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Diversity and evolution of secondary metabolism in the marine actinomycete genus *Salinispora*

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Access to genome sequence data has challenged traditional natural product discovery paradigms by revealing that the products of most bacterial biosynthetic pathways have yet to be discovered. Despite the insight afforded by this technology, little is known about the diversity and distributions of natural product biosynthetic pathways among bacteria and how they evolve to generate structural diversity. Here we analyze genome sequence data derived from 75 strains of the marine actinomycete genus *Salinispora* for pathways associated with polyketide and nonribosomal peptide biosynthesis, the products of which account for some of today's most important medicines. The results reveal high levels of diversity, with a total of 124 pathways identified and 229 predicted with continued sequencing. Recent horizontal gene transfer accounts for the majority of pathways, which occur in only one or two strains. Acquired pathways are incorporated into genomic islands and are commonly exchanged within and between species. Acquisition and transfer events largely involve complete pathways, which subsequently evolve by gene gain, loss, and duplication followed by divergence. The exchange of similar pathway types at the precise chromosomal locations in different strains suggests that the mechanisms of integration include pathway-level homologous recombination. Despite extensive horizontal gene transfer there is clear evidence of species-level vertical inheritance, supporting the concept that secondary metabolites represent functional traits that help define *Salinispora* species. The plasticity of the *Salinispora* secondary metabolome provides an effective mechanism to maximize population-level secondary metabolite diversity while limiting the number of pathways maintained within any individual genome.

genome sequencing | comparative genomics

Microbial secondary metabolites have long benefited human health and industry. They include important pharmaceutical agents such as the antibiotic penicillin, the anticancer agent vancomycin, and the immunosuppressant rapamycin among the more than 20 thousand biologically active microbial natural products reported as of 2002 (1). Secondary metabolites also have important ecological roles for the organisms that produce them, particularly in terms of nutrient acquisition, chemical communication, and defense (2). Many of these compounds are the products of polyketide synthase (PKS) and nonribosomal peptide synthetase (NRPS) pathways or hybrids thereof. These pathways are generally organized into gene clusters that can exceed 100 kb and include regulatory, resistance, and transport elements (3), thus making them well-suited for horizontal gene transfer (HGT) (4, 5). The architectures and functional attributes of PKS and NRPS genes have been reviewed in detail (3, 6, 7) and account for much of the structural diversity that is the hallmark of microbial natural products. Remarkably, PKS and NRPS enzymes build these complex secondary metabolites via the controlled assembly of simple biosynthetic building blocks such as acetate, propionate, and amino acids. These building blocks are incorporated in a combinatorial fashion via a series of sequential chemical condensation reactions encoded by ketosynthase (KS) and condensation (C) domains within PKS and NRPS genes, respectively (3).

The pathways responsible for secondary metabolite biosynthesis are among the most rapidly evolving genetic elements known (5). It has been shown that gene duplication, loss, and HGT have all played important roles in the distribution of PKSs among microbes (8, 9). Changes within PKS and NRPS genes also include mutation, domain rearrangement, and module duplication (5), all of which can account for the generation of new small-molecule diversity. The evolutionary histories of specific PKS and NRPS domains have proven particularly informative, with KS and C domains providing insight into enzyme architecture and function (10, 11). These studies have helped establish the extensive nature of HGT among biosynthetic genes (4, 12), which is reflected in the incongruence between PKS and NRPS gene phylogenies and those of the organisms in which they reside (13). Although resolving the evolutionary histories of entire pathways remains more challenging than individual genes or domains, comparative analyses of biosynthetic gene clusters have proven useful for the identification of pathway boundaries (14).

The exchange of PKS and NRPS pathways by HGT confounds the relationships between taxonomy and secondary metabolite

Significance

Microbial natural products are a major source of new drug leads, yet discovery efforts are constrained by the lack of information describing the diversity and distributions of the associated biosynthetic pathways among bacteria. Using the marine actinomycete genus *Salinispora* as a model, we analyzed genome sequence data from 75 closely related strains. The results provide evidence for high levels of pathway diversity, with most being acquired relatively recently in the evolution of the genus. The distributions and evolutionary histories of these pathways provide insight into the mechanisms that generate new chemical diversity and the strategies used by bacteria to maximize their population-level capacity to produce diverse secondary metabolites.

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The authors declare no conflict of interest.

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Data deposition: Genome sequences reported in this paper have been deposited in the Joint Genome Institute's Integrated Microbial Genomes (IMG) database, <http://img.jgi.doe.gov/cgi-bin/w/main.cgi> (accession nos. 2517572210, 2515154093, 2515154181, 2519103192, 2515154183, 2515154193, 2519103193, 2515154125, 2518285551, 2518285552, 2515154180, 2519103194, 2515154203, 641228504, 2516143022, 2518285553, 2519103185, 2518285554, 2517572137, 2515154186, 2515154088, 2515154135, 2515154127, 2517572233, 2518285555, 2515154137, 2515154188, 2517572152, 2515154187, 2517572153, 2518285558, 2519103195, 2518285559, 2518285560, 2517572154, 2517572155, 2515154178, 2515154194, 2518285561, 2518285562, 2515154129, 2518285563, 2517572157, 2515154184, 2515154126, 2515154177, 2517572158, 2515154202, 2517572159, 2515154200, 2515154124, 2517572160, 2515154185, 2517572161, 2515154182, 2518285550, 2517572162, 2515154170, 2515154128, 2517572163, 2518645626, 2518645627, 2517572194, 2517287019, 2516653042, 2516493032, 2517287023, 2517434008, 640427140, 2517572211, 2517572212, 2515154094, 2518645624, 2515154163, and 2517572164).

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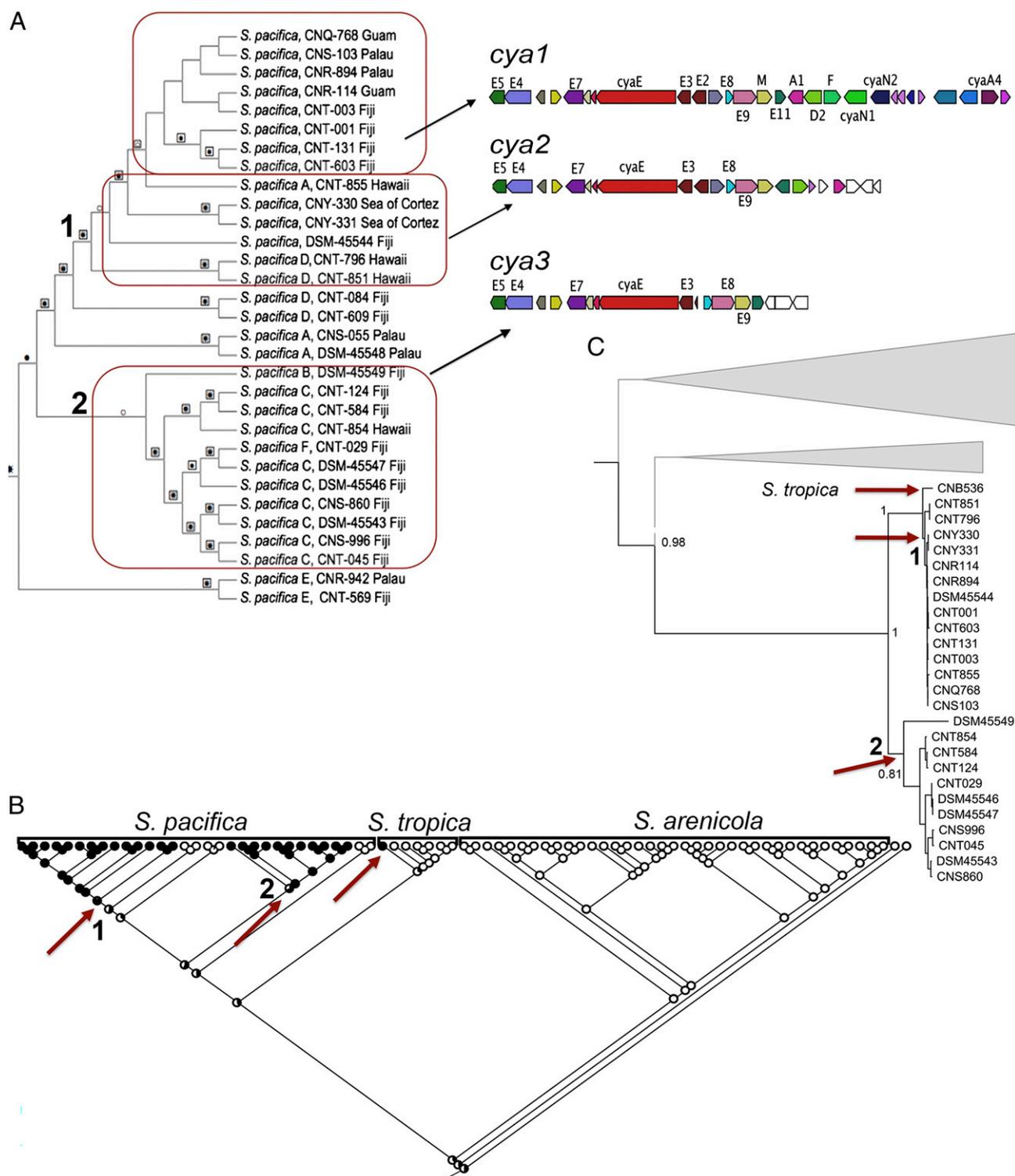


Fig. 2. Evolution of the *cya* pathway in *S. pacifica*. (A) The *cya* OBU contains three different versions of the pathway. The *cya1* version is responsible for the biosynthesis of cyanosporaside A, which is derived from an enediynes precursor (28). It was observed in all strains in the uppermost clade of the *Salinispora* species tree (boxed in red). Two truncated versions of the pathway were observed, with *cya2* appearing ancestral to *cya1* in the species tree. Genes missing in *cya2* and 3 include *cyaA4* (*O*-acyltransferase), *cyaN1* (epoxide hydrolase), and *cyaN2* (oxidoreductase), which are predicted to encode tailoring enzymes. Together, the *cya1*- and 2-containing strains form a single clade (clade 1) in this region of the *S. pacifica* species tree. The *cya3* pathway occurs in a separate *S. pacifica* lineage (clade 2). Products have yet to be identified from *cya2* and 3. (B) A likelihood analysis predicts three independent acquisition events for the *cya* pathway, one in *S. tropica* and two in *S. pacifica* (red arrows). The *S. pacifica* acquisition events correspond to clades 1 and 2 in the species tree. (C) Maximum-likelihood phylogeny of the *cyaE* enediynes PKS gene including the top 10 BLASTp matches (bootstrap values for 100 replicates are shown at major nodes) reveals two major lineages (red arrows, numbers 1 and 2) that correspond to the strains in clades 1 and 2 of the species tree. This supports the vertical inheritance of this gene subsequent to acquisition. The position of the *S. tropica* (CNB-536) *cyaE* homolog within *S. pacifica* clade 1 suggests that the acquisition event in *S. tropica* is the result of horizontal gene transfer with *S. pacifica* clade 1. Gene gain and loss are assumed to account for the variations in the *cya1*–3 pathways.

Table 1. *Salinispora* genome composition and pathway (OBU) statistics

Species	No. genomes analyzed	Avg. genome size, Mb	Avg. no. contigs*	Avg. no. OBUs per genome	OBU richness [†]	Avg. no. singletons [‡] per genome
<i>S. arenicola</i>	37	5.7 ± 0.14	78 ± 19	17.5 ± 1.9	47	0.49
<i>S. pacifica</i>	31	5.4 ± 0.19	93 ± 33	14.1 ± 2.7	88	1.00
<i>S. tropica</i>	7	5.4 ± 0.19	90 ± 19	13.6 ± 1.8	19	0.57

Averages reported are ±1 SD.

*Does not include the closed genomes of CNB-440 and CNS-205.

[†]Number of different OBUs observed.

[‡]OBUs observed in only one strain.

carbon skeletons were observed when the KS- and C-domain SIs fell below these cutoff values. MultiGeneBlast analyses were performed on pathways that occurred in at least five strains to better assess the OBU assignments. These analyses revealed high levels of synteny and SI among the shared genes within each OBU and sharply lower cumulative BLAST bit scores for strains that lacked the pathway. Intra-OBU differences occurred largely among genes predicted to encode tailoring enzymes, as observed in the *cya* pathway (Fig. 2). Nonetheless, given that minor structural differences can have a major impact on secondary metabolite biological activity, the products of different versions of a pathway that have been grouped into a single OBU may have different ecological functions. Although the KS- and C-domain clustering values used here appear appropriate for *Salinispora* species, it remains to be seen how well they will apply to other taxonomic groups.

Pathway Diversity. Comparable to prior studies (23, 24), the *Salinispora* genomes were enriched in PKS and NRPS biosynthetic pathways. On average, *S. arenicola* genomes were 300 kb larger

and contained four more OBUs per genome than *S. pacifica* or *S. tropica* (Table 1). Although more OBUs were detected per *S. arenicola* genome, considerably more OBU diversity was observed in *S. pacifica*, which contained a total of 88 different OBUs compared with 47 and 19 for *S. arenicola* and *S. tropica*, respectively. In total, 124 distinct OBUs were identified, including representatives of diverse PKS types (Fig. S3). Only nine of these OBUs have been formally linked to the production of specific secondary metabolites. These are *sal* (salinosporamides) (30), *slm* (salinilactam) (23), *cyl* (cyclomarins) (31), *cya* (cyanosporasides) (28), *spo* (sporolides) (29), *am* (arenimycin) (32), *rif* (rifamycins) (33), *lym* (lymphostin) (34), and *lom* (lomaiviticin) (35), whereas two others are predicted to yield enterocin (36) (PKS31) and arenicolide (37) (PKS28) based on bioinformatic analyses. Although there is no evidence that all pathways are functional, the 113 remaining OBUs far exceed the four *Salinispora* secondary metabolites (arenamides, pacificanones, salinipyrone, and saliniquinones) that have yet to be linked to specific pathways, suggesting

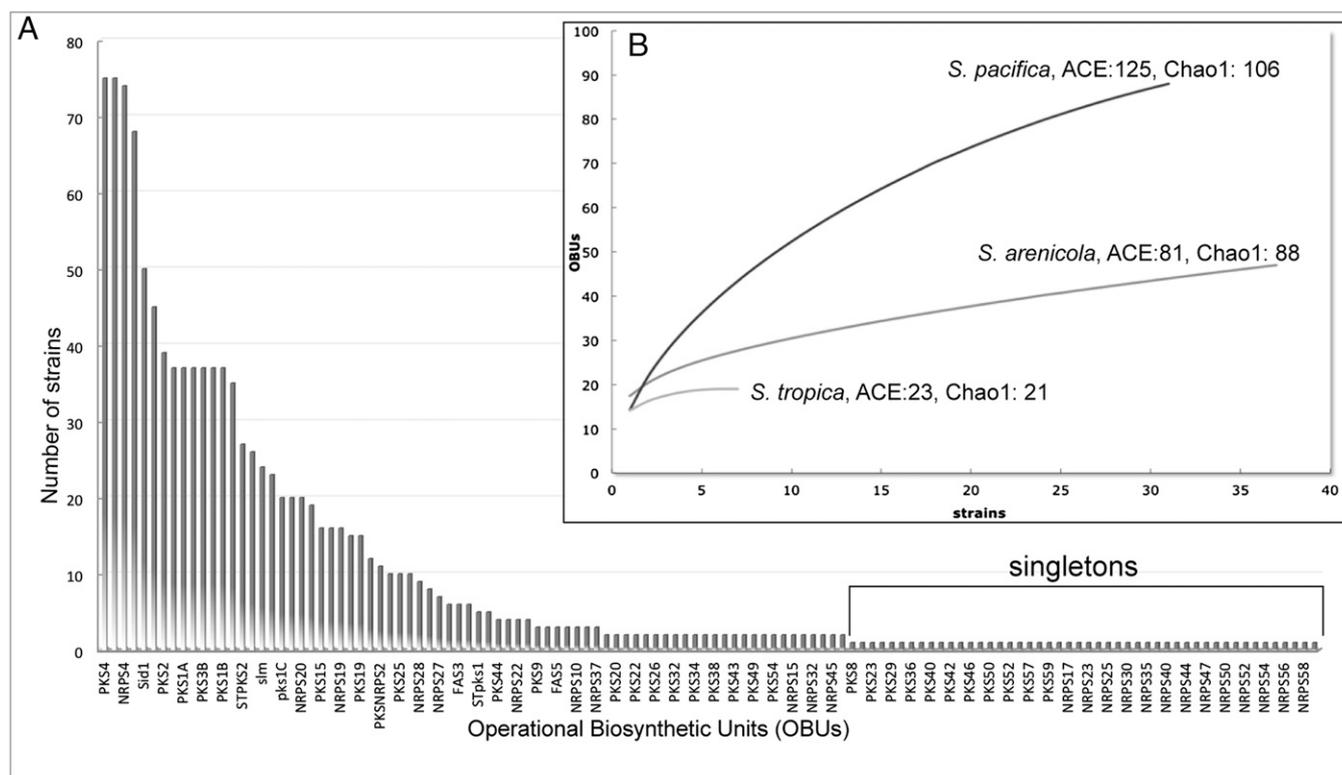


Fig. 3. Distribution and diversity of PKS and NRPS OBUs. (A) Rank-abundance curve showing the abundance of each OBU among the 75 strains analyzed (representative OBU names are shown). (B) Rarefaction curves with diversity estimators for each species.

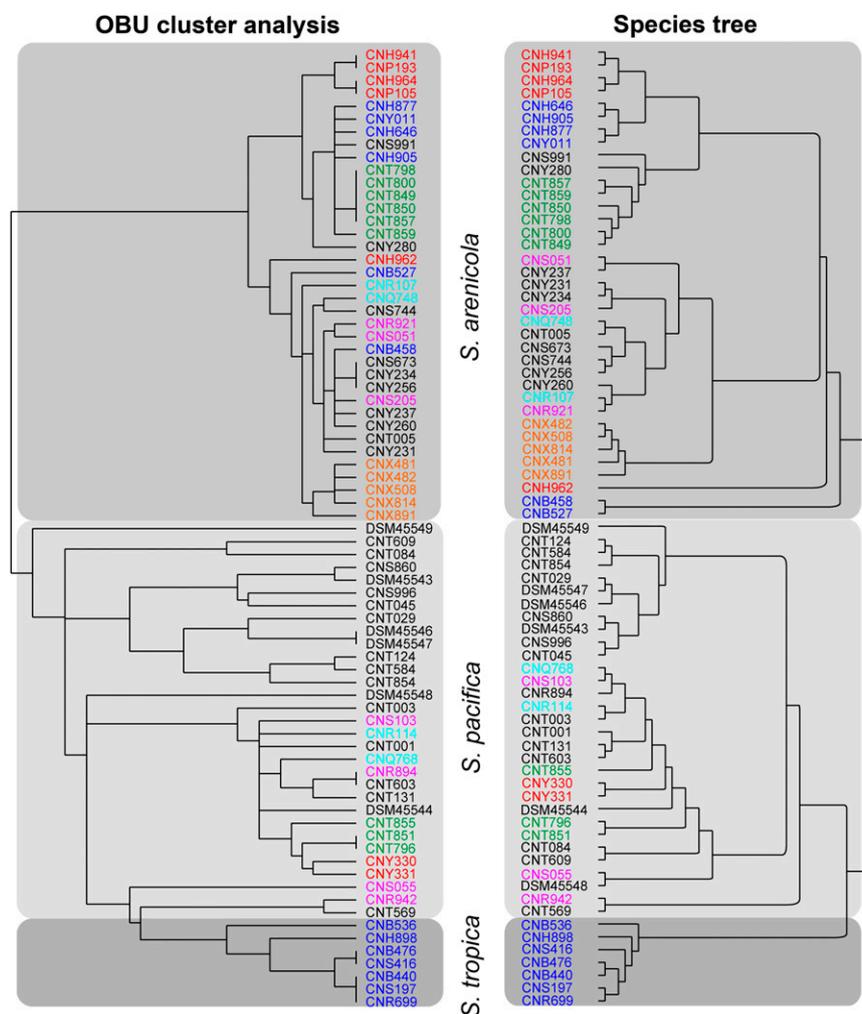


Fig. 4. OBU hierarchical cluster analysis and *Salinispora* species tree. Hierarchical cluster analysis based on OBU presence or absence. Maximum-likelihood species phylogeny generated from 10 housekeeping genes. Colors indicate the collection site: blue, Bahamas; pink, Palau; black, Fiji; red, Sea of Cortez; orange, Palmyra; turquoise, Guam; green, Hawaii.

that considerable chemical diversity remains to be discovered from this genus.

A rank-abundance curve describing the distribution of the OBUs among the 75 strains reveals a long right-hand tail, as is characteristic of a highly diverse community (Fig. 3). Remarkably, 48 of the OBUs were only observed in one strain (singletons), with an additional 24 occurring in two strains. These 72 OBUs account for 58% of the total number observed in the 75 genomes and illustrate extensive acquisition via horizontal gene transfer. In the case of *S. pacifica*, the most phylogenetically diverse of the three species (26), an average of one singleton was detected per genome sequenced (Table 1). Rarefaction curves, used primarily in community ecology to assess species richness (38), provide an assessment of OBU richness for the given sequencing effort and reveal that considerable diversity has yet to be detected (Fig. 3). This is particularly evident for *S. pacifica*, which shows little evidence of saturation, and is further supported by ACE and Chao1 diversity estimators, which predict as many as 229 distinct OBUs with continued sequencing of the three species (Fig. 3). This represents an extraordinary level of biosynthetic diversity for three bacterial species that share 99% 16S rRNA sequence identity (19).

Pathway Distributions. We next generated a well-supported *Salinispora* species phylogeny (Fig. S4) and a hierarchical cluster analysis based on pathway presence or absence. Despite the large

number of OBUs that occur in only one or two strains, these two dendrograms are highly congruent, with the exception that *S. pacifica* is paraphyletic with respect to *S. tropica* in the OBU cluster analysis (Fig. 4). Contributing to this congruence are species-specific OBUs (i.e., pathways commonly observed in one species but generally not in others). In *S. arenicola*, these include *rif*, *PKS1A/B*, *PKS2*, *PKS3A/B*, *PKS5*, *NRPS1*, and *NRPS2* (Table S2). In *S. tropica*, these include *spo*, *slm*, *sal*, *Sid3*, *Sid4*, *NRPS3*, and *STPKS1* (Table S3). Interestingly, only one OBU (*NRPS20*) appears commonly in *S. pacifica* and not in others (Table S4). These results support previous culture-based studies and KS fingerprinting analyses that revealed species-specific patterns of secondary metabolite production and gene distributions in *S. arenicola* and *S. tropica* (25, 39). There is some evidence of OBU clustering based on the location from which the strains originate (Fig. 4); however, a permutational multivariate analysis of variance (PERMANOVA) revealed a significant correlation between OBU and species ($R^2 = 0.54$, $P = 0.001$) and not location ($P = 0.075$), indicating the importance of taxonomy over biogeographic origin in terms of OBU distributions.

Pathway Evolution. To explore the evolutionary history of the pathways in relation to the strains in which they reside, likelihood analyses were performed on the KS- and C-domain sequences to assign the ancestral node(s) for each OBU in the

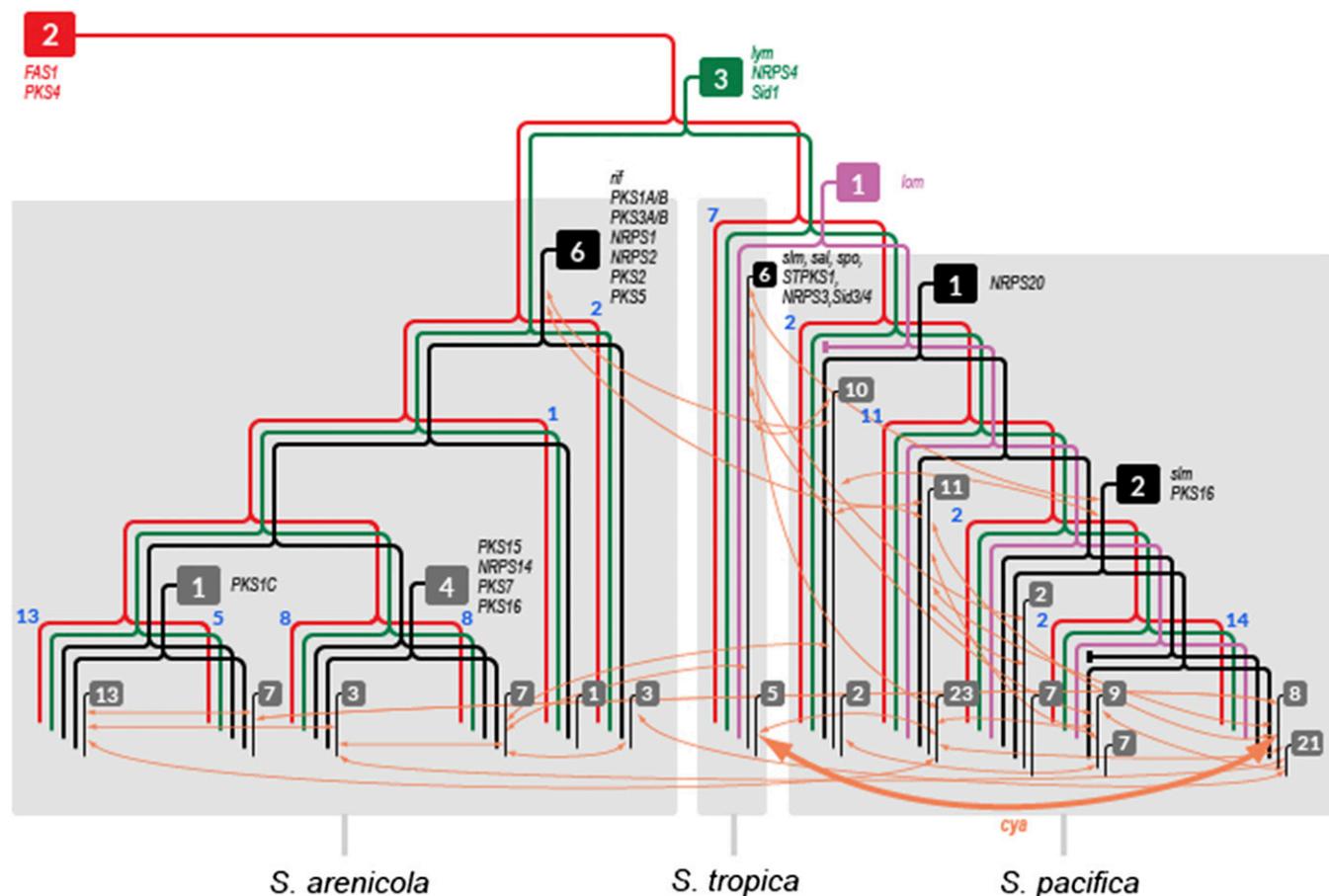


Fig. 5. *Salinispora* phylogeny depicting OBU inferred ancestry. A simplified species tree generated from 10 housekeeping genes (Fig. S4) shows 12 major *Salinispora* lineages with the number of strains in each indicated in blue adjacent to the node branch points. Boxes indicate the number of OBUs originating at various points in the species tree. Red, shared with a common ancestor of the genus; green, genus-specific; purple, shared with *S. tropica* and *S. pacifica*; black, species-specific; gray, clade-specific. Representative OBU names are indicated next to the point of acquisition. Orange arrows describe inter- and intraspecies OBU exchange events (*cya* exchange between *S. tropica* and *S. pacifica* is indicated in bold).

species tree. The results for the 124 OBUs were overlaid onto a simplified *Salinispora* phylogeny (Fig. 5) generated by collapsing the species tree (Fig. S4) into 12 lineages. The analysis reveals that only five OBUs were present in the common ancestor of the genus and only two of these (FAS1 and PKS4) were shared with the closely related genus *Micromonospora*. It can thus be inferred that the remaining pathways (96% of the total) were acquired by HGT at various points during the evolution of the genus. Phylogenetic analyses of key biosynthetic genes from each OBU confirm these evolutionary histories and indicate, based on congruence with the species tree, vertical inheritance for 65 of the OBUs subsequent to acquisition. Seven OBUs appear to have been acquired early in the evolution of *S. arenicola*. These include *rif*, which supports the consistent production of rifamycins by *S. arenicola* (25, 40). Likewise, six OBUs appear early in the evolutionary history of *S. tropica* and one in *S. pacifica* (Fig. 5). Most of the OBUs, however, were acquired relatively recently in the evolution of the genus, appearing toward the branch terminals in the tree. Based on BLAST analyses of the singleton PKS and NRPS genes, it appears that most of these pathways were acquired from other high-G+C bacteria such as *Streptomyces* spp. (Fig. S5), which also occur in marine sediments (41). The results for PKS17 suggest the independent acquisition of this pathway by four *S. arenicola* strains from Fiji and one *S. pacifica* strain from the Sea of Cortez (Fig. S6). Although these results may reflect sampling

effort, they suggest that location-dependent pathway acquisition warrants future study.

Phylogenetic analyses of key biosynthetic genes were also used to infer that 36 of the 124 OBUs identified (29%) were exchanged within or between species. One example is the *cya* pathway, which was exchanged between *S. pacifica* and *S. tropica* (Fig. 2). These transfer events were added to the simplified species tree to depict the complexity of pathway movement within the genus (Fig. 5). In total, it could be inferred that 23 OBUs moved once, 9 moved twice, and 4 (PKS17, *sal*, Sid1, and PKSNRPS2) moved three times. There was no evidence for KS- or C-domain exchange among OBUs or the formation of chimeric pathways, although events of these types may have been missed with the assembly methods used. Instead, OBUs evolved largely by gene gain, gene loss, and duplication followed by divergence. In the last case, NRPS4 is a genus-specific pathway observed in 72 of the 75 strains. A subset of *S. arenicola* (clade 6) and *S. pacifica* (clade 12) contains a second copy of this pathway (NRPS19) that is sufficiently diverged (i.e., shares <85% C-domain SI) to be considered a new OBU (Fig. S2). Thus, pathway duplication followed by divergence appears to be another mechanism by which OBU diversity is created in *Salinispora* spp.

Genomic Islands as Hot Spots for Secondary Metabolism. Pseudochromosomes were generated by mapping sequence contigs onto the closed genomes of *S. tropica* (CNB-440), *S. arenicola* (CNS-205), and a number of high-quality *S. pacifica* draft genomes that

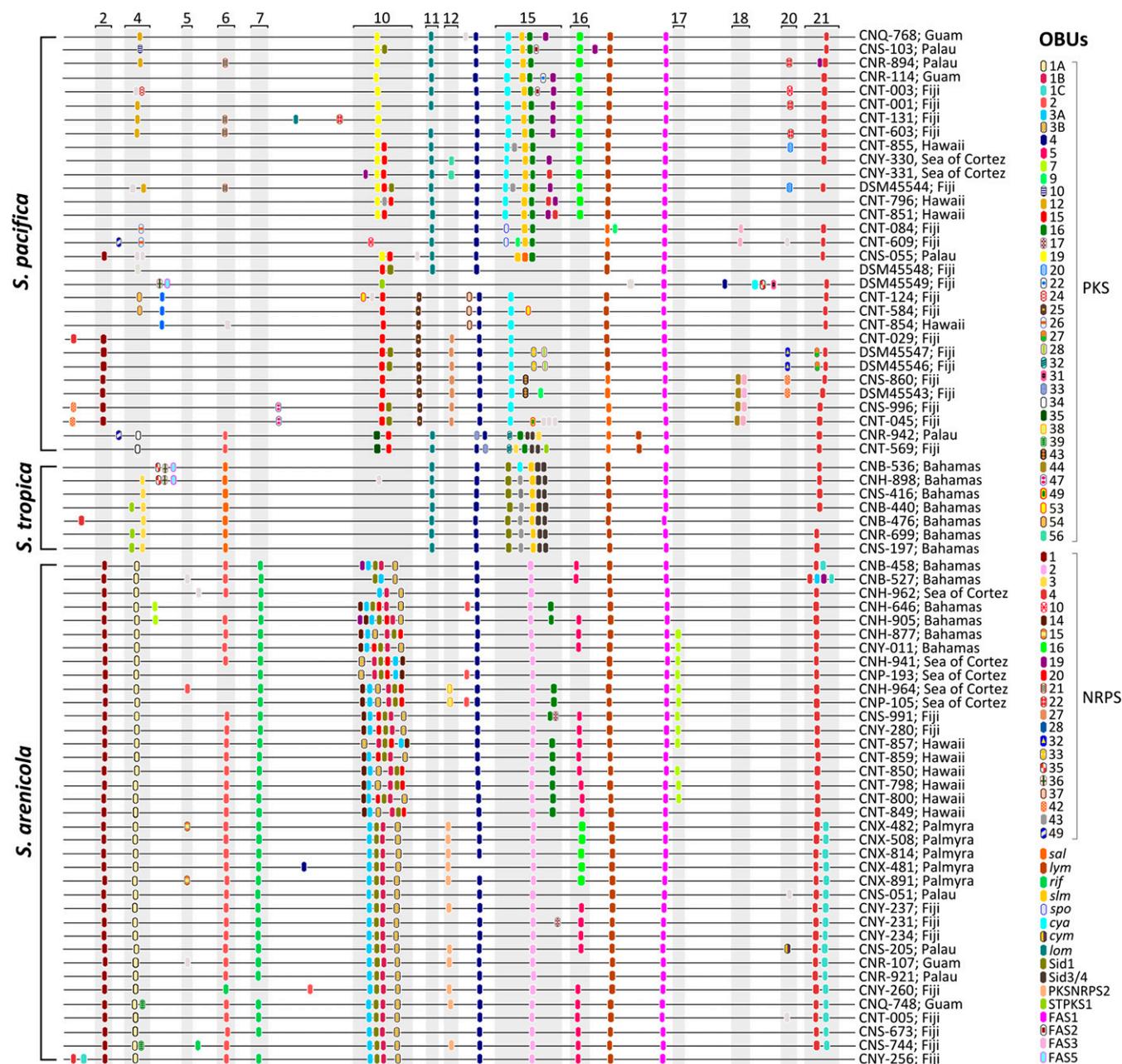


Fig. 6. Linear pseudochromosomes reveal the positioning of *Salinispora* OBUs within genomic islands (numbered and shaded) as identified based on previously defined boundaries (24). Pathway positions were mapped using PKS and NRPS genes as reference. Only the pathways that could be mapped onto the pseudochromosomes are depicted. Pathways are color-coded and listed on the right next to the strain name and geographic origin. Singletons are depicted in light gray.

were generated as part of this study. The results show that the OBUs are clustered in genomic islands (GIs) (Fig. 6), regions of bacterial chromosomes known to encode acquired, adaptive traits (42). *Salinispora* GIs were also enriched in mobile genetic elements, which may play a role in OBU acquisition and transfer, relative to other regions of the genome (Wilcoxon rank-sum test, $P < 0.05$). Remarkably, the flanking regions of 21 previously identified *Salinispora* GIs (24) are conserved across all 75 genome sequences, suggesting that island boundaries can be used as queries to identify similar regions in other strains. In some cases, OBUs that encode the biosynthesis of similar classes of compounds were exchanged at precisely the same island location. This type of pathway “swapping” was observed with three enediynes OBUs in *S. pacifica* (Fig. 1), and may represent

an example of pathway-level homologous recombination that is yet to be described.

Discussion

Major advances in our understanding of the molecular genetics of natural product biosynthesis have created unprecedented opportunities for pathway engineering (43) and the generation of new chemical diversity in high-priority scaffolds (44). Coupled with increased access to genome sequence data and the revelation that even well-studied taxa can harbor a wealth of biosynthetic pathways for which the products have yet to be discovered (45, 46), natural product research is undergoing a renaissance driven by the development of new discovery methods (47). Despite these advances, we have yet to gain perspective on the diversity and

distributions of the pathways responsible for secondary metabolism among groups of related bacteria and how these pathways evolve to generate new chemical diversity.

The 75 genome sequences analyzed here provide insight into the remarkable levels of pathway diversity that can be maintained among a group of bacteria that share 99% 16S rRNA gene sequence identity. This diversity can largely be attributed to the many pathways that were observed in only one or two strains and that are inferred to be the result of HGT events that occurred relatively recently in the evolutionary history of the genus. Although the effects of geographic origin on the OBUs maintained by individual strains warrant further study, the potential for location-specific acquisition suggests that differences in the local gene pool may account for some of the diversity reported here. Although the total number of OBUs maintained by these three closely related species remains unknown, it is extraordinarily high relative to the numbers observed in the individual strains (Table 1), with a total of 229 distinct PKS and NRPS OBUs predicted with continued sequencing.

Mapping the inferred ancestral nodes of the individual OBUs onto the *Salinispora* species phylogeny made it possible to trace pathway evolutionary histories relative to the strains in which they reside (Fig. 5). These analyses reveal that 105 of the 124 OBUs (85%) were acquired subsequent to the speciation events within the genus, which suggests that the ecological functions of secondary metabolites act largely at the subspecies level. However, the congruence observed between the species tree and the OBU cluster analysis (Fig. 4) suggests that secondary metabolites nonetheless represent functional traits that help define *Salinispora* spp. (25). The fixation of certain pathways within *S. arenicola* and *S. tropica* could be the result of periodic selection (48), which if driven by the products of these OBUs would indicate that they provide a strong selective advantage. Species-specific OBUs include *rif* and *sal*, which encode the production of the potent antibiotic rifamycin and the proteasome inhibitor salinosporamide A in *S. arenicola* and *S. tropica*, respectively. In *S. pacifica*, the most diverse of the three species (26), similar levels of fixation are not observed, yet many OBUs appear fixed among major clades within the species. Based on this, it could be speculated that *S. pacifica* is undergoing a series of nascent speciation events, with ecological divergence preventing periodic selection from fixing pathways at the currently defined species level.

The OBUs were concentrated in GIs whose boundaries were highly conserved among all strains. These GIs were enriched in mobile genetic elements, suggesting they are hot spots for pathway acquisition and evolution. The observed swapping of enediyne OBUs at the precise chromosomal locations in different strains (Fig. 1) suggests that recombination may function at the pathway level in a manner comparable to the domain-level homologous recombination observed in PKS and NRPS analyses (49). The absence of KS- or C-domain exchange among OBUs, a process that is generally considered important in PKS and NRPS evolution (5, 50), suggests that pathway HGT followed by gene gain or loss events is the major force driving the creation of OBU diversity in *Salinispora* spp. Although it is unclear how these results apply to other bacteria, the continued sequencing of large numbers of closely related strains will provide additional insight into the evolutionary processes by which bacteria generate new secondary metabolite diversity.

A better understanding of the taxonomic distributions and evolutionary histories of the pathways responsible for secondary metabolite biosynthesis will provide opportunities for the development of the theory-based sampling strategies that capitalize on the genetic potential of individual strains to produce new chemical scaffolds or compounds within a privileged chemical class. Recognition that some pathways diverge in lineage-specific patterns indicates that related strains within the same species can be the source of related compounds within the same chemical

class (39), thus providing an alternative to synthetic chemistry as an approach to generating structural diversity. The plasticity of secondary metabolism in *Salinispora* spp. provides a glimpse into the evolutionary strategies by which bacteria capitalize on the benefits afforded by these compounds. Despite not knowing the ecological functions of most *Salinispora* secondary metabolites, extensive pathway sampling provides a mechanism to maximize the population-level secondary metabolome while limiting the number of pathways maintained within any individual genome. The potentially vast array of molecules produced at the population level would increase the likelihood of an effective response to new selective pressures and thus provide an ecological rationale for the extensive pathway diversity observed in this study.

Materials and Methods

Genome Sequencing and Assembly. *Salinispora* strains were obtained in culture as previously described (41, 51). DNA was extracted following US Department of Energy Joint Genome Institute (JGI) protocols (<http://my.jgi.doe.gov/general/protocols.html>) and submitted to the JGI for sequencing, assembly, and annotation. The sequencing and annotation of *S. arenicola* CNS-205 and *S. tropica* CNB-440 were as previously described (23, 24). For the remaining 73 strains, short- and long-insert paired-end libraries were constructed and sequenced by the JGI using the Illumina HiSeq 2000 system. Filtered reads were assembled using Velvet (52) and ALLPATHS-LG (53), and possible misassemblies were corrected with manual editing in Consed (54). Gap closure was accomplished using repeat resolution software and sequencing of bridging PCR fragments with Sanger and/or PacBio technologies. Genes were identified using Prodigal (55), followed by a round of manual curation using GenePRIMP (56). Predicted coding DNA sequences were translated and used to search the National Center for Biotechnology Information (NCBI) nonredundant (nr) database, UniProt, TIGRFam, Pfam, Kyoto Encyclopedia of Genes and Genomes, Clusters of Orthologous Groups, and InterPro databases. Strains and accession numbers are provided in Table S1.

Pathway and OBU Identification. Genome sequences in FASTA format were screened for PKS and NRPS genes by searching for KS and C domains, respectively, using NaPDoS (<http://napdos.ucsd.edu>) with default settings (57). The associated genes and gene environments were then analyzed using BLAST (<http://blast.ncbi.nlm.nih.gov/Blast.cgi>), IMG/ER (<https://img.jgi.doe.gov/cgi-bin/er/main.cgi>), and antiSMASH (27) to confirm association with secondary metabolism, assess the similarities among pathways, and create links to known secondary metabolites based on homology to experimentally characterized pathways. Pathways split onto different contigs were assembled with the aid of complete pathways or when KS- and C-domain phylogenies revealed that the sequences claded together. Pathways were grouped into OBUs when BLAST analyses revealed that homologous KS and C domains shared $\geq 90\%$ and $\geq 85\%$ amino acid sequence identity, respectively. OBUs were assigned a unique identifier (e.g., PKS1, NRPS1) or a formal name if linked to an experimentally characterized pathway. A database of all genomes was created and OBU assignments were verified for pathways that occurred in five or more strains using MultiGeneBlast (58) based on the synteny and SI of conserved genes in each pathway and cumulative BLAST bit scores, which dropped precipitously in strains that did not possess the pathway (10).

***Salinispora* Species Phylogeny.** Nucleotide sequences for 10 unlinked, single-copy genes (*dnaA*, *gyrB*, *pyrH*, *recA*, *pgi*, *trpB*, *atpD*, *sucC*, *rpoB*, *topA*) were extracted, aligned using Muscle in Geneious Pro v5.5 (Biomatters; www.geneious.com), and concatenated using Mesquite v2.75 (59). MODELTEST (60) was run and the best model [generalized time reversible (GTR)+G] was used to create a maximum-likelihood (ML) tree using PhyML 3.0 (61) and a neighbor-joining tree using MEGA5 (62). Nodal support values were obtained using 1,000 bootstrap replicates. Concatenated Bayesian tree and posterior probabilities were created using MRBAYES (63) with 1 million generations.

OBU Phylogeny. Nucleotide sequences from at least two conserved genes from each OBU observed in two or more of the 12 major *Salinispora* clades presented in Fig. 5 were aligned in Muscle and manually curated. ML phylogenies were created using PhyML 3.0 under the GTR model of nucleotide substitution with 100 bootstrap replicates or a fast approximate likelihood-ratio test performed as a measure of branch support. Other common models

of nucleotide substitution were used with no significant changes in the results. If the phylogenies for the genes within an OBU were congruent, this phylogeny was assumed for the whole pathway.

Statistics. Hierarchical cluster analyses were performed using Cluster 3.0 (<http://bonsai.hgc.jp/~mdehoon/software/cluster/software>) with presence/absence OBU matrices as the input files (Tables S2–S4) using a correlation-centered similarity metric with the complete linkage clustering method. A PERMANOVA was implemented with the vegan package in R (www.r-project.org). EstimateS (<http://viceroy.eeb.uconn.edu/estimates>) was used to generate rarefaction curves and diversity estimates. The Wilcoxon rank-sum test implemented in R was used to compare the fraction of mobile genetic elements inside and outside of GIs.

Ancestral State Reconstruction. The ancestral node for each OBU was inferred in the species tree using the trace character history function implemented in Mesquite v2.75 (59). A categorical character matrix was created for all OBUs, and likelihood calculations were performed using the Mk1 model. Likelihood scores >50% were used to infer the points of OBU acquisition (ancestral nodes) in the species tree. OBU ML phylogenies were used to corroborate points of acquisition based on congruence with the species tree and to infer inter- and intraspecies exchange events as shown in Fig. 2.

Pseudochromosome Assembly, OBU Localization, and Genomic Island Analysis. Draft genomes were assembled into linear “pseudochromosomes” using the CONTIGuator 2 web application (64) and oriented with *dnaA* as the first gene. The closed genomes *S. arenicola* CNS-205 (24) and *S. tropica* CNB-440 (23) were used as templates for the assembly of these species. High-quality draft *S. pacifica* genomes (one 5-Mb scaffold and one to three contigs of 10–100 kb) from strains DSM-45544, DSM-45548, and DSM-45543 were used as reference templates for the assembly of *S. pacifica* phylotypes ST, A, and C. For other phylotypes, the template that gave the best assembly was used. The chromosomal position of the OBUs present in ≥3 strains was determined using the Assembly function in Geneious Pro v5.5 and a PKS or NRPS gene

from the predicted OBU as reference. All remaining OBUs were mapped by searching for KS- and C-domain amino acid sequences using Custom-BLAST in Geneious Pro v5.5. In a previous study of *S. arenicola* CNS-205 and *S. tropica* CNB-440, 21 GIs were identified based on regions of conservation flanking regions >20 kb that shared <40% gene orthology (24). Conserved regions 5 kb up- and downstream of genomic islands were extracted from CNS-205 and located in the pseudochromosomes by BLAST in Geneious Pro v5.5. Mobile genetic elements were quantified in closed and high-quality draft genomes (*S. arenicola* CNS-205 and CNS-991, *S. tropica* CNB-440, and *S. pacifica* DSM-45543, DSM-45544, DSM-45546, DSM-45547, DSM-45548, and DSM-45549) by counting annotated recombinase, transposase, phage, integrase, and tRNA genes inside and outside of GIs.

Source of Singleton OBUs. All KS and C domains that occurred in one *Salinispora* strain (singletons) were subjected to BLAST analyses using the NCBI/nr protein database to assess the taxonomic distribution of homologous domains in other microorganisms. A total of 330 KS domains (from 16 pathways) and 1,100 C domains (from 26 pathways) was analyzed. The top 10 BLAST hits of every query were sorted by taxonomy in Geneious Pro v5.5 to calculate the distribution per taxonomic group.

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Supporting Information

Ziemert et al. 10.1073/pnas.1324161111

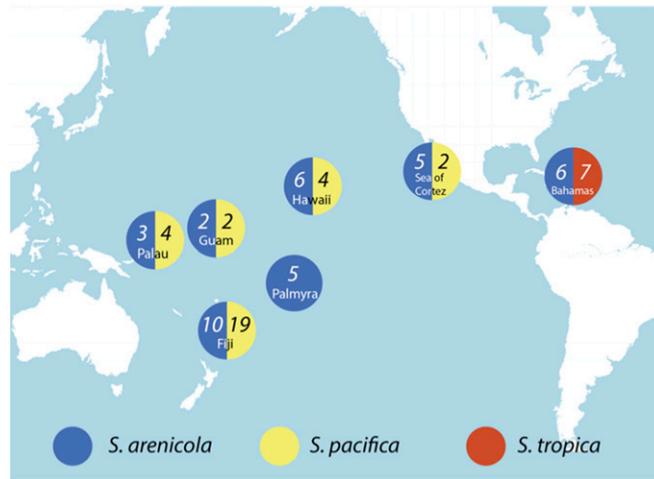


Fig. S1. Geographic origin and numbers of *Salinispora* strains used in this study.

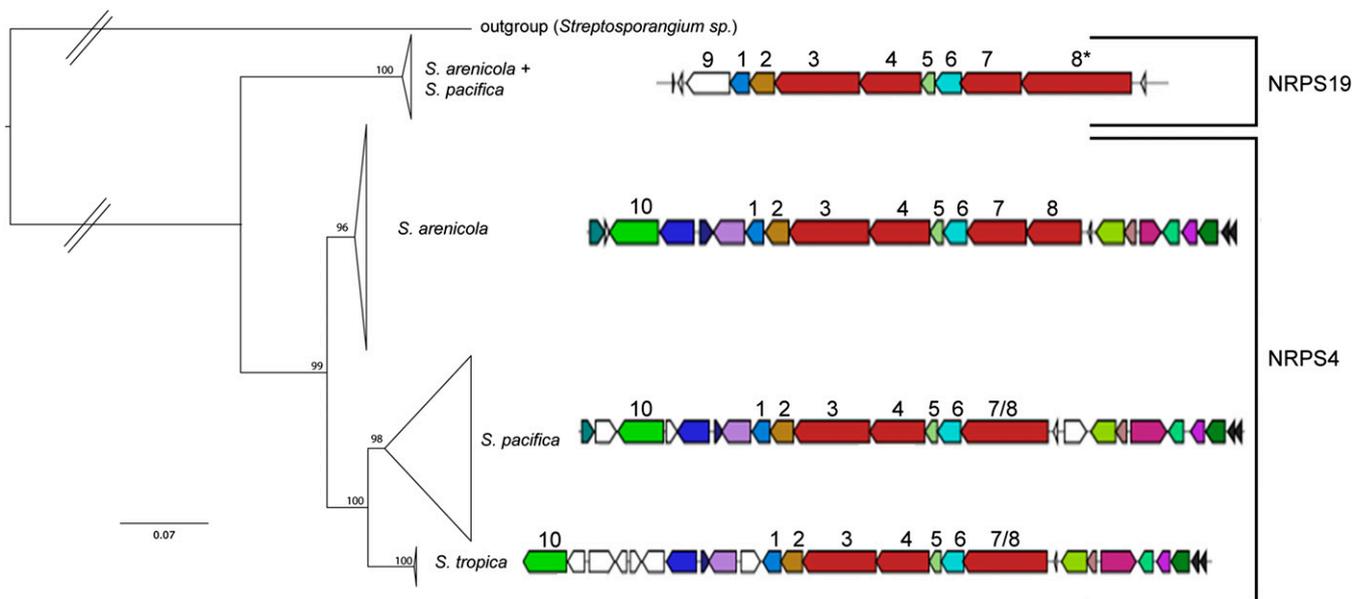


Fig. S2. Operational biosynthetic unit (OBU) phylogeny supports duplication followed by divergence. Nonribosomal peptide synthetase (NRPS)4 was detected in all but one of the 75 *Salinispora* strains. NRPS19 was placed in a separate OBU that shared ca. 80% homologous C-domain sequence identity with NRPS4. It possesses an additional C domain in the NRPS gene Orf8 and was observed in 16 *S. arenicola* and *S. pacifica* strains. Individual phylogenies of the NRPS genes orf3 and 4 and the kynurenine monooxygenase orf6 from these two pathways all revealed a sister relationship between the NRPS4 and NRPS19 clades, which can best be explained by a duplication event. The products of these pathways have yet to be identified. 1, methyltransferase; 2, major facilitator superfamily; 3, NRPS; 4, NRPS; 5, MbtH; 6, kynurenine-3-monooxygenase; 7, NRPS; 8, NRPS; 9, lantibiotic dehydratase; 10, penicillin amidase.

OBU diversity

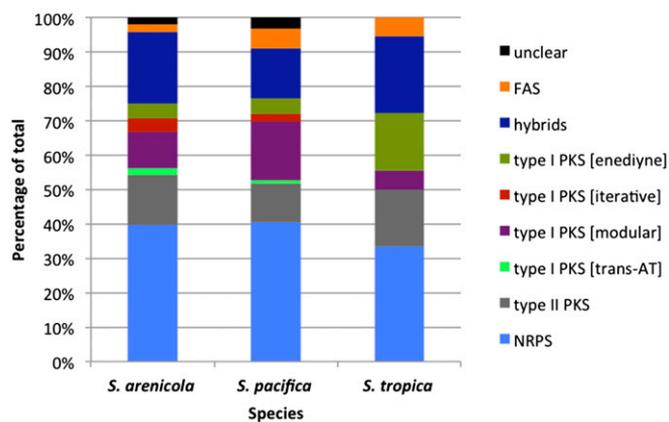


Fig. S3. Polyketide synthase (PKS) and NRPS relative abundance and NaDPos PKS classification (1). FAS, fatty acid synthase.

1. Ziemert N, et al. (2012) The natural product domain seeker NaDPos: A phylogeny based bioinformatic tool to classify secondary metabolite gene diversity. *PLoS ONE* 7(3):e34064.

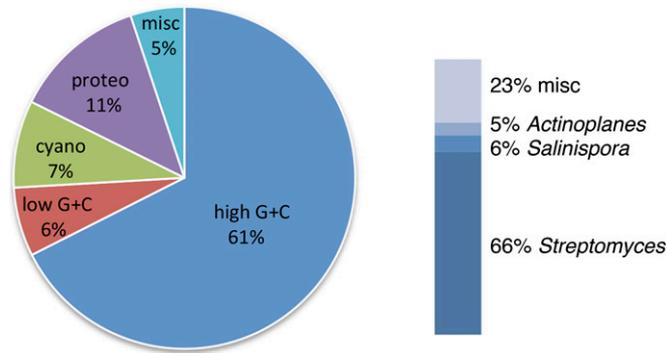


Fig. 55. Taxonomic assignments of top BLAST matches for OBUs observed in one strain (singletons). Cyano, cyanobacteria; proteo, proteobacteria.

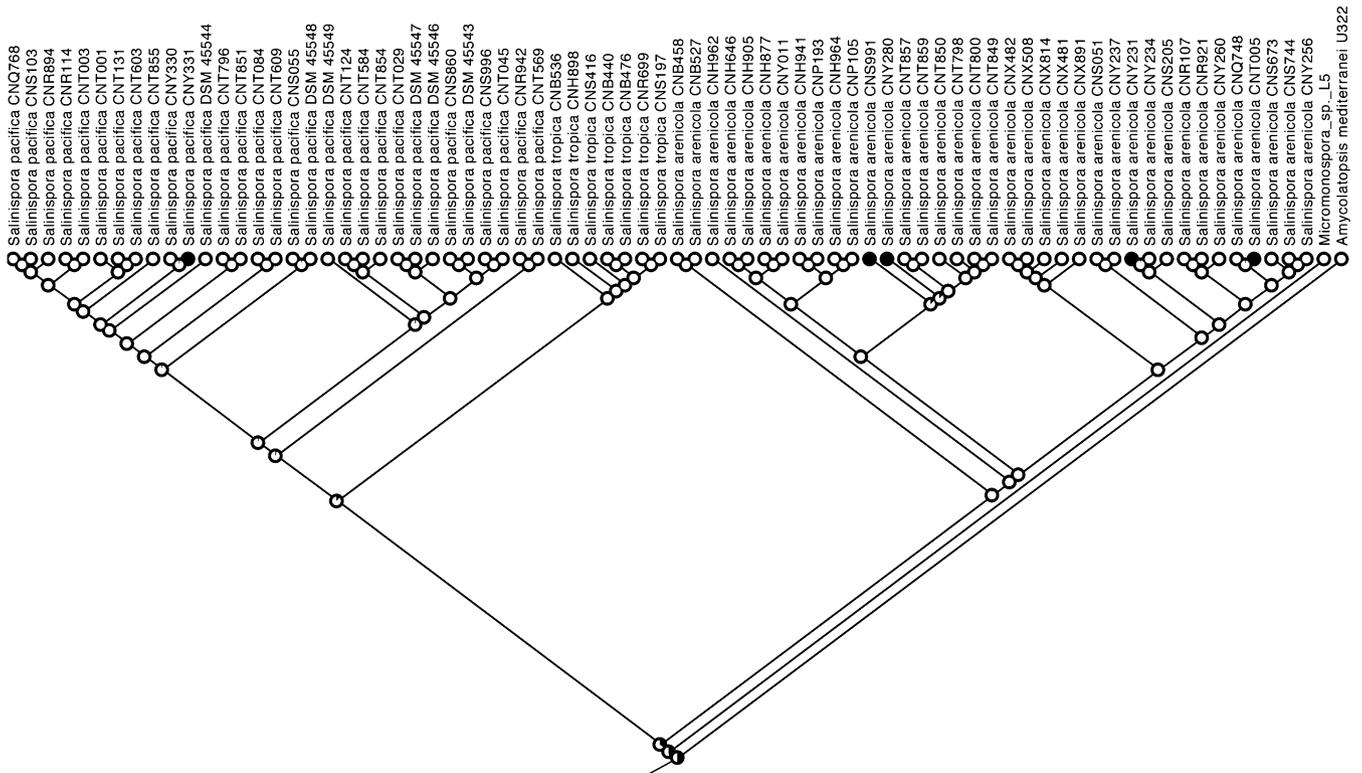


Fig. 56. Location-specific pathway acquisition. Likelihood analysis showing multiple ancestral nodes for PKS17 on the *Salinispora* species tree (black circles). This result was used to infer that the OBU had been acquired independently by four *S. arenicola* strains from Fiji (CNS-991, CNT-005, CNY-231, and CNY-280) and one *S. pacifica* strain from the Sea of Cortez (CNY-331).

Table S1. *Salinispora* strains and sequence accession numbers

Species and strain	IMG genome ID	NCBI taxon ID
<i>S. arenicola</i> CNB-458	2517572210	1136425
<i>S. arenicola</i> CNB-527	2515154093	1137250
<i>S. arenicola</i> CNH-646	2515154181	1136427
<i>S. arenicola</i> CNH-877	2519103192	1169176
<i>S. arenicola</i> CNH-905	2515154183	1137251
<i>S. arenicola</i> CNH-941	2515154193	1137252
<i>S. arenicola</i> CNH-962	2519103193	1169175
<i>S. arenicola</i> CNH-964	2515154125	1136430
<i>S. arenicola</i> CNP-105	2518285551	1169174
<i>S. arenicola</i> CNP-193	2518285552	1169170
<i>S. arenicola</i> CNQ-748	2515154180	1144929
<i>S. arenicola</i> CNR-107	2519103194	1169167
<i>S. arenicola</i> CNR-921	2515154203	1136429
<i>S. arenicola</i> CNS-205	641228504	391037
<i>S. arenicola</i> CNS-991	2516143022	999546
<i>S. arenicola</i> CNS-051	2518285553	1169178
<i>S. arenicola</i> CNS-673	2519103185	1144930
<i>S. arenicola</i> CNS-744	2518285554	1169168
<i>S. arenicola</i> CNT-005	2517572137	1137255
<i>S. arenicola</i> CNT-798	2515154186	1137256
<i>S. arenicola</i> CNT-800	2515154088	1137253
<i>S. arenicola</i> CNT-850	2515154135	1136428
<i>S. arenicola</i> CNT-857	2515154127	1137254
<i>S. arenicola</i> CNT-859	2517572233	1169163
<i>S. arenicola</i> CNX-481	2518285555	1169169
<i>S. arenicola</i> CNX-482	2515154137	1136426
<i>S. arenicola</i> CNX-508	2515154188	1137257
<i>S. arenicola</i> CNX-814	2517572152	1169171
<i>S. arenicola</i> CNX-891	2515154187	1137258
<i>S. arenicola</i> CNY-011	2517572153	1169162
<i>S. arenicola</i> CNY-231	2518285558	1169179
<i>S. arenicola</i> CNY-234	2519103195	1169165
<i>S. arenicola</i> CNY-256	2518285559	1169166
<i>S. arenicola</i> CNY-260	2518285560	1169177
<i>S. arenicola</i> CNY-280	2517572154	1169173
<i>S. pacifica</i> CNQ-768	2517572155	1169193
<i>S. pacifica</i> CNR-114	2515154178	1137260
<i>S. pacifica</i> CNR-894	2515154194	1137261
<i>S. pacifica</i> CNR-942	2518285561	1169187
<i>S. pacifica</i> CNS-055	2518285562	1169182
<i>S. pacifica</i> CNS-103	2515154129	1137262
<i>S. pacifica</i> CNS-860	2518285563	1169186
<i>S. pacifica</i> CNS-996	2517572157	1169189
<i>S. pacifica</i> CNT-001	2515154184	1136416
<i>S. pacifica</i> CNT-003	2515154126	1136417
<i>S. pacifica</i> CNT-029	2515154177	1136418
<i>S. pacifica</i> CNT-045	2517572158	1169190
<i>S. pacifica</i> CNT-084	2515154202	1136419
<i>S. pacifica</i> CNT-124	2517572159	1169188
<i>S. pacifica</i> CNT-131	2515154200	1136420
<i>S. pacifica</i> CNT-569	2515154124	1137263
<i>S. pacifica</i> CNT-584	2517572160	1169191
<i>S. pacifica</i> CNT-603	2515154185	1136424
<i>S. pacifica</i> CNT-609	2517572161	1169184
<i>S. pacifica</i> CNT-796	2515154182	1206102
<i>S. pacifica</i> CNT-849	2518285550	1137264
<i>S. pacifica</i> CNT-851	2517572162	1169180
<i>S. pacifica</i> CNT-854	2515154170	1137265
<i>S. pacifica</i> CNT-855	2515154128	1137266
<i>S. pacifica</i> CNY-237	2517572163	1169185
<i>S. pacifica</i> CNY-330	2518645626	1169192
<i>S. pacifica</i> CNY-331	2518645627	1169181
<i>S. pacifica</i> DSM-45543	2517572194	168694

Table S1. Cont.

Species and strain	IMG genome ID	NCBI taxon ID
<i>S. pacifica</i> DSM-45544	2517287019	999543
<i>S. pacifica</i> DSM-45546	2516653042	1050198
<i>S. pacifica</i> DSM-45547	2516493032	1050199
<i>S. pacifica</i> DSM-45548	2517287023	999544
<i>S. pacifica</i> DSM-45549	2517434008	999545
<i>S. tropica</i> CNB-440	640427140	369723
<i>S. tropica</i> CNB-476	2517572211	1137247
<i>S. tropica</i> CNB-536	2517572212	1136431
<i>S. tropica</i> CNH-898	2515154094	1137248
<i>S. tropica</i> CNR-699	2518645624	1169198
<i>S. tropica</i> CNS-197	2515154163	1137249
<i>S. tropica</i> CNS-416	2517572164	1169195

IMG, Integrated Microbial Genomes database; NCBI, National Center for Biotechnology Information.

Table S3. Pathway (OBU) distributions among *Salinispora tropica* strains

Pathway	Strain						
	CNB-440	CNB-476	CNB-536	CNH-898	CNS-197	CNS-416	CNR-699
PKS4	1	1	1	1	1	1	1
FAS1	1	1	1	1	1	1	1
NRPS4	1	1	1	1	1	1	1
lym	1	1	1	1	1	1	1
Sid1	1	1	1	1	1	1	1
lom	1	1	1	1	1	1	1
slm	1	1	1	1	1	1	1
sal	1	1	1	1	1	1	1
Sid3	1	1	1	1	1	1	1
Sid4	1	1	1	1	1	1	1
NRPS3	1	1	0	1	1	1	1
spo	1	1	0	1	1	1	1
STpks1	1	0	0	0	1	0	1
FAS5	0	0	1	1	0	0	0
NRPS36	0	0	1	1	0	0	0
cya	0	0	1	0	0	0	0
PKS41	0	0	1	0	0	0	0
PKS42	0	0	0	1	0	0	0
NRPS41	0	0	0	1	0	0	0

