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CRISPR-Cas9 enrichment, a new strategy in microbial metagenomics to investigate complex genomic regions: the case of an environmental integron

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1 CRISPR-CAS9 ENRICHMENT, A NEW STRATEGY IN MICROBIAL
2 METAGENOMICS TO INVESTIGATE COMPLEX GENOMIC REGIONS: THE CASE
3 OF AN ENVIRONMENTAL INTEGRON

4

5 **Running title**

6 **CRISPR-Cas9 enrichment for metagenomics**

7

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15 **Abstract**

16 Environmental integrons are ubiquitous in natural microbial communities, but they are
17 mostly uncharacterized and their role remains elusive. Thus far, research has been
18 hindered by methodological limitations. Here, we successfully used an innovative approach
19 combining CRISPR-Cas9 enrichment with long-read nanopore sequencing to target, in a
20 complex microbial community, a putative adaptive environmental integron, InOPS, and to
21 unravel its complete structure and genetic context. A contig of 20 kb was recovered
22 containing the complete integron from the microbial metagenome of oil-contaminated
23 coastal sediments. InOPS exhibited typical integron features. The integrase, close to
24 integrases of marine Desulfobacterota, possessed all the elements of a functional integron
25 integrase. The gene cassettes harboured mostly unknown functions hampering inferences
26 about their ecological importance. Moreover, the putative InOPS host, likely a
27 hydrocarbonoclastic marine bacteria, might question the adaptive potential of InOPS in
28 response to oil contamination. Additionally, several mobile genetic elements were
29 intertwined with InOPS highlighting likely genomic plasticity, and providing a source of
30 genetic novelty. This case study showed the power of CRISPR-Cas9 enrichment to
31 elucidate the structure and context of specific DNA regions for which only a short sequence
32 is known. This method is a new tool for environmental microbiologists working with complex

33 microbial communities to target low abundant, large or repetitive genetic structures that are
34 hard to recover by classical metagenomics. More precisely, here, it offers new perspectives
35 to comprehensively assess the eco-evolutionary significance of environmental integrons.

36

37 **Keywords**

38 complex genomic regions, CRISPR-Cas9 enrichment, environmental integrons, microbial
39 communities, microbial metagenomics, mobile genetic elements

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44 **1. Introduction**

45 Integrons are genetic elements that acquire, excise, rearrange and express gene cassettes
46 (Fig. 1) (Escudero *et al.*, 2015; Stokes & Hall, 1989). They are notorious for mediating bacterial
47 adaptation in clinical settings through the spread of antibiotic resistance genes (Escudero *et*
48 *al.*, 2015; Gillings, 2014; Souque *et al.*, 2021). Several clues suggest that integrons in the

49 environmental may also participate in the bacterial functional response to selective pressures,
50 *e.g.*, their occurrence in numerous environments (*e.g.*, Abella, Bielen, *et al.*, 2015; Abella,
51 Fahy, *et al.*, 2015; Antelo *et al.*, 2021; Boucher *et al.*, 2007; Elsaied, Stokes, Nakamura *et al.*,
52 2007; Elsaied, Stokes, Kitamura *et al.*, 2011; Elsaied, Stokes, Yoshioka *et al.*, 2014; Ghaly,
53 Penesyan *et al.*, 2022; Mazel, 2006; Nemergut *et al.*, 2004; Stokes *et al.*, 2001), distribution in
54 diverse bacterial taxa (Cambray *et al.*, 2010; Cury *et al.*, 2016), wide gene cassette functional
55 repertory (*e.g.*, Ghaly, Geoghegan *et al.*, 2019; Pereira *et al.*, 2020), and relation to
56 environmental disturbances (Abella, Fahy, *et al.*, 2015; Elsaied, Stokes, Kitamura *et al.*, 2011;
57 Koenig, Boucher *et al.*, 2008; Koenig, Sharp *et al.*, 2009; Nemergut *et al.*, 2004). Nonetheless,
58 in contrast to clinical integrons, environmental integrons remain mostly uncharacterized and
59 their role is still elusive (Sandoval-Quintana *et al.*, 2022).

60 Establishing their adaptive role in the environment requires the characterization of their
61 complete genetic structures including the integrase gene, gene cassettes, recombination sites,
62 and the genetic context, to reveal the function of their gene cassettes, their functionality, their
63 dynamics and eventually, their host. However, targeting putative adaptive integrons and their
64 complete platforms in complex communities is a difficult task hindered by methodological
65 limitations (Pereira *et al.*, 2020; Sandoval-Quintana *et al.*, 2022). To date, integrons in natural
66 environments have been mainly recovered through amplicon sequencing (*e.g.*, Abella, Bielen

67 *et al.*, 2015; Antelo *et al.*, 2021; Ghaly, Geoghegan *et al.*, 2019; Ghaly, Penesyan *et al.*, 2022).
68 Because of the constraints imposed by the design of the primers located in the conserved and
69 known regions of integrases and recombination sites (Elsaied, Stokes, Nakamura *et al.*, 2007;
70 Stokes *et al.*, 2001) and the impediments in amplifying large fragments, efforts have until
71 recently mainly focused either on gene cassettes (e.g., Ghaly, Geoghegan *et al.*, 2019; Koenig,
72 Boucher *et al.*, 2008; Koenig, Sharp *et al.*, 2009; Stokes *et al.*, 2001) or integrase genes (e.g.
73 Abella, Bielen *et al.*, 2015; Elsaied, Stokes, Nakamura *et al.*, 2007; Nield *et al.*, 2001),
74 preventing the comprehensive examination of entire environmental integron platforms.

75 Although these efforts did reveal the extent of their diversity, their dynamics (integration,
76 excision events, dispersal) were poorly assessed, despite attempts to infer ongoing integron-
77 response to selective pressures being developed (Huang *et al.*, 2009). Overall, however, all
78 these PCR-based strategies are still impaired by the well-known PCR bias, the inability to
79 position gene cassettes in the array, and the difficulties of designing universal primers to target
80 environmental integrons. Together with PCR approaches, DNA/DNA hybridization screening
81 techniques were also used to recover novel environmental integrases from large metagenomic
82 clone libraries (Jacquiod *et al.*, 2014, Moura, Henriques *et al.*, 2010). Nevertheless, this
83 approach can suffer from parasite signals, unspecific probe hybridization, and low target
84 recovery (Jacquiod *et al.*, 2014; Moura, Henriques *et al.*, 2010).

85 Whole genome and metagenome sequencing and subsequent analyses with adequate
86 bioinformatic tools offer the opportunity to mine for integrons in isolated strains and in
87 uncultured microorganisms, respectively (Cury *et al.*, 2016; Pereira *et al.*, 2020). Nevertheless,
88 the highly fragmented nature of shotgun sequence data and the frequent association of
89 integrons to repetitive regions (Pereira *et al.*, 2020; Sonbol & Siam, 2021) have often impeded
90 the assembly of large contigs, and thus, the recovery of full-length integrons preventing further
91 conclusions about their ecological-evolutionary significance.

92 The main objective of our study was to propose a new methodology to recover the complete
93 platforms of putative adaptive integrons to investigate their role in the environment. The first
94 step of the study consisted in the identification of a putative adaptive integron in a complex
95 microbial community. We thus experimentally mimicked an environmental disturbance, an oil
96 contamination, on coastal sediments maintained in mesocosms. We then proposed a new
97 approach based on CRISPR-Cas9 enrichment to recover the InOPS environmental integron
98 from the complex microbial metagenome. This method allowed successfully to decipher the
99 complete structure of InOPS, highlighting its relevance to assess the eco-evolutionary
100 significance of this integron.

101

102 2. Material and methods

103 2.1. Coastal sediment samples

104 Coastal marine sediments (Atlantic Ocean, Brittany, France) were maintained during 9
105 months in mesocosms as previously described (Stauffert *et al.*, 2013). Mesocosms were
106 contaminated by oil addition (OIL). Control mesocosms (CTRL) were maintained without
107 contamination. Samples (0 to 2 cm depth) were collected at different times: just after the oil
108 contamination (T0), after one month, six months, and nine months.

109 2.2. Identification and quantification of *intI*OPS

110 Metagenomic DNA was extracted with Ultraclean soil DNA isolation kit (MoBio Laboratories,
111 Carlsbad, CA, USA). Integron integrase gene (*intI*) libraries of approximately 770 bp fragments
112 were obtained from mesocosms incubated during 9 months under oil contamination or no
113 contamination as previously described (Abella, Fahy, *et al.*, 2015). Sanger sequencing was
114 performed by GATC Biotech (Ebersberg, Germany). Sequences were corrected with
115 Sequencher® (Accession numbers: FR718193-FR718248), then were clustered at 100%
116 identity using CD-HIT (Fu *et al.*, 2012) before calculating Shannon (Shannon, 1948), evenness
117 (Pielou, 1966), and coverage (Good, 1953) indexes.

118 Quantitative PCRs were performed in duplicate on metagenomic DNA from mesocosms.
119 DNA was quantified with Quant-iT™ PicoGreen® dsDNA (Invitrogen, Waltham, MA, USA).

120 Standard curves, constructed with plasmid carrying cloned genes, were used to quantify
121 *intIOPS* and 16S rRNA genes, respectively. The primers ICC60 (5'-
122 GAAACCGTTCGGTTGAGGGTC-3') and ICC71 (5'-TTTACGGGCCAGCGCACCGGG-3')
123 were used to specifically amplify *intIOPS*. The primers 338F and 518R (Lane, 1991) were used
124 to amplify the 16S rRNA genes. The reaction mixture contained 1 μ L of template DNA, 0.2 μ M
125 of each primer and 12.5 μ L of Power SYBR® green PCR master mix (Applied Biosystem,
126 Waltham, MA, USA) for a final volume of 25 μ L. All real-time PCRs were performed on a
127 MX3005P (Stratagene, San Diego, CA, USA). Amplification parameters were as follows: 10
128 min at 95°C, 40 cycles of 30 s at 95°C, 30 s at 56°C (*intIOPS* gene) or 55°C (16S rRNA gene),
129 and 45 s at 72°C. After amplification, a melting curve was carried out to confirm the
130 amplification of specific products.

131 **2.3. CRISPR-Cas9 targeted enrichment of InOPS from metagenomic DNA coupled** 132 **to nanopore sequencing**

133 High molecular weight (HMW) DNA was obtained using the DNeasy PowerSoil Pro Kit
134 (QiAgen, Hilden, Germany) with slight modifications to prevent DNA shearing. DNA
135 quantification was performed using the Qubit™ dsDNA BR Assay Kit (Thermo Fisher Scientific,
136 Waltham, MA, USA). DNA quality and integrity were assessed through standard absorbance
137 ratios and using a 4200 TapeStation System (Agilent, Santa Clara, CA, USA), respectively.

138 CRISPR RNA (crRNA) specific probes were designed to target *intIOPS* within the integron
139 integrase additional domain region (Messier & Roy, 2001), according to several criteria,
140 including probe directionality (here, upstream or downstream the region of interest),
141 downstream presence of a protospacer adjacent motif (PAM) site (5' - NGG - 3'), and on-target
142 efficiency score (Stangl *et al.*, 2020). crRNA were designed mainly using the *IDT Custom Alt-*
143 *R® CRISPR-Cas9 gRNA tool* (IDT, Coralville, IA, USA) and additionally *CHOPCHOP* (Labun
144 *et al.*, 2019) and *CRISPOR* (Concordet & Haeussler, 2018). As working with metagenomes,
145 no reference genome and no off-target values were considered. One crRNA (5'-
146 AAAAAGGCGGAAAAGAGCTG -3') was designed to uncover the unknown 5' part of the
147 integron, expected to be its genetic context. The other crRNA (5'-
148 TCCACCGACAAGGTTTTGGA -3') was designed to uncover the unknown 3' part of the
149 integron, expected to be the gene cassette array. Custom Alt-R® crRNAs were ordered from
150 Integrated DNA Technologies (IDT, Coralville, IA, USA).

151 Cleavage of a 378 bp amplicon of the target DNA obtained with ICC66
152 (5'-GATCGACAACCATGGGGGAG-3') and ICC67 (5'-TGGTGACGCCGCTTGACACC-3')
153 primers was performed to validate the efficiency of the crRNAs prior to metagenomic
154 enrichment. Digestion was performed according to IDT recommendation (*Alt-R CRISPR-Cas9*
155 *system—in vitro cleavage of target DNA with RNP complex* protocol) with slight modifications

156 (excess of ribonucleoprotein complexes (RNPs) for digestion, 20 min digestion and addition of
157 a final step at 72°C for 5 min to inactivate proteinase K and obtain the complete Cas9 release)
158 and checked on a 4200 TapeStation System (Agilent).

159 CRISPR-Cas9 mediated enrichment of InOPS from HMW metagenomic DNA was
160 performed following the protocol of (Stangl *et al.*, 2020). Two enrichments were independently
161 performed, one with the crRNA targeting the genetic context and the other with the crRNA
162 targeting the gene cassette array. In brief, approximately 4.3 µg of HMW metagenomic DNA
163 were dephosphorylated. crRNA was annealed to the trans-activating CRISPR RNA (tracrRNA)
164 and then, RNP were formed by adding HiFi Cas9 enzyme (IDT, Coralville, IA, USA). The Cas9
165 RNP were mixed with the dephosphorylated DNA, dATP and Taq polymerase to produce the
166 targeted double-strand breaks and facilitate dA-tailing. Oxford Nanopore Technologies (ONT)
167 specific sequencing adapters (SQK-LSK109, ONT, Oxford, UK) were ligated to the free
168 phosphorylated ends. Libraries were purified with Agencourt AMPure XP beads (Beckman
169 Coulter, Brea, CA, USA) with fragments below 3 kb washed away. The DNA concentration of
170 the enriched libraries was measured using the Qubit™ dsDNA BR Assay Kit (Thermo Fisher
171 Scientific). The two libraries were pooled prior to sequencing on a single ONT flow cell (R9.4,
172 ONT, Oxford, UK) according to the manufacturer's protocol. Sequencing was performed on a

173 GridION X5 instrument (ONT, Oxford, UK; Utrecht Sequencing Facility, Utrecht, The
174 Netherlands).

175 **2.4. Characterization of the InOPS contig**

176 Base-calling of nanopore reads was performed by Guppy (ONT, Oxford, UK) with the high
177 accuracy model (Q-score cut-off >7). Sequencing library statistics were generated using
178 Nanoplot (v 1.28.2) (De Coster *et al.*, 2018). ONT adapters were trimmed off using Porechop
179 (v. 0.2.4) (Wick, 2018) with default parameters. Reads were mapped to the *intIOPS* reference
180 sequence (FR718193.1) using primarily minimap2 (-x -map-ont) (v. 2.6) (Li, 2018), then BWA-
181 MEM (-k:12, -O:4, -L: 5, -B: 1, -U:12) (v. 0.7.17) (Li & Durbin, 2010) and NCBI BLAST+ blastn
182 (v. 2.10.1) (Camacho *et al.*, 2009) with default parameters for accuracy. Files were sorted and
183 indexed with Samtools (v. 1.4.1) (Li *et al.*, 2009) and Bamtools (v. 2.4.0) (Barnett *et al.*, 2011).
184 Sequences were aligned to the *intIOPS* reference sequence with the MUSCLE Multiple
185 Alignment tool (Edgar, 2004). A manually curated consensus was created. This contig (InOPS
186 contig) bearing the InOPS integron was validated by Sanger sequencing.

187 The contig was annotated using different annotation tools and pipelines to gain as much
188 accuracy as possible. The open reading frames (ORFs) and coding sequences were predicted
189 using Prokka (--meta and --evaluate 1e-06) (v. 1.14.6) (Seemann, 2014), DFAST (--
190 Metageannotator) (v. 1.5.0) (Tanizawa *et al.*, 2018), RASTtk (Brettin *et al.*, 2015), Contig

191 Annotation Tool (CAT_prepare_20210107 and --add_names) (v. 5.0.3) (von Meijenfeldt *et al.*,
192 2019), MetaGeneAnnotator (--meta option) (Noguchi *et al.*, 2008), MetaGeneMark (v. 3.25)
193 (Zhu *et al.*, 2010) and/or GeneMarkS (Besemer *et al.*, 2001)/S-2 (Lomsadze *et al.*, 2018).
194 Integron Finder (v. 1.5.1) (Cury *et al.*, 2016) was used for integron detection (--local-max
195 --evaluate-attc 1) and *attC* sites detection (--local-max --evaluate-attc 4 and --dt 6000). *attC*
196 secondary structure was predicted using *mfold* (UNAFold) (Markham & Zuker, 2008) and the
197 RNAfold program (ViennaRNA Package) (-- p -d2) (Lorenz *et al.*, 2011). The *attI* site was
198 searched manually and aligned against an *attI* site database constructed from (Collis & Hall,
199 2004; Elsaied, Stokes, Kitamura *et al.*, 2011; Nield *et al.*, 2001; Partridge *et al.*, 2000).
200 Promoters were identified using BPROM (Solovyev & Salamov, 2011) and PePPER (de Jong
201 *et al.*, 2012) and further manually curated. The putative functionality of the annotated genes
202 was inferred through Prokka, DFAST, RASTtk, EggNOG-mapper (--evaluate 0.001 --itype
203 metagenome --genepred prodigal --pfam_realign none) (v. 2.1.6) (Cantalapiedra *et al.*, 2021),
204 InterProScan (--pathways --goterms) (v. 5.54-87.0) (Jones *et al.*, 2014) and HMMER (--
205 hmmscan) (v. 2.41.2) (Potter *et al.*, 2018) against different databases (NCBI, SEED, Clusters
206 of Orthologs Groups (COGs), Pfam, SMART, TIGRFAM, SFLD, SUPERFAMILY, PANTHER,
207 Gene3d, HAMAP, PROSITE, Coils, PRINTS, PIRSR, PIRSF). The genes annotated as
208 putative gene cassettes were confronted to the INTEGRALL database (Moura, Soares *et al.*,

209 2009) using local BLASTn algorithm. Kraken2 (v. 2.1.1) (Wood *et al.*, 2019) and CAT were
210 used to perform taxonomic classification of the annotated genes.

211 Insertion sequences (IS) were annotated using ISsaga (v. 2.0) (Varani *et al.*, 2011) and
212 OASIS (Robinson *et al.*, 2012). The putative insertion sequences (IS) were further analysed
213 with the ISFinder (Siguiet *et al.*, 2006) BLAST interface. IS putative ORFs were compared
214 against local IS91 and ISCR databases through local Blastp algorithm. Group II introns were
215 identified against the bacterial Group II intron database (Candales *et al.*, 2012).

216 For synteny analysis, the annotated genes within the InOPS contig were compared to
217 databases through BLAST searches (<https://blast.ncbi.nlm.nih.gov/Blast.cgi>): *blastn* against
218 the *nr/nt* database and the *wgs* database (*Desulfobacterales* taxid: 23118); *blastx* and *blastp*
219 against *nr/nt* and *env_nr* databases (NCBI). Resultant genomes (> 70% identity and 50%
220 coverage) were downloaded from NCBI constituting a database of 76 genomes after
221 dereplication. The genomic dataset was submitted to M1CR0B1AL1Z3R (Avram *et al.*, 2019)
222 along with the InOPS contig. Two different ortholog detections (≥ 80 or 50% identity and 0.01
223 as maximal *e-value*) were performed. To refine the ortholog detection, a second
224 M1CR0B1AL1Z3R was run over the genomes which produced a hit in the first run.
225 SimpleSynteny (Veltri *et al.*, 2016) was used for visualization with parameters in regular mode
226 (1 *e-value* and 25% coverage) using the *all-to-all comparison* mode.

227 2.5. Conservation and phylogeny of the InOPS integrase

228 InOPS integrase (IntIOPS) was compared against available databases (INTEGRALL
229 (Moura, Soares *et al.*, 2009) and NCBI) using BLAST (<https://blast.ncbi.nlm.nih.gov/Blast.cgi>)
230 in *blastn*, *blastx* and *blastp* mode. IntIOPS, IntI1-4 (AHL30833.1, AAT72891.1, AAO32355.1,
231 AAC38424.1) whose functionality has been largely studied, IntIs issued from natural
232 environments (IntINeu: WP_011112687.1, InPstQ: AAN16061.1, SamIntIA: WP_011759470.1,
233 IntIPac: AAK73287.1, IntISon: WP_011072111.1) whose activity has been experimentally
234 proved and the *Escherichia coli* XerD recombinase (P0A8P8.1) were aligned using MUSCLE
235 Multiple Alignment tool (Edgar, 2004). The alignment was manually edited with BioEdit®
236 software.

237 For the IntI tree, a dataset was built by selecting 128 amino acid sequences of complete
238 integron integrases (IntI). Sequences were retrieved from *nr/nt* and *env_nr* databases (NCBI)
239 using both *blastx* and *blastp* and selected based on their identity to the integrase of the InOPS
240 integron, IntIOPS ($\geq 50\%$ identity and coverage). To avoid redundancy, the sequences were
241 clustered to 90% identity using CD-HIT. Within each cluster, the representative sequence was
242 kept and, considering its environmental origin, the closest sequence from each different
243 environmental origin, if any, were identified and kept too. Sequences of clinical IntIs, IntI1-IntI4
244 (AHL30833.1, AAT72891.1, AAO32355.1, AAC38424.1), and the integron integrases

245 belonging to the genus *Desulfosarcina* (WP_051374975.1, WP_027353082.1, BBO66607.1,
246 BBO93164.1, BBO87010.1, BBO79603.1, WP_083456647.1, WP_198012316.1,
247 WP_155322972.1) were also included. The final dataset comprised 107 integron integrase
248 sequences. The tyrosine recombinase XerD sequence of *Escherichia coli* (P0A8P8.1) was
249 included as outgroup for the construction of the tree. Analysis were done using NGPhylogeny.fr
250 (Lemoine *et al.*, 2019) with the options of MAFFT align and BMGE alignment curation. The
251 PhyML program (Guindon *et al.*, 2010) was used for tree construction with the SMS option
252 (Lefort *et al.*, 2017) and a bootstrapping branch support of 1000. The tree was submitted to
253 iTOL (Letunic & Bork, 2021) for visualization and design.

254

255 3. Results

256 3.1. Mimicking environmental disturbance identified InOPS as a putative adaptive integrons

257 We investigated coastal sediments exposed to oil contamination in mesocosms to trigger
258 microbial community adaptive response (Stauffert *et al.*, 2013). We revealed, using PCR
259 targeting integron integrase genes (*intl*) (Abella, Bielen, *et al.*, 2015), the predominance of a
260 sequence, named *intlOPS*. This sequence represented nearly 27% (over 156 amplicon
261 sequences) of the *intl* pool in the amplicon libraries generated from the mesocosms incubated
262 under oil contamination while no *intlOPS* sequences (over 46 amplicon sequences) were

263 detected in the library generated from the control (without contamination). Diversity indexes
264 supported the lower diversity and divergent relative abundance of *intl* in the contaminated
265 sediments compared to the control (Shannon: 3.14 and 3.41 vs 3.61, Evenness: 0.82 and 0.87
266 vs 0.98). The increase of *intlOPS* after contamination was further supported using quantitative
267 PCR (Fig. S1). Therefore, *intlOPS* might belong to an environmental integron responding to
268 the oil contamination. We named this integron InOPS.

269 3.2. Based FUDGE CRISPR-Cas9 enrichment to target *intlOPS* integrase gene

270 The InOPS integron was recovered from the complex microbial metagenome by an
271 innovative approach derived from FUDGE (Stangl *et al.*, 2020), a CRISPR-Cas9 enrichment
272 method coupled to nanopore sequencing, that only targets a short-conserved sequence (Fig.
273 2A for full description). Two crRNAs were designed within a 62 bp region of the *intlOPS*
274 additional domain to obtain both flanking unknown regions (Fig. 2A, 2B). Sequencing of the
275 enriched nanopore libraries representing 1.21 Gb of sequence data resulted in 546 194 good
276 quality reads (N50: 3 337 bp, average read length: 1 453.6 bp). We recovered 90 reads
277 towards the 3' unknown part of the integron containing the array of gene cassettes (N50: 4 258
278 bp, longest read: 13 201 bp) and 51 reads towards the 5' unknown part of the integron
279 corresponding to the genetic context (N50: 4 146 bp, longest read: 8 606 bp) (Fig. 2B). Overall,

280 0.03% of the reads covered the targeted sequences. The consensus contig (20 069 bp) was
281 further polished using Sanger sequencing.

282 3.3. Unraveling the InOPS full integron platform structure and its genetic context

283 The contig annotation showed that the complete InOPS integron was recovered. It exhibited
284 the typical integron features (Sandoval-Quintana *et al.*, 2022): an integron integrase gene,
285 putative functional *attI* site, P_{intI} and P_c promoters and regulator binding sites, as well a gene
286 cassette array (Fig. 3; Fig. S2; Tables S1 and S2). The integrase possessed the catalytic
287 residues and most of the conserved motifs of integron integrases (Messier & Roy, 2001) (Fig.
288 S3) suggesting the enzyme is functional. It only presented 72% identity to its closest relative
289 and was divergent from the clinical integron integrase classes ($\leq 50\%$ identity). InOPS
290 integrase clustered with integron integrases issued from environmental sources, in a
291 consistent manner from marine environments from which InOPS originated, and with integron
292 integrases belonging to Desulfobacterota (Fig. S4).

293 The cassette array consists of 12 gene cassettes with their own *attC* recombination site.
294 Variable in length and sequences, 8 *attC* presented the typical secondary structure of *attC*
295 sites suggesting their possible recombinogenic activity (Fig. S5). Most gene cassettes (apart
296 the first one) encoded unknown functions or were ORFans, while others exhibited conserved

297 domains without obvious relationships with the oil contamination. Moreover, none were
298 referenced as gene cassettes in the INTEGRALL database (Moura, Soares *et al.*, 2009).

299 Interestingly, several mobile genetic elements (MGEs) were intertwined with InOPS. The
300 first gene cassette contained a complete IS of the IS91 family. IS91 can mobilize adjacent DNA
301 sequences and therefore participate in genomic plasticity (Garcillán-Barcia & de la Cruz,
302 2002). Here, it might disseminate InOPS elements. The 5' InOPS genetic context harbored a
303 complete IS1634 as well as other putative IS-like elements (Table S3). Such configurations
304 have been previously described (Cury *et al.*, 2016; Huyen *et al.*, 2020). A putative CALIN
305 embedded within this IS-rich region was also consistent with their frequent association with IS
306 (Cury *et al.*, 2016). Additionally, reverse transcriptase and maturase domains of a putative
307 group IIB intron were identified in the 3' InOPS genetic context. Of note, group II introns have
308 previously been observed associated with integrons (Léon & Roy, 2009; Sonbol & Siam, 2021),
309 and in some cases, hypothesized to be implicated in the genesis of gene cassettes (Léon &
310 Roy, 2009).

311 3.4. Deciphering the origin of InOPS

312 The lack of synteny evidenced that the configuration of ORFs within the contig is unique.
313 Variation in GC content over the contig clearly distinguished the gene cassettes (except IS91)
314 from the genetic context (Fig. 3), suggesting a different origin. The genetic context gave clues

315 about the InOPS host, likely belonging to Desulfobacterales (Table S1) and more precisely to
316 *Desulfosarcina ovata*, a sulfate-reducing hydrocarbon-degrading and marine bacteria
317 (Watanabe *et al.*, 2020). However, InOPS integrase divergence from *Desulfosarcina*
318 integrases suggests the acquisition of InOPS functional platform from another
319 Desulfobacterota (Fig. S4).

320

321 4. Discussion

322 With CRISPR-Cas9 enrichment we propose a new strategy in microbial metagenomics to
323 capture large and specific regions in a simple way, without DNA amplification, with minimum
324 required information, and avoiding time-consuming and haphazard metagenomic mining.
325 While all our previous attempts failed, thanks to CRISPR-Cas9 enrichment, we retrieved and
326 reliably deciphered the complete structure of the InOPS environmental integron. InOPS is an
327 example of low abundant metagenomic regions but also complex, harboring repetitive
328 sequences that jeopardize the use of standard metagenomic approaches.

329 Although the percentage of reads targeting the region we wished to study appeared low,
330 the reads generated was abundant enough to retrieve InOPS. This case study demonstrated
331 the efficiency of CRISPR-Cas9 enrichment in microbial metagenomics. It allowed to reach a
332 level of resolution rarely equaled in the study of environmental integrons. Most gene cassettes

333 encoded unknown functions or were ORFans, a common feature for environmental integrons
334 (Pereira *et al.*, 2020), raising more broadly the question about the origin of gene cassettes of
335 integrons. Thus, the functions of InOPS gene cassettes are mostly unresolved, precluding
336 conclusions about their ecological importance. Because we inferred the InOPS host, likely a
337 hydrocarbonoclastic marine bacteria, the adaptive potential of InOPS facing oil contamination
338 remains questionable. Tight association of InOPS with MGEs highlight that this region is
339 subjected to genomic plasticity, as previously suggested for integrons in hypersaline
340 environments (Sonbol & Siam, 2021), and might promote genetic novelty.

341 CRISPR-Cas9 enrichment offers the opportunity to reconsider studies that have previously
342 identified adaptive gene cassettes (e.g., Elsaied, Stokes, Yoshioka *et al.*, 2014; Koenig, Sharp
343 *et al.*, 2009; Nemergut *et al.*, 2004) or environmental integron integrases (e.g., Abella, Fahy,
344 *et al.*, 2015; Elsaied, Stokes, Nakamura *et al.*, 2007; Nield *et al.*, 2001). Compiling such case
345 studies, complemented with further molecular investigation on functionality and dynamics of
346 integrons, could serve as a lever to assess the eco-evolutionary significance of environmental
347 integrons. For instance, it could be of interest to decipher the interplay of environmental
348 integrons with MGEs more comprehensively.

349 Overall, InOPS constitute a proof of concept that opens perspectives to document the dark
350 matter of metagenomes and for which little information is available.

351

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- 618

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620 Data Accessibility and Benefit-Sharing**621 Data Accessibility Statement**

622 The raw sequences of the intl libraries are available in GenBank under the accession
623 numbers: FR718193-FR718248. The InOPS contig is available in Genbank under the
624 accession number ON260918.

625 Benefit-Sharing Statement

626 Benefits from this research accrue from the sharing of our data and results on public
627 databases as described above.

628

629 Author contributions

630 ESQ, BL and CC conceived and designed the study. BL and CC supervised the study. CC,
631 LH and RD collected the samples. CC and LH identified *intlOPS*. ESQ performed the CRISPR-
632 Cas9 experiments, analyzed the data and characterized the InOPS contig. CS, GM, and IR
633 contributed to the CRISPR-Cas9 enrichment and sequencing. BL, CC, RD and GH provided

634 fundings. ESQ, BL and CC wrote the manuscript. All authors read and approved the
 635 manuscript.

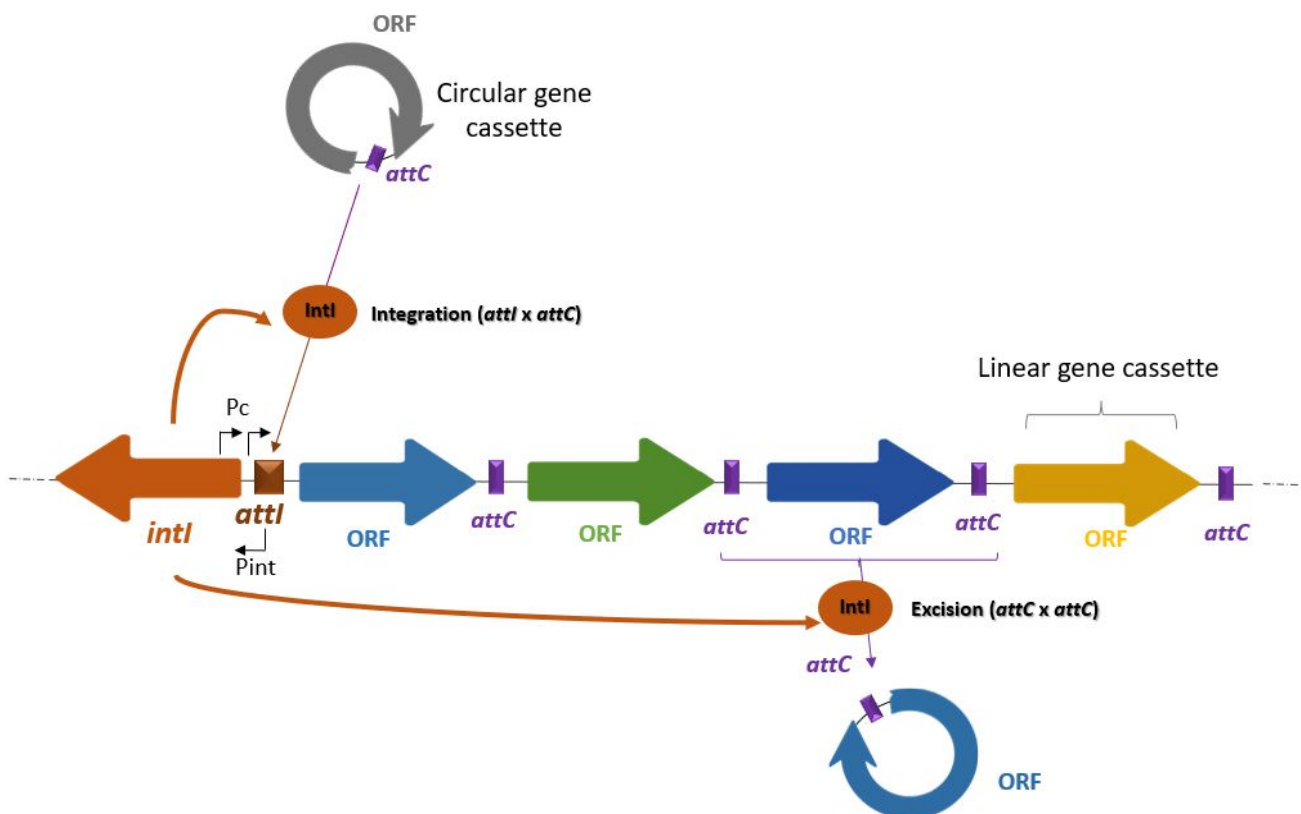
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640 **Figures with captions**

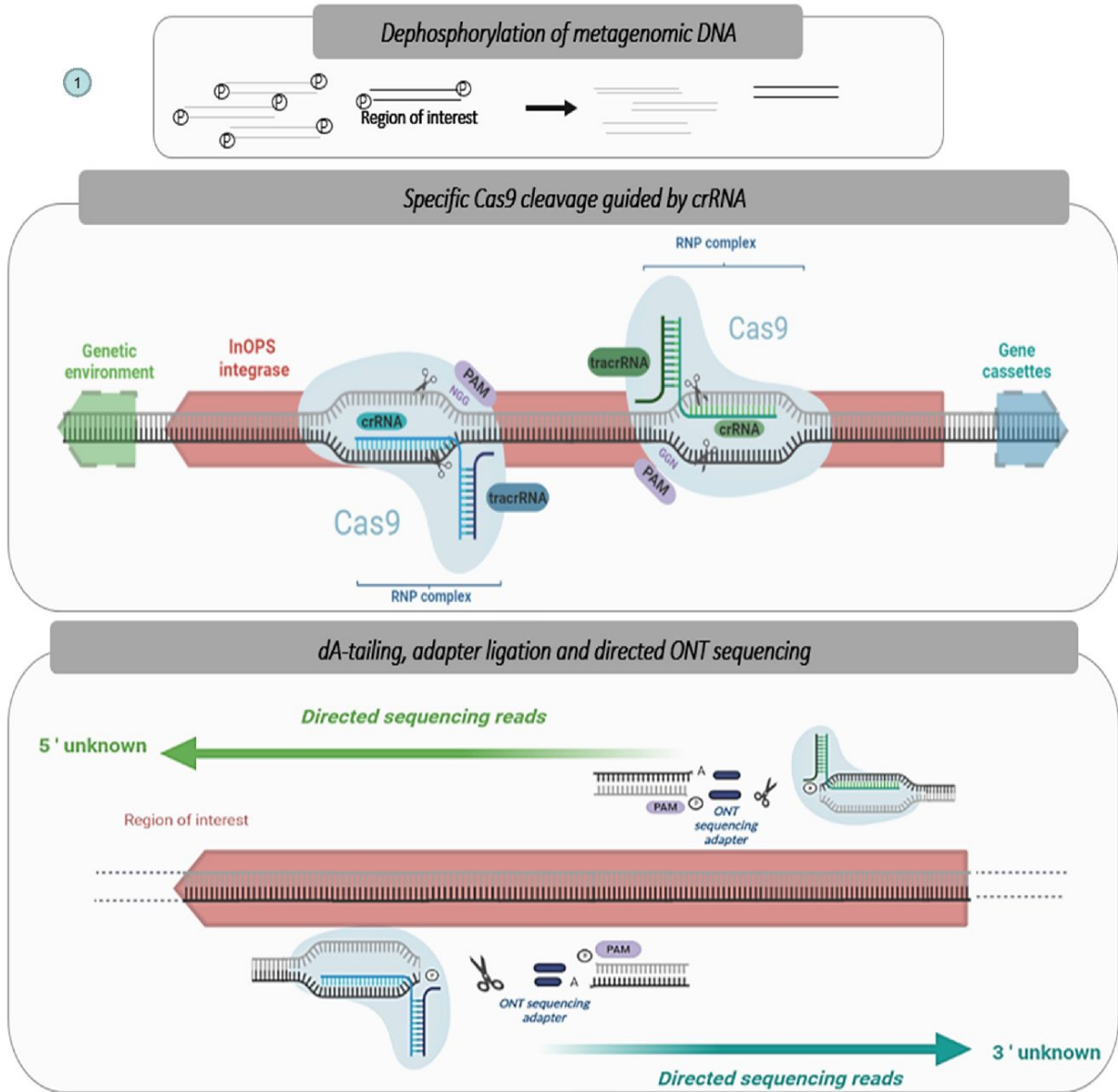


641 **Figure 1. Integron general structure and functioning.** Integrons are formed by a functional
 642 platform composed of a gene (*intI*) encoding an integrase (IntI), a promoter (*Pc*), and a
 643 recombination site (*attI*). Usually an array of gene cassettes follows this platform. The gene
 644 cassettes generally consist of an open reading frame (ORF) and a recombination site (*attC*).

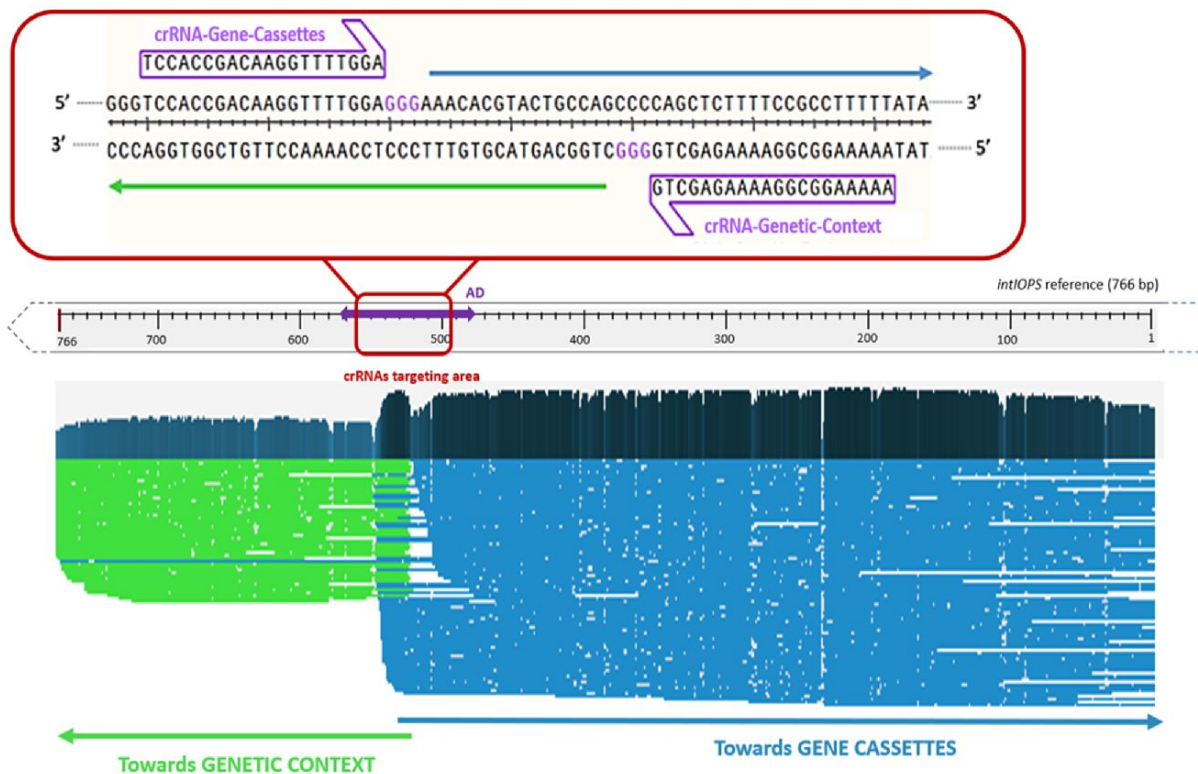
645 The integron integrase catalyses the insertion and excision of gene cassettes by site-specific
646 recombination. The promoters Pc (two possible locations) and PintI allow the expression of the
647 gene cassettes and integrase, respectively.

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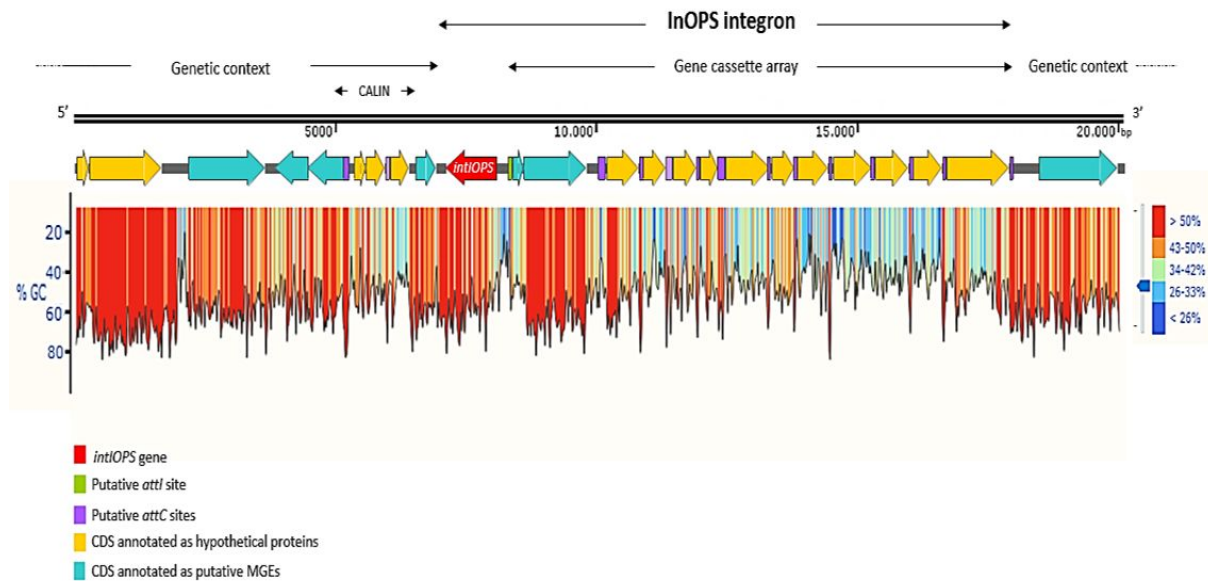
A.



B.



649 **Figure 2. Recovery of InOPS reads by CRISPR-Cas9 enrichment and nanopore sequencing.**
650 **A) General workflow of CRISPR-Cas9 enrichment.** 1) Dephosphorylation of metagenomic
651 DNA, 2) Specific Cas9 cleavages guided by the crRNAs. The two CRISPR RNA (crRNA) target
652 a short and known sequence of the region of interest, in order to ensure the sequencing of
653 both sides of this region in an overlapping manner. The design of crRNA requires the presence
654 of a PAM site (5'-NGG-3') on the target sequences. The crRNA and the trans-activating
655 CRISPR RNA (tracrRNA) link to the Cas9 nuclease constitute the ribonucleoprotein (RNP)
656 complex. Once bound to the DNA, Cas9 produce a double-strand cleavage in the DNA in the
657 15-30 bp prior to the PAM site. 3) dA-tailing, adapters ligation and directed ONT sequencing.
658 After dA-tailing, Oxford Nanopore Technology (ONT) specific sequencing adapters are ligated
659 only to the DNA containing the PAM sequence, while the other end is blocked by Cas9 enzyme.
660 Therefore, the sequencing is directed on only one direction spanning towards the unknown
661 region of the targeted sequence. Merging both enrichment allows to sequence at the same
662 time the whole region of interest. **B) Directional design of crRNA guides to target the gene**
663 ***intIOPS* and read mapping:** 1) the crRNAs target a region within the additional domain (AD) of
664 the InOPS integrase gene (*intIOPS*): positions 500 to 567 of the reference sequence (partial
665 *intIOPS*, accession number FR718193.1). The PAM sites (5'-NGG-3') are indicated in violet.
666 The arrows, in green and in blue, represent the direction of sequencing, towards the InOPS
667 genetic context (5' unknown of the integron) and towards the gene cassette array (3' unknown
668 of the integron), respectively. 2) Mapping of the recovered reads against the *intIOPS* reference
669 sequence.
670



671

672 **Figure 3. InOPS contig and annotated features.** The 20 069 bp InOPS contig is presented. The
 673 complete InOPS integron comprises the *intIOPS* gene (red) encoding an integron integrase
 674 and a gene cassette array. The *attI* (green) and *attC* (purple if search parameter: --value-attC
 675 1; lighter purple if search parameter: --value-attC 4) recombination sites are presented. A
 676 CALIN (cluster of *attC* sites lacking integron-integrases) is found within the 5'-InOPS genetic
 677 context. CDS encoding hypothetical proteins with no further annotation are represented in
 678 yellow. The CDS with annotations related to putative MGEs are represented in blue. The GC
 679 percentage along the contig is presented below the contig schema.

680

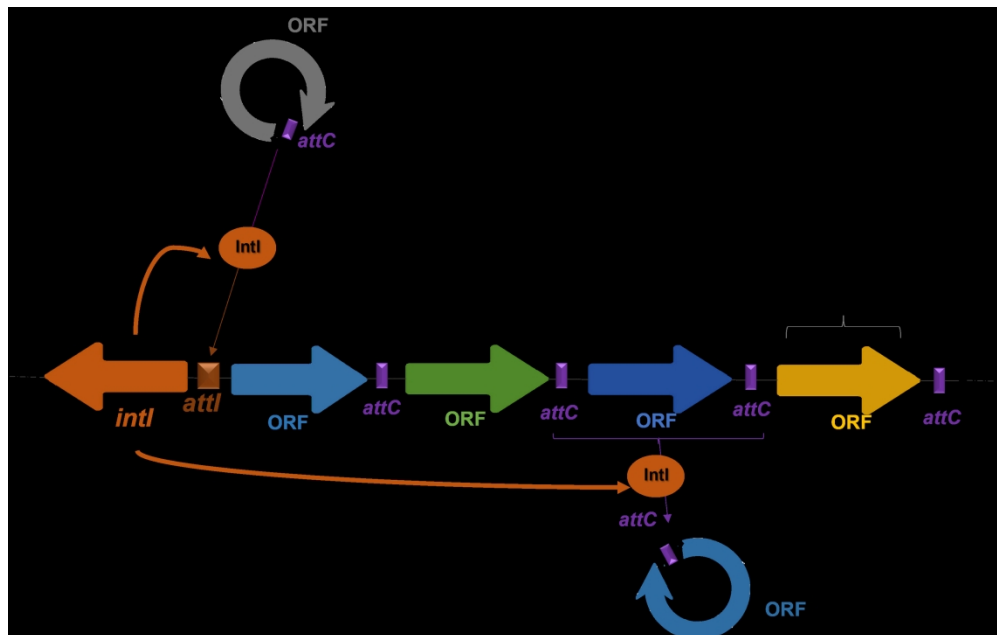
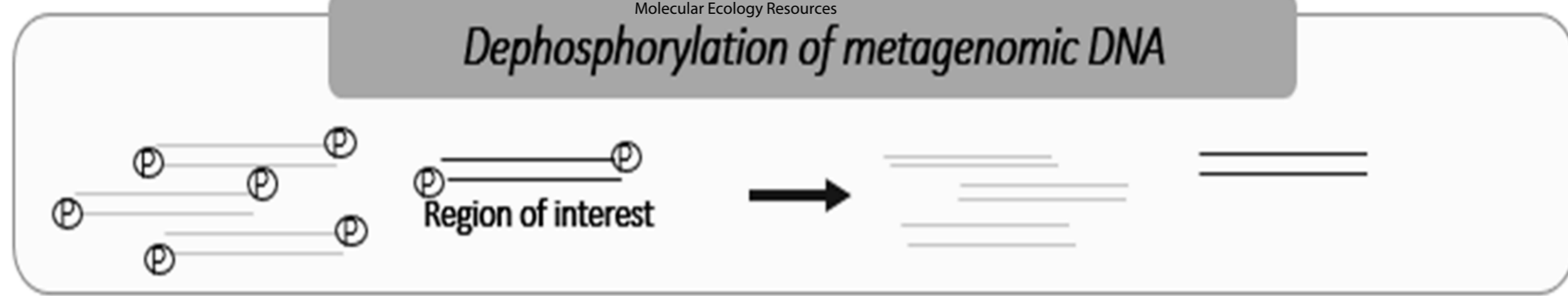


Figure 1. Integron general structure and functioning. Integrons are formed by a functional platform composed of a gene (*intI*) encoding an integrase (IntI), a promoter (*P_c*), and a recombination site (*attI*). Usually an array of gene cassettes follows this platform. The gene cassettes generally consist of an open reading frame (ORF) and a recombination site (*attC*). The integron integrase catalyses the insertion and excision of gene cassettes by site-specific recombination. The promoters *P_c* (two possible locations) and *P_{intI}* allow the expression of the gene cassettes and integrase, respectively.

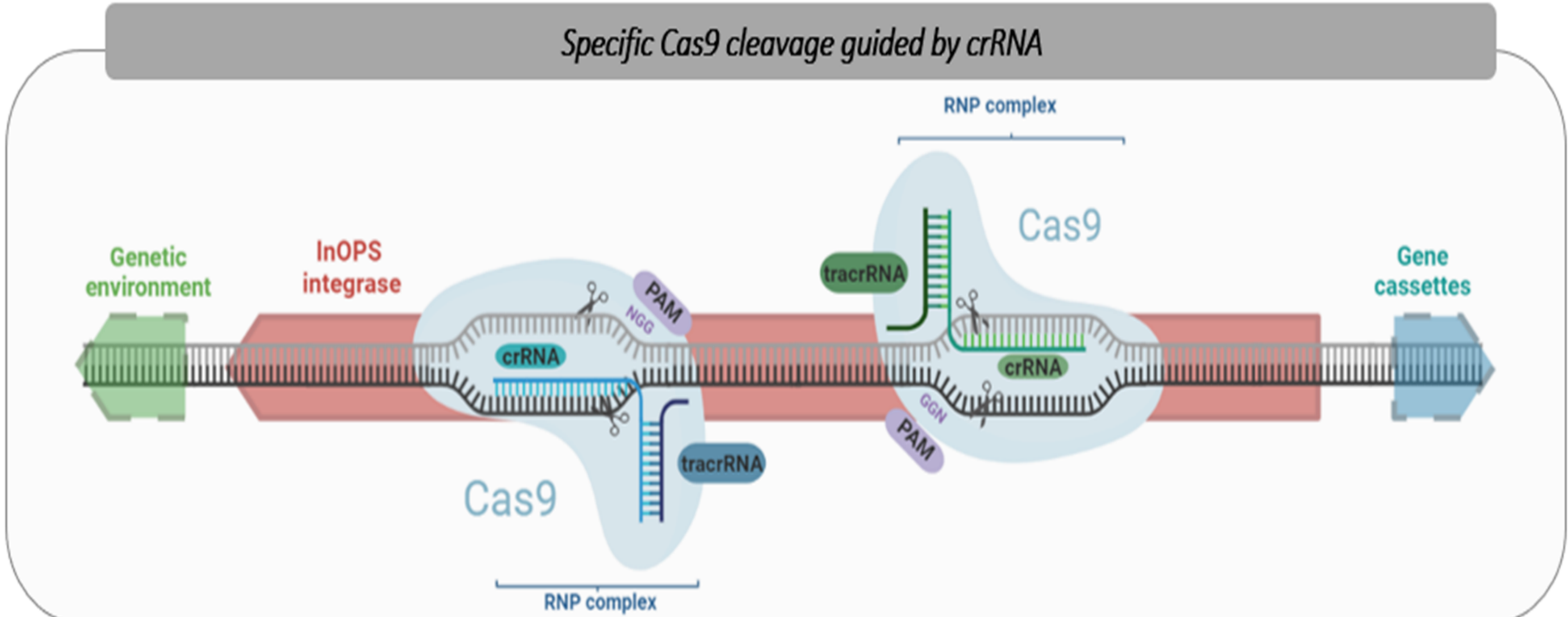
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A.

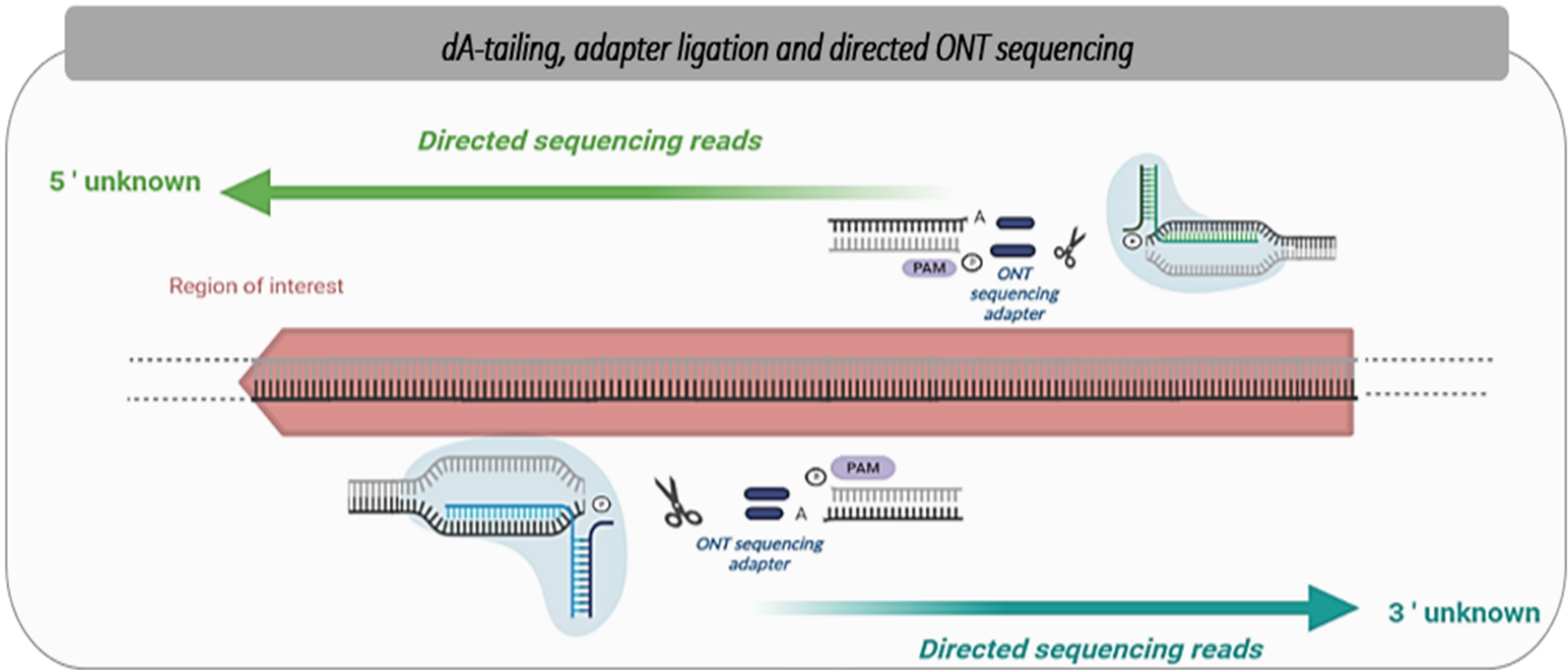
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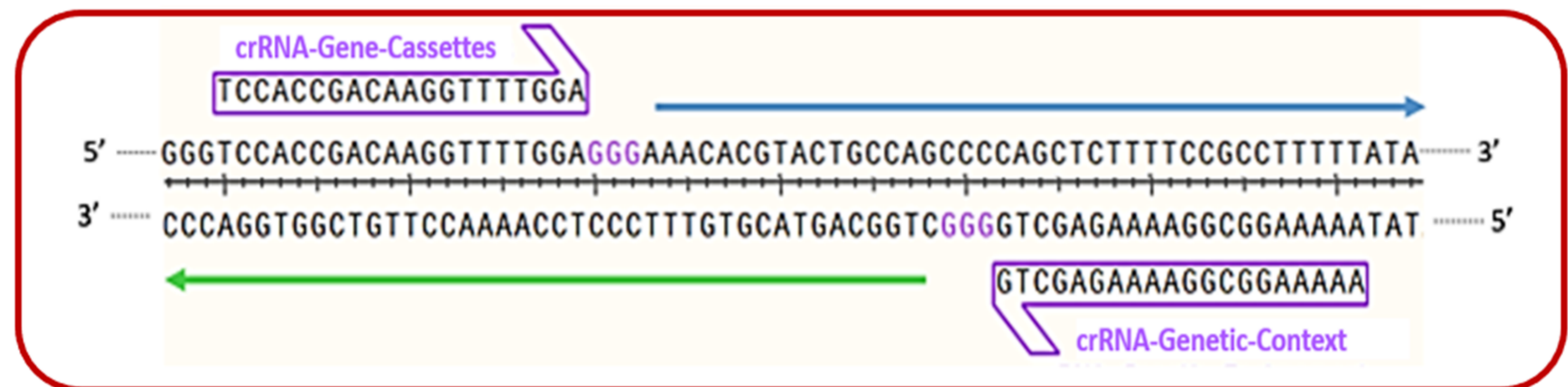


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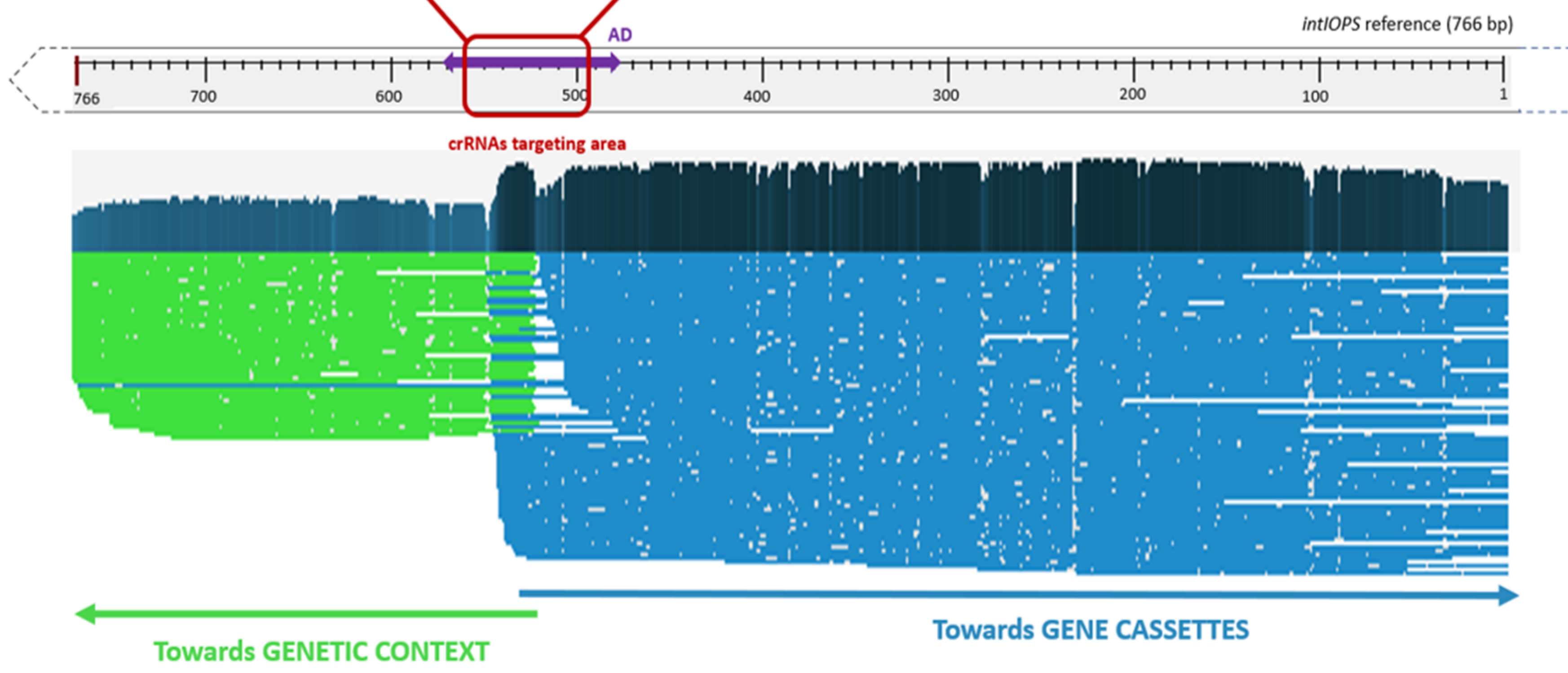


B.

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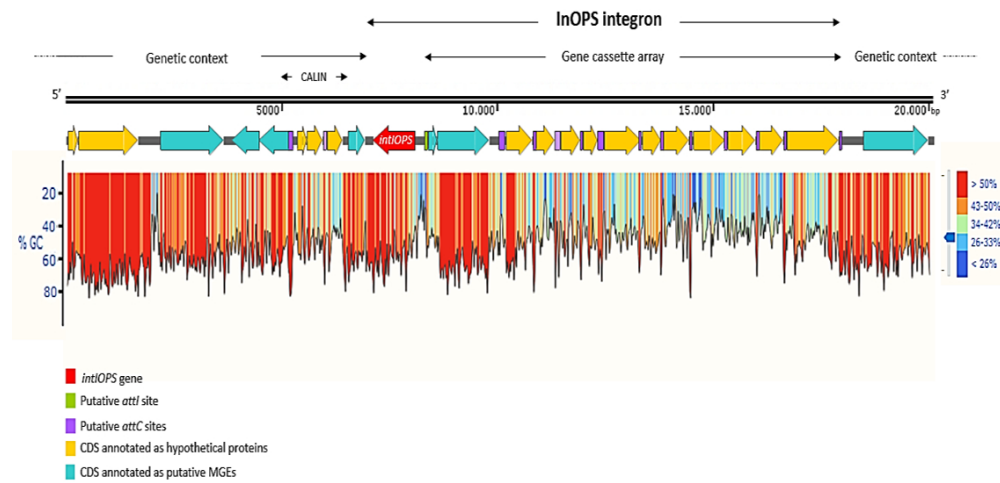


Figure 3. InOPS contig and annotated features. The 20 069 bp InOPS contig is presented. The complete InOPS integron comprises the *intIOPS* gene (red) encoding an integron integrase and a gene cassette array. The attI (green) and attC (purple if search parameter: --value-attC 1; lighter purple if search parameter: --value-attC 4) recombination sites are presented. A CALIN (cluster of attC sites lacking integron-integrases) is found within the 5'-InOPS genetic context. CDS encoding hypothetical proteins with no further annotation are represented in yellow. The CDS with annotations related to putative MGEs are represented in blue. The GC percentage along the contig is presented below the contig schema.

300x151mm (96 x 96 DPI)