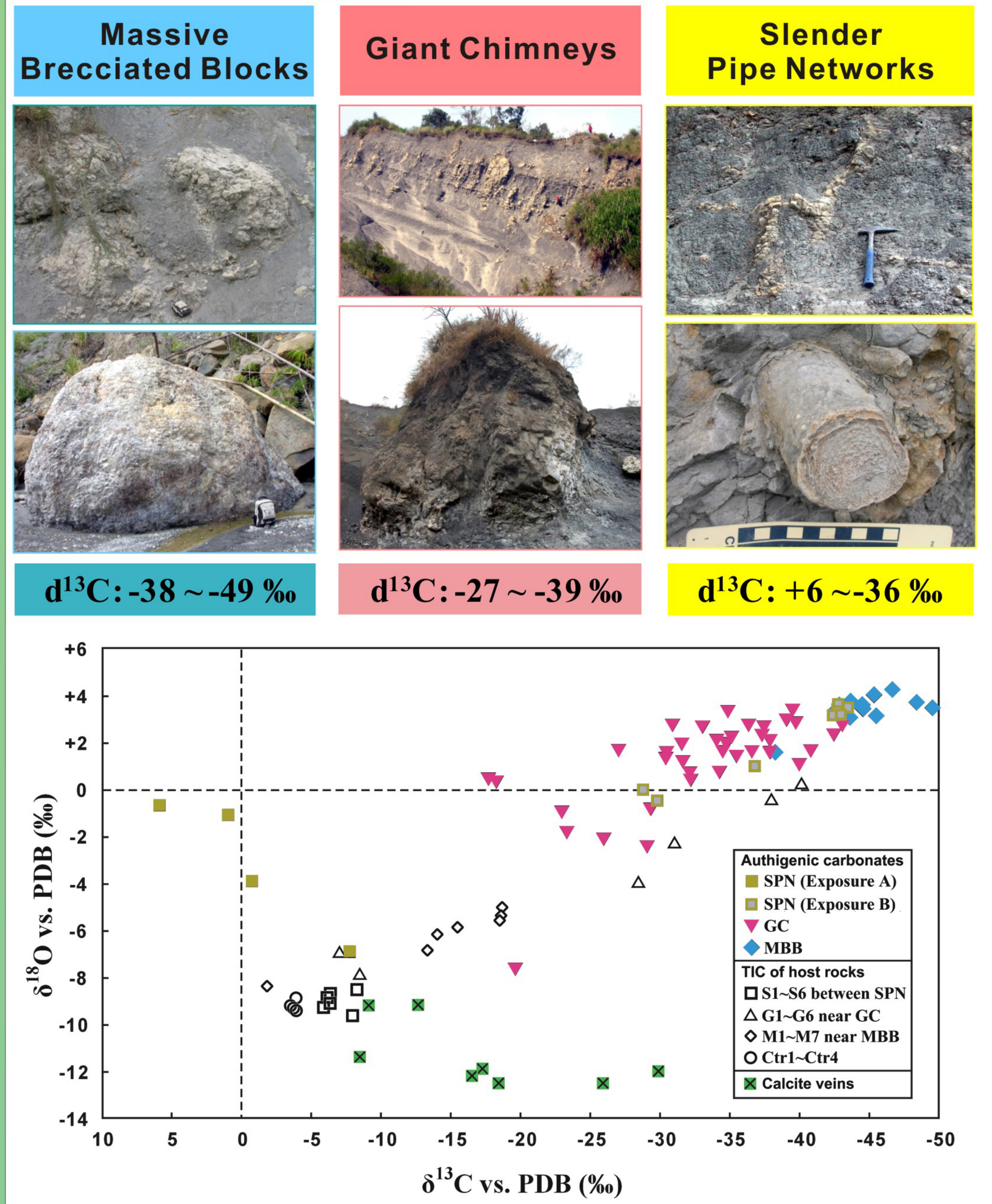


Fig. 3: Field occurrences and carbon/oxygen isotope compositions of three types of authigenic carbonate concretions of the Chiahsien paleoseep.

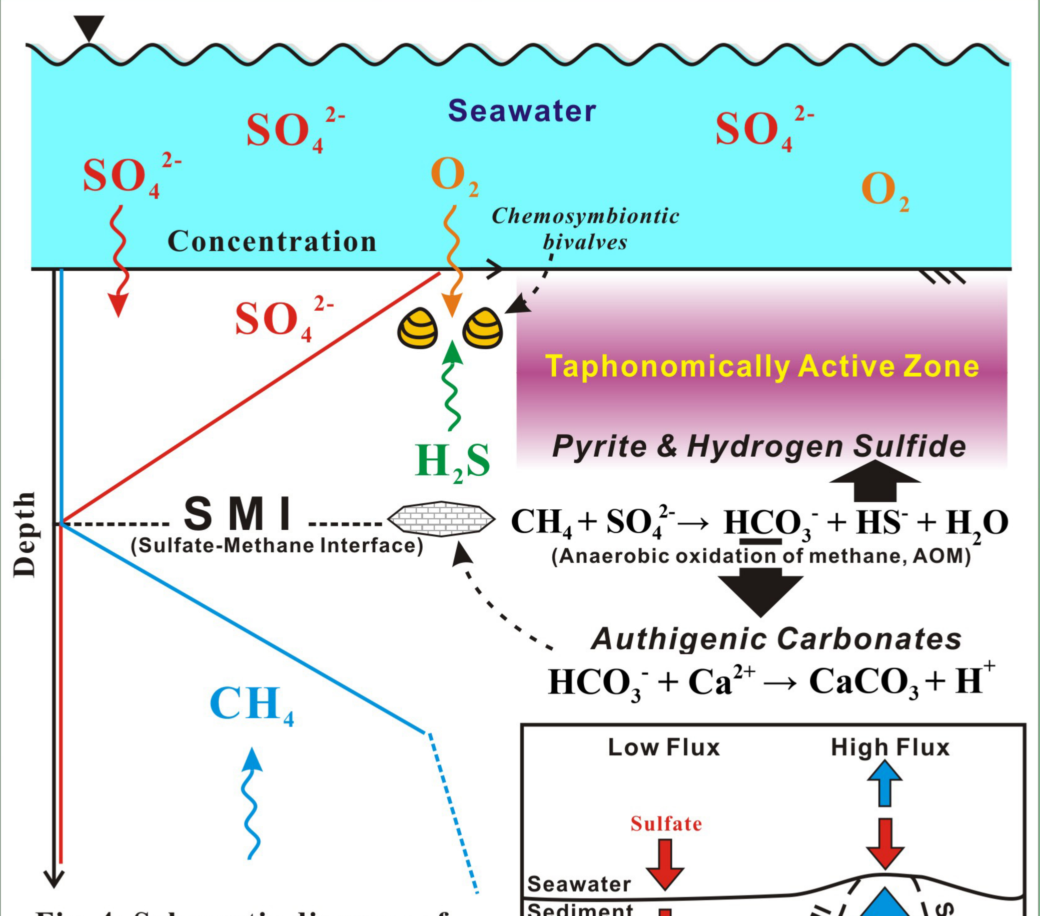
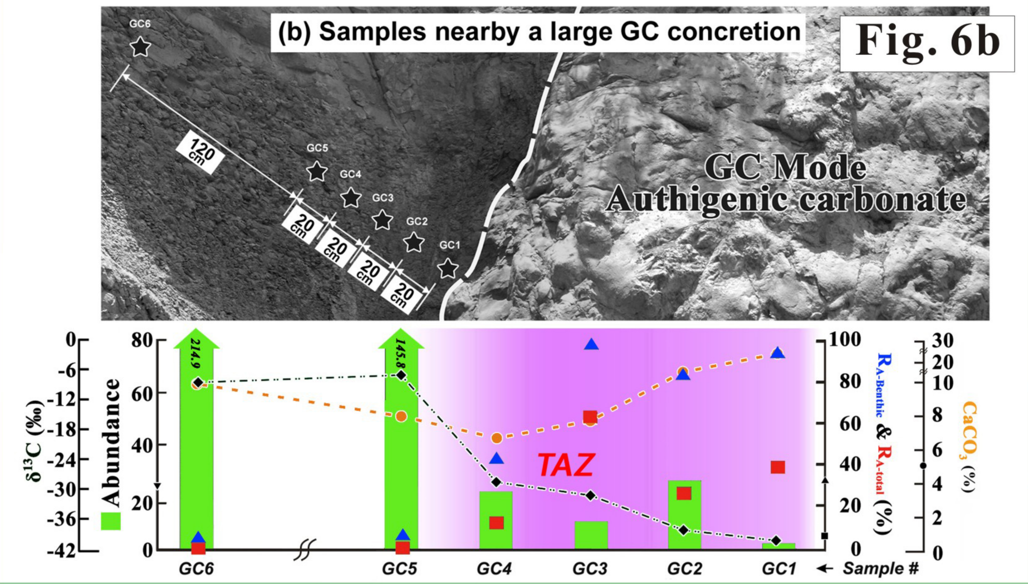
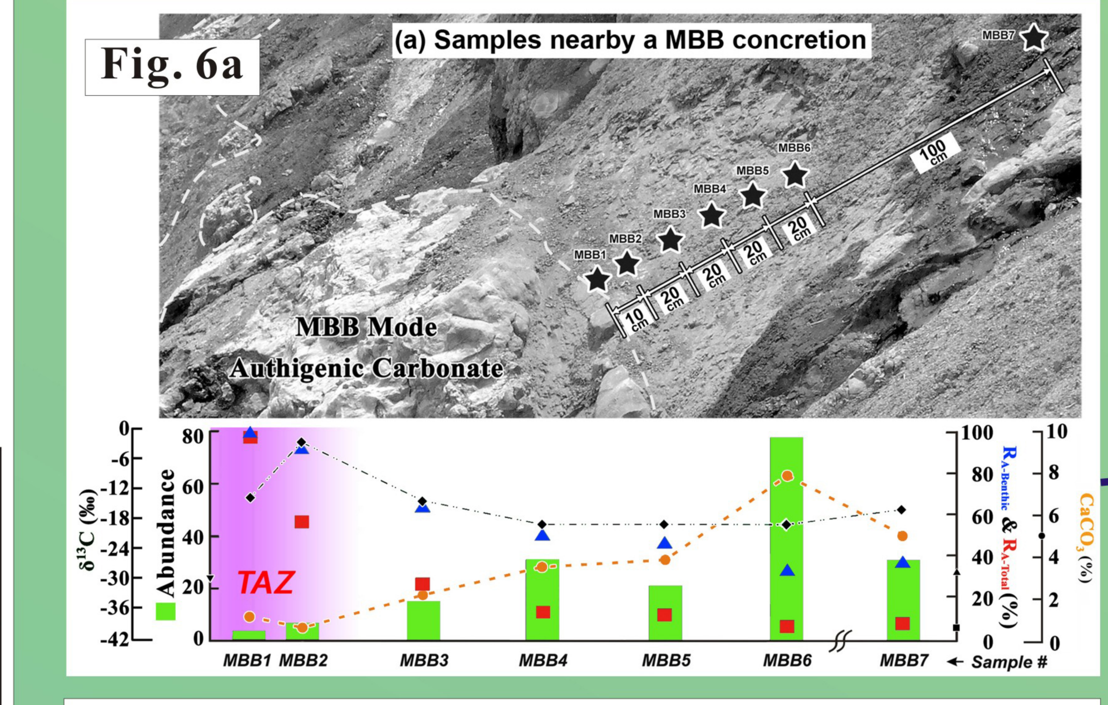


Fig. 4: Schematic diagram of geochemical interfaces and associated products in methane seeps.

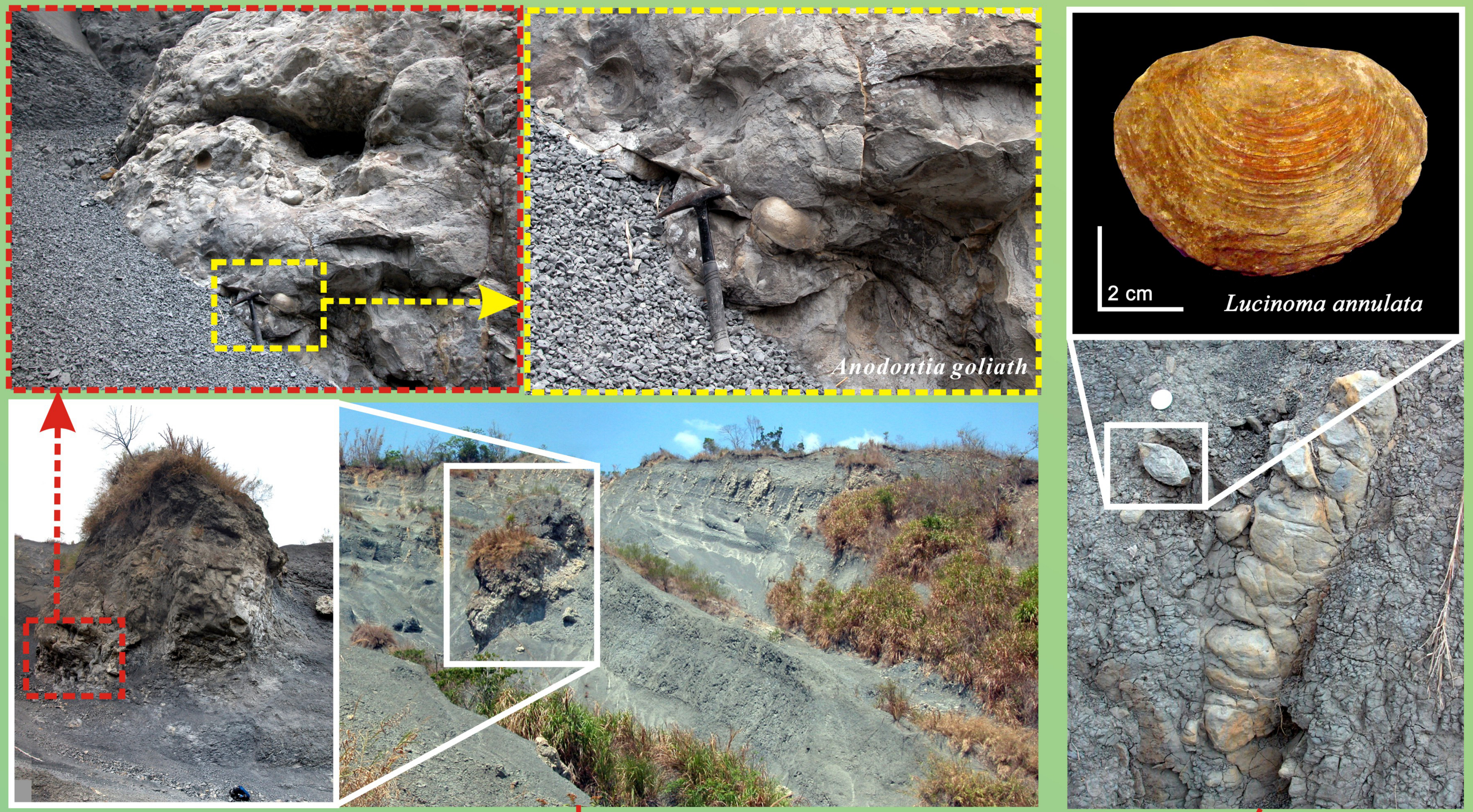
There are three modes of ACCs (Fig. 3): (I) ***Massive brecciated blocks*** (MBBs; typically 2 to 4 m long, 1 to 2 m wide, and 3 to 5 m high; $\delta^{13}C$: −49.6~−38.2‰, averagely −44.2‰) are large, whitish gray to grayish yellow colored, mound-shaped carbonate bodies, with or without vent and pipe structures, in the exposure A along the Chihshanhsi River (Fig. 5). Chemosymbiotic lucinid pelecypods *Anodontia goliath* (Yokoyama) fossils were found within MBBs; (II) ***Giant Chimneys*** (GCs; each ca. 2 to 5 m wide and 30 m high; $\delta^{13}C$: −43.1~−17.7‰, averagely −32.9‰) are large and thick cylindrical or fusiform concretions developing upwardly perpendicular to bedding in the exposure A (Fig. 5). They occur either in isolation or parallel to each other, and contain of vent/pipe structures (diameter >15 cm) clustered with irregular shaped carbonates. Abundant in situ *Anodontia goliath* (Yokoyama) fossils occurred in the margin of one large fusiform GC body (size: ca. 5 m x 5 m x 10 m; Fig. 4); and (III) ***Slender pipe networks*** (SPNs; $\delta^{13}C$: −43.5~5.9‰, averagely −25.9‰) are composed ofelongated small carbonate cylinders with a diameter commonly 5 to 15 cm. They occurred both in exposure A and B, and bank of the Chihshanhsi river. The "pipes" develop upwardly perpendicular to the host mudstone bedding, and some are branched or connected horizontally with same pipes (Fig. 5). We also found a few lucinid fossils *Lucinoma annulata* (Reeve) together with some pipes (Fig. 5).





$R_{A-Total}$: ratio of agglutinated foraminiferal individuals to total foraminiferal individuals

$R_{A-Benthic}$: ratio of agglutinated foraminiferal individuals to benthic foraminiferal individuals



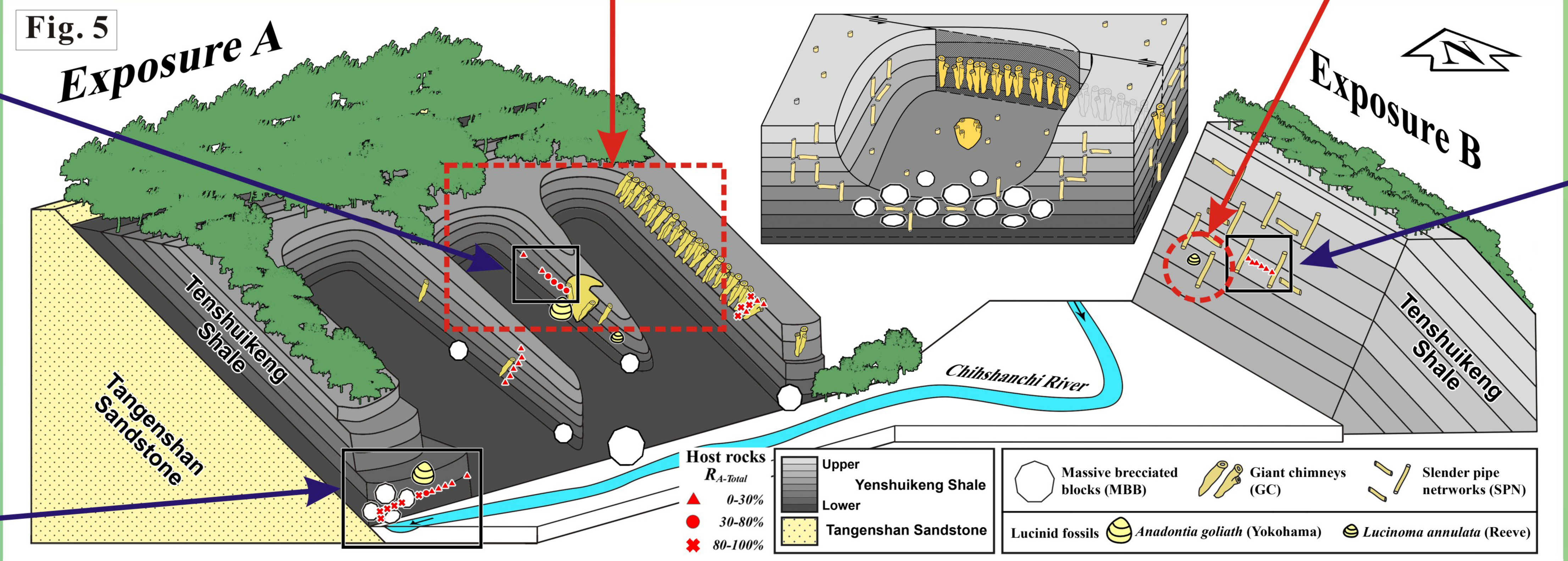
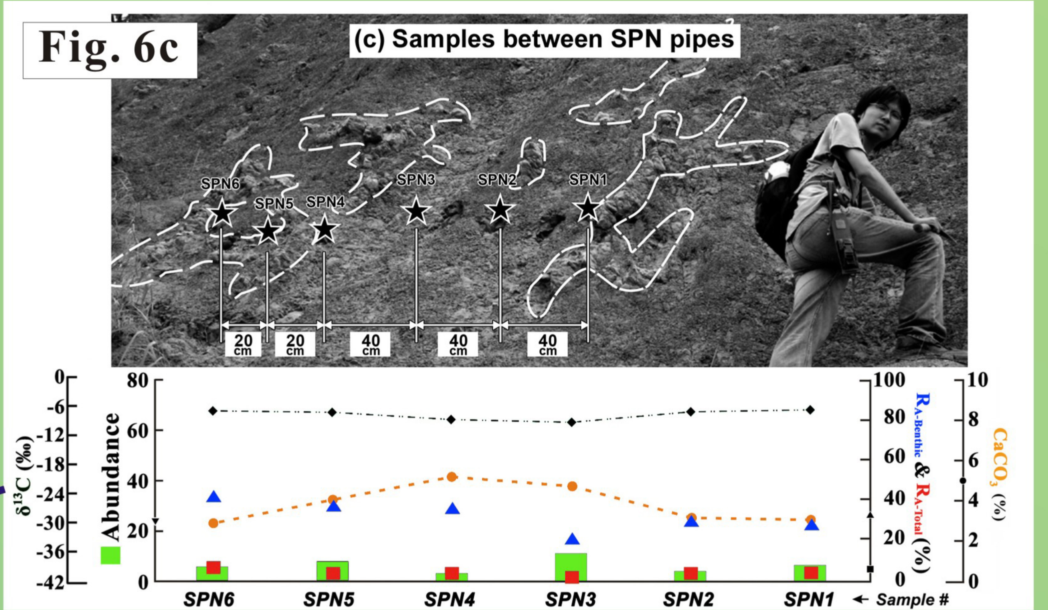


Fig. 5: Semi-schematic diagram of studied outcrops, occurrences of three types of authigenic carbonate concretions and licinid fossils, sampling locations of host rocks, and reconstructed spatial distribution of authigenic carbonate concretions. The attitude of strata is N40°E, 35°E. Dip angle and distance are not in scale.

Comparing to the non-seep controls in the Yenshuiken Shale (Fig. 6d), muddy host rocks that were <30 cm around MBBs yield low $CaCO_3$ contents (<1%), low foraminiferal abundances (<6.3 individual per gram of sediments), high percentages of agglutinated benthic foraminifera (>98%), and almost absence of calcareous foraminifera (both benthic and planktonic) (Fig. 6a); however, host rocks that were >30 cm away from MBBs yield " normal marine" assemblages (high foraminiferal abundance: 20.7-77.5 individuals/per gram of sediments; low agglutinated foraminifera percentages: <13.4%; fair $CaCO_3$ contents: 3.4-7.8%) (Fig. 6a). Host rocks that were <80 cm around GCs also yield abnormal assemblages, whereas those were >80cm away from GCs yield normal assemblages (Fig. 6b). Host rocks around and between SPNs yield consistent characteristics to control sites (Fig. 6c, d).

Absence of calcareous tests of foraminiferal fossils is due to pore water acidification within the taphonomically active zone (TAZ), which is triggered and accelerated by anaerobic oxidation of methane (AOM) in the methane seep environments (Fig. 4). We suggest that foraminiferal assemblages can be influenced by methane seep activities, therefore they can reflect and record geochemical interface (e.g. TAZ; sulfate-methane transition zone (SMTZ) or sulfate-methane interface (SMI)where AOMoccurs) shifting within paleoseeps.



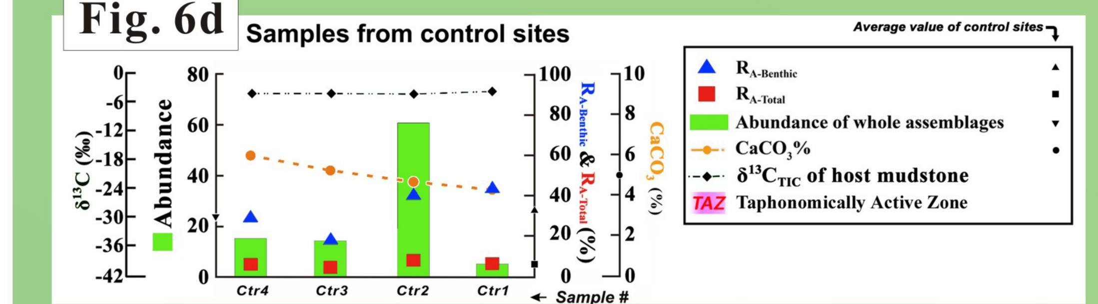


Fig. 6: Summary of foraminiferal fauna, $CaCO_3$ content, and carbon isotopic composition of total inorganic carbon of host rock samples picked adjacent to (a) a MBB and (b) a large GC, (C) between SPNs, and (d) from control sites.

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