Public Health Viral Genomics (Theiagen)

Release 1.4.3

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CONTENTS

CHAPTER

ONE

CONTENTS

1.1 Public Health Viral Genomics

The Theiagen Public Health Viral Genomics repository hosts a collection of WDL workflows for genomic characterization, submission preparation, and genomic epidemiology of the SARS-CoV-2 virus. While these workflows can be run locally or on an HPC system at the command-line with Cromwell or miniWDL, we strongly recommend use through Terra, a bioinformatics web application developed by the Broad Institute of MIT and Harvard in collaboration with Microsoft and Verily Life Sciences.

1.1.1 Getting Started

A series of introductory training videos that provide conceptual overviews of methodologies and walkthrough tutorials on how to utilize our WDL workflows through Terra are available on the Theiagen Genomics YouTube page:

1.1.2 Support

For questions or general support regarding the WDL workflows in this repository, please contact support@theiagen.com

1.2 Titan Workflow Series

The Titan Workflow Series is a collection of WDL workflows developed for performing genomic characterization and genomic epidemiology of viral samples to support public health decision-making. As of today (May 4th, 2021) these workflows are specific to SARS-CoV-2 amplicon read data, but work is underway to allow for the analysis of other viral pathogens of concern.

1.2.1 Titan Workflows for Genomic Characterization

Genomic characterization, *i.e.* generating consensus assemblies (FASTA format) from next-generation sequencing (NGS) read data (FASTQ format) to assign samples with relevant nomenclature designation (e.g. PANGO lineage and NextClade clades) is an increasingly critical function to public health laboratories around the world.

The Titan Series includes four separate WDL workflows (Titan_Illumina_PE, Titan_Illumina_SE, Titan_ClearLabs, and Titan_ONT) that process NGS read data from four different sequencing approaches: Illumina paired-end, Illumina single-end, Clear Labs, and Oxford Nanopore Technology (ONT)) to generate consensus assemblies, produce relevant quality-control metrics for both the input read data and the generated assembly, and assign samples with a lineage and clade designation using Pangolin and NextClade, respectively.

All four Titan workflows for genomic characterization will generate a viral assembly by mapping input read data to a reference genome, removing primer reads from that alignment, and then calling the consensus assembly based on the primer-trimmed alignment. These consensus assemblies are then fed into the Pangolin and NextClade CLI tools for lineage and clade assignments.

The major difference between each of these Titan workflows is in how the read mapping, primer trimming, and consensus genome calling is performed. More information on the technical details of these processes and information on how to utilize and apply these workflows for public health investigations is available below.

A series of introductory training videos that provide conceptual overviews of methodologies and walkthrough tutorials on how to utilize these Titan workflows through Terra are available on the Theiagen Genomics YouTube page:

Titan_Illumina_PE

The Titan_Illumina_PE workflow was written to process Illumina paired-end (PE) read data. Input reads are assumed to be the product of sequencing tiled PCR-amplicons designed for the SARS-CoV-2 genome. The most common read data analyzed by the Titan_Illumina_PE workflow are generated with the Artic V3 protocol. Alternative primer schemes such as the Qiaseq Primer Panel, however, can also be analysed with this workflow. The primer sequence coordinates of the PCR scheme utilized must be provided along with the raw paired-end Illumina read data in BED and FASTQ file formats, respectively.

Note: By default, this workflow will assume that input reads were generated using a 300-cycle kit (i.e. 2 x 150 bp reads). Modifications to the optional parameter for trimmomatic_minlen may be required to accommodate for shorter read data, such as 2 x 75bp reads generated using a 150-cycle kit.

Upon initiating a Titan_Illumina_PE job, the input primer scheme coordinates and raw paired-end Illumina read data provided for each sample will be processed to perform consensus genome assembly, infer the quality of both raw read data and the generated consensus genome, and assign samples SARS-CoV-2 lineage and clade types as outlined in the Titan_Illumina_PE data workflow below.

Consensus genome assembly with the Titan_Illumina_PE workflow is performed by first de-hosting read data with the NCBI SRA-Human-Scrubber tool then trimming low-quality reads with Trimmomatic and removing adapter sequences with BBDuk. These cleaned read data are then aligned to the Wuhan-1 reference genome with BWA to generate a Binary Alignment Mapping (BAM) file. Primer sequences are then removed from the BAM file using the iVar Trim sub-command. The iVar consensus sub-command is then utilized to generate a consensus assembly in FASTA format. This assembly is then used to assign lineage and clade designations with Pangolin and NextClade. NCBI'S VADR tool is also employed to screen for potentially errant features (e.g. erroneous frame-shift mutations) in the consensus assembly.

More information on required user inputs, optional user inputs, default tool parameters and the outputs generated by Titan_Illumina_PE are outlined below.

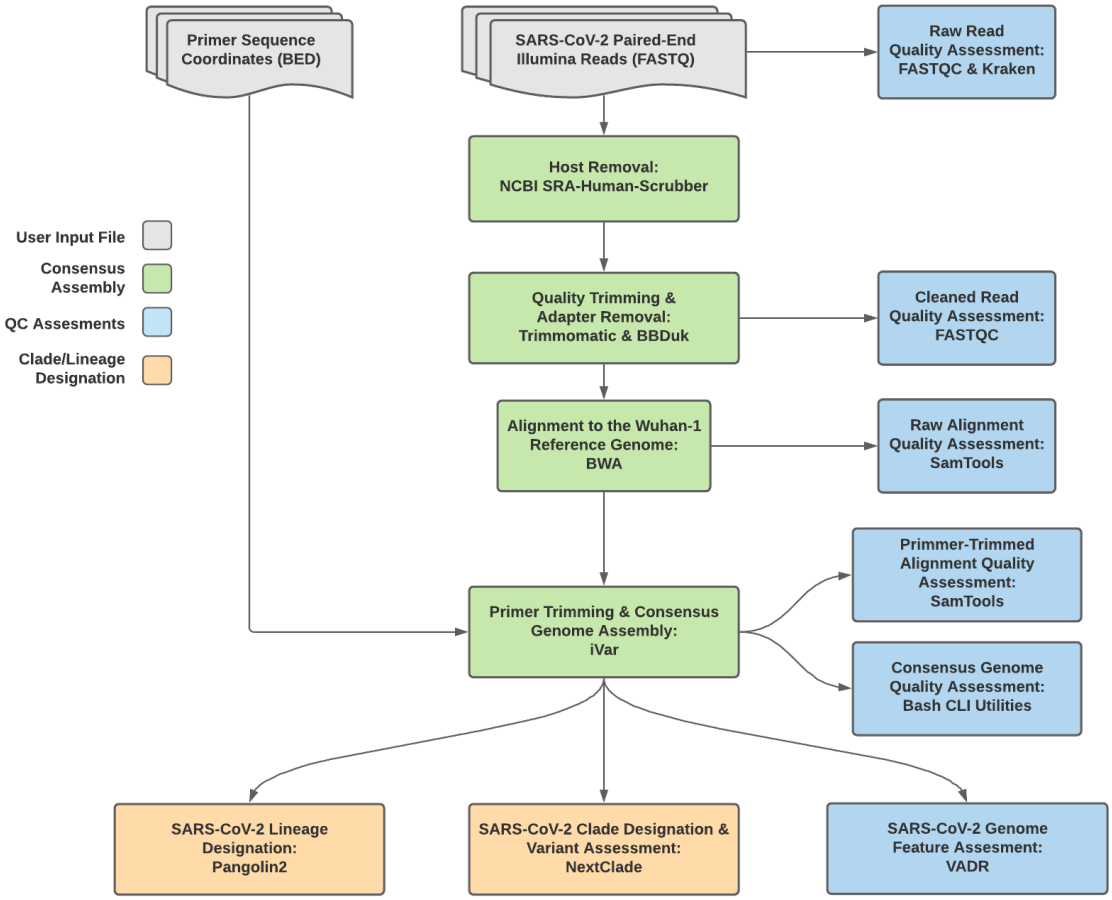

Fig. 1: **Titan_Illumina_PE v1.4.4 Data Workflow**

Required User Inputs

Download CSV: `Titan_Illumina_PE_required_inputs.csv`

Task	Input Variable	Data Type	Description
titan_illumina_pe	primer_bed	File	Primer sequence coordinates of the PCR scheme utilized in BED file format
titan_illumina_pe	read1_raw	File	Forward Illumina read in FASTQ file format
titan_illumina_pe	read2_raw	File	Reverse Illumina read in FASTQ file format
titan_illumina_pe	samplename	String	Name of the sample being analyzed

Optional User Inputs

Download CSV: `Titan_Illumina_PE_optional_inputs.csv`

Task	Variable Name	Data Type	Description	Default
bedtools_cov	primer_bed	String	Path to the primer sequence coordinates of the PCR scheme utilized in BED file format	/artic-ncov2019/primer_schemes/nCoV-2019/V3/nCoV-2019_amplicon.bed
bedtools_cov	fail_threshold	String	Minimum coverage threshold to determin amplicon sequencing failture	20x
bwa	reference_genome	String	Path to the reference genome within the staphb/ivar:1.2.2_artic20200528 Docker container	/artic-ncov2019/primer_schemes/nCoV-2019/V3/nCoV-2019.reference.fasta
bwa	cpus	Int	CPU resources allocated to the BWA task runtime environment	6

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Task	Variable Name	Data Type	Description	Default
consensus	ref_gff	String	Path to the general feature format of the reference genome within the staphb/ivar:1.2.2_artic20200528 Docker container	/reference/GCF_009858895.2_ASM985889v3_genomic.gff
consensus	ref_genome	String	Path to the reference genome within the staphb/ivar:1.2.2_artic20200528 Docker container	/artic-ncov2019/primer_schemes/nCoV-2019/V3/nCoV-2019.reference.fasta
consensus	min_qual	Int	Minimum quality threshold for sliding window to pass for iVar consensus	20
consensus	min_freq	Float	Minimum frequency threshold(0 - 1) to call variants for iVar consensus	0.6
consensus	min_depth	Int	Minimum read depth to call variants for iVar consensus	10
consensus	min_bq	Int	Minimum mapping quality for an alignment to be used for SAMtools mpileup before running iVar consensus	0
consensus	max_depth	Int	Maximum reads read at a position per input file for SAMtools mpileup before running iVar consensus	600000

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Task	Variable Name	Data Type	Description	Default
consensus	disable_baq	Boolean	Disable read-pair overlap detection for SAMtools mpileup before running iVar consensus	TRUE
consensus	count_orphans	Boolean	Do not skip anomalous read pairs in variant calling for SAMtools mpileup before running iVar consensus	TRUE
consensus	char_unknown	String	Character to print in regions with less than minimum coverage for iVar consensus	N
nextclade_one_sample	dataset_sequence	File	Custom reference sequence file for NextClade	None
nextclade_one_sample	qc_config_json	File	Custom QC configuraiton file for NextClade	None
nextclade_one_sample	pcr_primers_csv	File	Custom PCR primers file for NextClade	None
nextclade_one_sample	gene_annotations_json	File	Custom gene annotation file for NextClade	None
nextclade_one_sample	docker	String	Docker tag used for running NextClade	neherlab/nextclade:0.14.2
nextclade_one_sample	phylogeny_reference_tree_json	File	Custom reference tree file for NextClade	None
pangolin3	inference_engine	String	pangolin inference engine for lineage designations (usher or pangolarn)	usher
pangolin3	min_length	Int	Minimum query length allowed for pangolin to attempt assignment	10000

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Task	Variable Name	Data Type	Description	Default
pangolin3	max_ambig	Float	Maximum proportion of Ns allowed for pangolin to attempt assignment	0.5
primer_trim	keep_noprimer_reads	Boolean	Include reads with no primers for iVar trim	True
read_QC_trim	trimmomatic_window_size	Int	Specifies the number of bases to average across for Trimmomatic	4
read_QC_trim	trimmomatic_quality_trim_score	Int	Specifies the average quality required for Trimmomatic	30
read_QC_trim	trimmomatic_minlen	Int	Specifies the minimum length of reads to be kept for Trimmomatic	75
titan_illumina_pe	seq_method	String	Description of the sequencing methodology used to generate the input read data	Illumina paired-end
titan_illumina_pe	pangolin_docker_image	String	Docker tag used for running Pangolin	staphb/pangolin:2.4.2-pangolearn-2021-05-19
vadr	docker	String	Docker tag used for running VADR	staphb/vadr:1.2.1
vadr	maxlen	Int	Maximum length for the fasta-trim-terminal-ambigs.pl VADR script	30000
vadr	minlen	Int	Minimum length subsequence to possibly replace Ns for the fasta-trim-terminal-ambigs.pl VADR script	50

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Task	Variable Name	Data Type	Description	Default
vadr	vadr_opts	String	Options for the v-annotate.pl VADR script	–glsearch -s -r –nomisc –mkey sarscov2 –alt_fail lowscore,fstukcnf,insertnn,deletinn –mdir /opt/vadr/vadr-models/
vadr	skip_length	Int	Minimum assembly length (unambiguous) to run vadr	10000
variant_call	ref_gff	String	Path to the general feature format of the reference genome within the staphb/ivar:1.2.2_artic20200528 Docker container	/reference/GCF_009858895.2_ASM985889v3_genomic.gff
variant_call	ref_genome	String	Path to the reference genome within the staphb/ivar:1.2.2_artic20200528 Docker container	/artic-ncov2019/primer_schemes/nCoV-2019/V3/nCoV-2019.reference.fasta
variant_call	min_qual	Int	Minimum quality threshold for sliding window to pass for iVar variants	20
variant_call	min_freq	Float	Minimum frequency threshold(0 - 1) to call variants for iVar variants	0.6
variant_call	min_depth	Int	Minimum read depth to call variants for iVar variants	10
variant_call	min_bq	Int	Minimum mapping quality for an alignment to be used for SAMtools mpileup before running iVar variants	0

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Task	Variable Name	Data Type	Description	Default
variant_call	max_depth	Int	Maximum reads read at a position per input file for SAMtools mpileup before running iVar variants	600000
variant_call	disable_baq	Boolean	Disable read-pair overlap detection for SAMtools mpileup before running iVar variants	TRUE
variant_call	count_orphans	Boolean	Do not skip anomalous read pairs in variant calling for SAMtools mpileup before running iVar variants	TRUE
version_capture	timezone	String	User time zone in valid Unix TZ string (e.g. America/New_York)	None

Outputs

Download CSV: `Titan_Illumina_PE_default_outputs.csv`

Output Name	Data Type	Description
aligned_bai	File	Index companion file to the bam file generated during the consensus assembly process
aligned_bam	File	Primer-trimmed BAM file; generated during conensus assembly process
assembly_fasta	File	Consensus genome assembly
assembly_length_unambiguous	Int	Number of unambiguous basecalls within the SC2 consensus assembly
assembly_mean_coverage	Float	Mean sequencing depth throughout the conesnsus assembly generated after performing primer trimming–calculated using the SAMtools coverage command
assembly_method	String	Method employed to generate consensus assembly

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Output Name	Data Type	Description
auspice_json	File	Auspice-compatable JSON output generated from NextClade analysis that includes the NextClade default samples for clade-typing and the single sample placed on this tree
bbduk_docker	String	Docker image used to run BBDuk
bwa_version	String	Version of BWA used to map read data to the reference genome
consensus_flagstat	File	Output from the SAMtools flagstat command to assess quality of the alignment file (BAM)
consensus_stats	File	Output from the SAMtools stats command to assess quality of the alignment file (BAM)
dehosted_read1	File	Dehosted forward reads; suggested read file for SRA submission
dehosted_read2	File	Dehosted reverse reads; suggested read file for SRA submission
fastqc_clean_pairs	String	Number of paired reads after SeqyClean filtering as determined by FastQC
fastqc_clean1	Int	Number of forward reads after seqyclean filtering as determined by FastQC
fastqc_clean2	Int	Number of reverse reads after seqyclean filtering as determined by FastQC
fastqc_raw_pairs	String	Number of paired reads identified in the input fastq files as determined by FastQC
fastqc_raw1	Int	Number of forward reads identified in the input fastq files as determined by FastQC
fastqc_raw2	Int	Number of reverse reads identified in the input fastq files as determined by FastQC
fastqc_version	String	Version of the FastQC software used for read QC analysis
ivar_tsv	File	Variant descriptor file generated by iVar variants
ivar_variant_version	String	Version of iVar for running the iVar variants command
ivar_version_consensus	String	Version of iVar for running the iVar consensus command
ivar_version_primtrim	String	Version of iVar for running the iVar trim command
kraken_human	Float	Percent of human read data detected using the Kraken2 software
kraken_human_dehosted	Float	Percent of human read data detected using the Kraken2 software after host removal
kraken_report	File	Full Kraken report
kraken_report_dehosted	File	Full Kraken report after host removal
kraken_sc2	Float	Percent of SARS-CoV-2 read data detected using the Kraken2 software
kraken_sc2_dehosted	Float	Percent of SARS-CoV-2 read data detected using the Kraken2 software after host removal
kraken_version	String	Version of Kraken software used
meanbaseq_trim	Float	Mean quality of the nucleotide basecalls aligned to the reference genome after primer trimming
meanmapq_trim	Float	Mean quality of the mapped reads to the reference genome after primer trimming
nextclade_aa_dels	String	Amino-acid deletions as detected by NextClade
nextclade_aa_subs	String	Amino-acid substitutions as detected by NextClade
nextclade_clade	String	NextClade clade designation
nextclade_json	File	NexClade output in JSON file format
nextclade_tsv	File	NextClade output in TSV file format
nextclade_version	String	Version of NextClade software used
number_Degenerate	Int	Number of degenerate basecalls within the consensus assembly
number_N	Int	Number of fully ambiguous basecalls within the consensus assembly

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Output Name	Data Type	Description
number_Total	Int	Total number of nucleotides within the consensus assembly
pango_lineage	String	Pango lineage as detremined by Pangolin
pango_lineage_report	File	Full Pango lineage report generated by Pangolin
pangolin_conflicts	String	Number of lineage conflicts as deteremed by Pangolin
pangolin_docker	String	Docker image used to run Pangolin
pangolin_notes	String	Lineage notes as deteremined by Pangolin
pangolin_version	String	Pangolin and PangoLEARN versions used
percent_reference_coverage	Float	Percent coverage of the reference genome after performing primer trimming; calculated as assembly_length_unambiguous / length of reference genome (SC2: 29,903) x 100
primer_trimmed_read_percent	Float	Percent of read data with primers trimmed as deteremined by iVar trim
read1_clean	File	Forward read file after quality trimming and adapter removal
read2_clean	File	Reverse read file after quality trimming and adapter removal
samtools_version	String	Version of SAMtools used to sort and index the alignment file
samtools_version_consensus	String	Version of SAMtools used to create the pileup before running iVar consensus
samtools_version_primtrim	String	Version of SAMtools used to create the pileup before running iVar trim
samtools_version_stats	String	Version of SAMtools used to assess quality of read mapping
seq_platform	String	Description of the sequencing methodology used to generate the input read data
titan_illumina_pe_analysis_date	String	Date of analysis
titan_illumina_pe_version	String	Version of the Public Health Viral Genomics (PHVG) repository used
trimmomatic_version	String	Version of Trimmomatic used
vadr_alerts_list	File	File containing all of the fatal alerts as determined by VADR
vadr_docker	String	Docker image used to run VADR
vadr_num_alerts	String	Number of fatal alerts as determined by VADR

Titan_Illumina_SE

The Titan_Illumina_SE workflow was written to process Illumina single-end (SE) read data. Input reads are assumed to be the product of sequencing tiled PCR-amplicons designed for the SARS-CoV-2 genome. The most common read data analyzed by the Titan_Illumina_SE workflow are generated with the Artic V3 protocol. Alternative primer schemes such as the Qiaseq Primer Panel, however, can also be analysed with this workflow. The primer sequence coordinates of the PCR scheme utilized must be provided along with the raw paired-end Illumina read data in BED and FASTQ file formats, respectively.

Note: By default, this workflow will assume that input reads were generated using a 35-cycle kit (i.e. 1 x 35 bp reads). Modifications to the optional parameter for trimmomatic_minlen may be required to accommodate for longer read data.

Upon initiating a Titan_Illumina_SE job, the input primer scheme coordinates and raw paired-end Illumina read data

provided for each sample will be processed to perform consensus genome assembly, infer the quality of both raw read data and the generated consensus genome, and assign samples SARS-CoV-2 lineage and clade types as outlined in the Titan_Illumina_PE data workflow below.

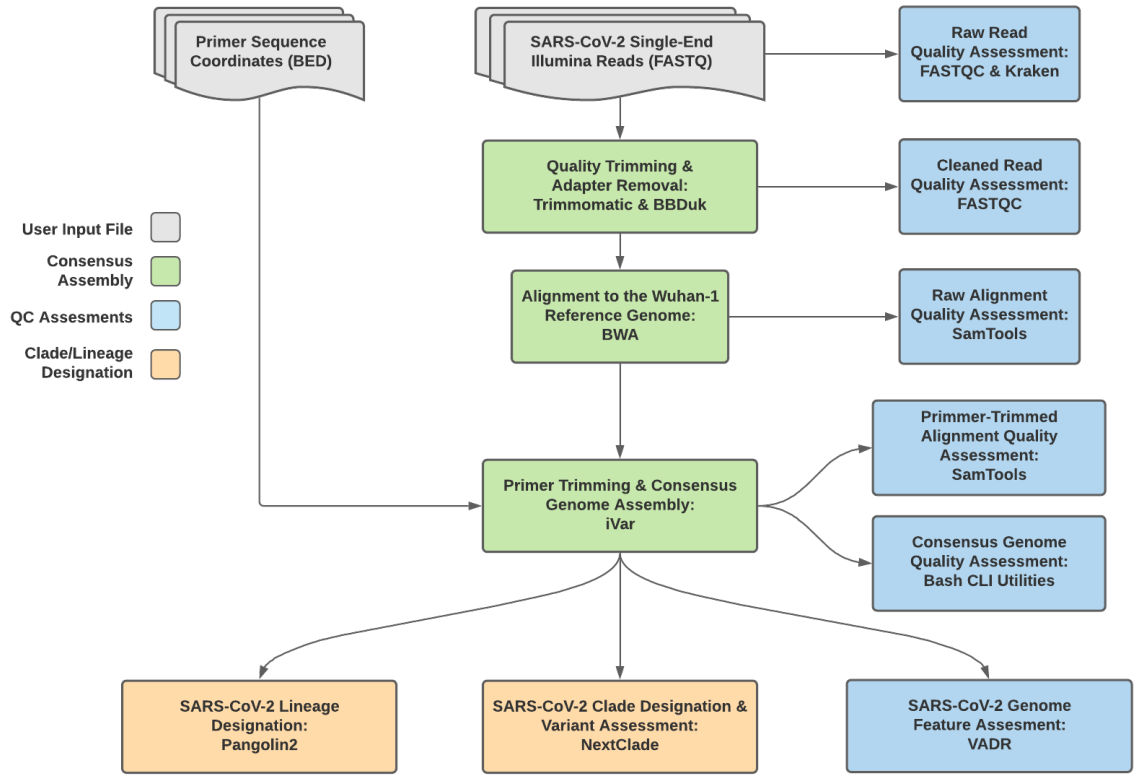

Fig. 2: **Titan_Illumina_SE v1.4.4 Data Workflow**

Consensus genome assembly with the Titan_Illumina_SE workflow is performed by first trimming low-quality reads with Trimmomatic and removing adapter sequences with BBDuk. These cleaned read data are then aligned to the Wuhan-1 reference genome with BWA to generate a Binary Alignment Mapping (BAM) file. Primer sequences are then removed from the BAM file using the iVar Trim sub-command. The iVar consensus sub-command is then utilized to generate a consensus assembly in FASTA format. This assembly is then used to assign lineage and clade designations with Pangolin and NextClade. NCBI'S VADR tool is also employed to screen for potentially errant features (e.g. erroneous frame-shift mutations) in the consensus assembly.

More information on required user inputs, optional user inputs, default tool parameters and the outputs generated by Titan_Illumina_SE are outlined below.

Required User Inputs

Download CSV: `Titan_Illumina_SE_required_inputs.csv`

Task	Input Variable	Data Type	Description
titan_illumina_pe	primer_bed	File	Primer sequence coordinates of the PCR scheme utilized in BED file format
titan_illumina_pe	read1_raw	File	Single-end Illumina read in FASTQ file format
titan_illumina_pe	samplename	String	Name of the sample being analyzed

Optional User Inputs

Download CSV: `Titan_Illumina_SE_optional_inputs.csv`

Task	Variable Name	Data Type	Description	Default
bedtools_cov	primer_bed	String	Path to the primer sequence coordinates of the PCR scheme utilized in BED file format	/artic-ncov2019/primer_schemes/nCoV-2019/V3/nCoV-2019_amplicon.bed
bedtools_cov	fail_threshold	String	Minimum coverage threshold to determin amplicon sequencing failture	20x
bwa	reference_genome	String	Path to the reference genome within the staphb/ivar:1.2.2_artic20200528 Docker container	/artic-ncov2019/primer_schemes/nCoV-2019/V3/nCoV-2019_reference.fasta
bwa	cpus	Int	CPU resources allocated to the BWA task runtime environment	6
bwa	read2	File	Optional input file for the bwa task that is not applicable to this workflow	None
consensus	ref_gff	String	Path to the general feature format of the reference genome within the staphb/ivar:1.2.2_artic20200528 Docker container	/reference/GCF_009858895.2_ASM985889v3_genomic.gff
consensus	ref_genome	String	Path to the reference genome within the staphb/ivar:1.2.2_artic20200528 Docker container	/artic-ncov2019/primer_schemes/nCoV-2019/V3/nCoV-2019_reference.fasta

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Task	Variable Name	Data Type	Description	Default
consensus	min_qual	Int	Minimum quality threshold for sliding window to pass for iVar consensus	20
consensus	min_freq	Float	Minimum frequency threshold(0 - 1) to call variants for iVar consensus	0.6
consensus	min_depth	Int	Minimum read depth to call variants for iVar consensus	10
consensus	min_bq	Int	Minimum mapping quality for an alignment to be used for SAMtools mpileup before running iVar consensus	0
consensus	max_depth	Int	Maximum reads read at a position per input file for SAMtools mpileup before running iVar consensus	600000
consensus	disable_baq	Boolean	Disable read-pair overlap detection for SAMtools mpileup before running iVar consensus	TRUE
consensus	count_orphans	Boolean	Do not skip anomalous read pairs in variant calling for SAMtools mpileup before running iVar consensus	TRUE
consensus	char_unknown	String	Character to print in regions with less than minimum coverage for iVar consensus	N

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Task	Variable Name	Data Type	Description	Default
nextclade_one_sample	dataset_sequence	File	Custom reference sequence file for NextClade	None
nextclade_one_sample	qc_config_json	File	Custom QC configuraiton file for NextClade	None
nextclade_one_sample	pcr_primers_csv	File	Custom PCR primers file for NextClade	None
nextclade_one_sample	gene_annotations_json	File	Custom gene annotation file for NextClade	None
nextclade_one_sample	docker	String	Docker tag used for running NextClade	neherlab/nextclade:0.14.2
nextclade_one_sample	auspice_reference_tree_json	File	Custom reference tree file for NextClade	None
pangolin3	inference_engine	String	pangolin inference engine for lineage designations (usher or pangolarn)	usher
pangolin3	min_length	Int	Minimum query length allowed for pangolin to attempt assignment	10000
pangolin3	max_ambig	Float	Maximum proportion of Ns allowed for pangolin to attempt assignment	0.5
primer_trim	keep_noprimer_reads	Boolean	Include reads with no primers for iVar trim	True
read_QC_trim	trimmomatic_window_size	Int	Specifies the number of bases to average across for Trimmomatic	4
read_QC_trim	trimmomatic_quality_trim_score	Int	Specifies the average quality required for Trimmomatic	30

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Task	Variable Name	Data Type	Description	Default
read_QC_trim	trimmomatic_minlen	Int	Specifies the minimum length of reads to be kept for Trimmomatic	25
titan_illumina_pe	seq_method	String	Description of the sequencing methodology used to generate the input read data	Illumina paired-end
titan_illumina_pe	pangolin_docker_image	String	Docker tag used for running Pangolin	staphb/pangolin:2.4.2-pangolearn-2021-05-19
vadr	docker	String	Docker tag used for running VADR	staphb/vadr:1.2.1
vadr	maxlen	Int	Maximum length for the fasta-trim-terminal-ambigs.pl VADR script	30000
vadr	minlen	Int	Minimum length subsequence to possibly replace Ns for the fasta-trim-terminal-ambigs.pl VADR script	50
vadr	vadr_opts	String	Options for the v-annotate.pl VADR script	–glsearch -s -r –nomisc –mkey sarscov2 –alt_fail lowscore,fstukcnf,insertnn,deletinn –mdir /opt/vadr/vadr-models/
vadr	skip_length	Int	Minimum assembly length (unambiguous) to run vadr	10000
variant_call	ref_gff	String	Path to the general feature format of the reference genome within the staphb/ivar:1.2.2_artic20200528 Docker container	/reference/GCF_009858895.2_ASM985889v3_genomic.gff

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Table 3 – continued from previous page

Task	Variable Name	Data Type	Description	Default
variant_call	ref_genome	String	Path to the reference genome within the staphb/ivar:1.2.2_artic20200528 Docker container	/artic-ncov2019/primer_schemes/nCoV-2019/V3/nCoV-2019.reference.fasta
variant_call	min_qual	Int	Minimum quality threshold for sliding window to pass for iVar variants	20
variant_call	min_freq	Float	Minimum frequency threshold(0 - 1) to call variants for iVar variants	0.6
variant_call	min_depth	Int	Minimum read depth to call variants for iVar variants	10
variant_call	min_bq	Int	Minimum mapping quality for an alignment to be used for SAMtools mpileup before running iVar variants	0
variant_call	max_depth	Int	Maximum reads read at a position per input file for SAMtools mpileup before running iVar variants	600000
variant_call	disable_baq	Boolean	Disable read-pair overlap detection for SAMtools mpileup before running iVar variants	TRUE
variant_call	count_orphans	Boolean	Do not skip anomalous read pairs in variant calling for SAMtools mpileup before running iVar variants	TRUE

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Task	Variable Name	Data Type	Description	Default
version_capture	timezone	String	User time zone in valid Unix TZ string (e.g. America/New_York)	None

Outputs

Download CSV: `Titan_Illumina_SE_default_outputs.csv`

Output Name	Data Type	Description
aligned_bai	File	Index companion file to the bam file generated during the consensus assembly process
aligned_bam	File	Primer-trimmed BAM file; generated during conensus assembly process
assembly_fasta	File	Consensus genome assembly
assembly_length_unambiguous	Int	Number of unambiguous basecalls within the SC2 consensus assembly
assembly_mean_coverage	Float	Mean sequencing depth throughout the conesnsus assembly generated after performing primer trimming–calculated using the SAMtools coverage command
assembly_method	String	Method employed to generate consensus assembly
auspice_json	File	Auspice-compatable JSON output generated from NextClade analysis that includes the NextClade default samples for clade-typing and the single sample placed on this tree
bbduk_docker	String	Docker image used to run BBDuk
bwa_version	String	Version of BWA used to map read data to the reference genome
consensus_flagstat	File	Output from the SAMtools flagstat command to assess quality of the alignment file (BAM)
consensus_stats	File	Output from the SAMtools stats command to assess quality of the alignment file (BAM)
fastqc_clean	Int	Number of reads after SeqyClean filtering as determined by FastQC
fastqc_raw	Int	Number of reads after seqyclean filtering as determined by FastQC
fastqc_version	String	Version of the FastQC software used for read QC analysis
ivar_tsv	File	Variant descriptor file generated by iVar variants
ivar_variant_version	String	Version of iVar for running the iVar variants command
ivar_version_consensus	String	Version of iVar for running the iVar consensus command
ivar_version_primtrim	String	Version of iVar for running the iVar trim command
kraken_human	Float	Percent of human read data detected using the Kraken2 software
kraken_report	String	Full Kraken report
kraken_sc2	Float	Percent of SARS-CoV-2 read data detected using the Kraken2 software
kraken_version	String	Version of Kraken software used
meanbaseq_trim	Float	Mean quality of the nucleotide basecalls aligned to the reference genome after primer trimming

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Output Name	Data Type	Description
meanmapq_trim	Float	Mean quality of the mapped reads to the reference genome after primer trimming
nextclade_aa_dels	String	Amino-acid deletions as detected by NextClade
nextclade_aa_subs	String	Amino-acid substitutions as detected by NextClade
nextclade_clade	String	NextClade clade designation
nextclade_json	File	NexClade output in JSON file format
nextclade_tsv	File	NextClade output in TSV file format
nextclade_version	String	Version of NextClade software used
number_Degenerate	Int	Number of degenerate basecalls within the consensus assembly
number_N	Int	Number of fully ambiguous basecalls within the consensus assembly
number_Total	Int	Total number of nucleotides within the consensus assembly
pango_lineage	String	Pango lineage as detremined by Pangolin
pango_lineage_report	File	Full Pango lineage report generated by Pangolin
pangolin_conflicts	String	Number of lineage conflicts as deteremed by Pangolin
pangolin_docker	String	Docker image used to run Pangolin
pangolin_notes	String	Lineage notes as deteremined by Pangolin
pangolin_version	String	Pangolin and PangoLEARN versions used
percent_reference_coverage	Float	Percent coverage of the reference genome after performing primer trimming; calculated as assembly_length_unambiguous / length of reference genome (SC2: 29,903) x 100
primer_trimmed_read_percent	Float	Percent of read data with primers trimmed as deteremined by iVar trim
read1_clean	File	Forward read file after quality trimming and adapter removal
samtools_version	String	Version of SAMtools used to sort and index the alignment file
samtools_version_consensus	String	Version of SAMtools used to create the pileup before running iVar consensus
samtools_version_primtrim	String	Version of SAMtools used to create the pileup before running iVar trim
samtools_version_stats	String	Version of SAMtools used to assess quality of read mapping
seq_platform	String	Description of the sequencing methodology used to generate the input read data
titan_illumina_se_analysis_date	String	Date of analysis
titan_illumina_se_version	String	Version of the Public Health Viral Genomics (PHVG) repository used
trimmomatic_version	String	Version of Trimmomatic used
vadr_alerts_list	File	File containing all of the fatal alerts as determined by VADR
vadr_docker	String	Docker image used to run VADR
vadr_num_alerts	String	Number of fatal alerts as determined by VADR

Titan_ClearLabs

The Titan_ClearLabs workflow was written to process ClearLabs WGS read data for SARS-CoV-2 Artic V3 amplicon sequencing.

Upon initiating a Titan_ClearLabs run, input ClearLabs read data provided for each sample will be processed to perform consensus genome assembly, infer the quality of both raw read data and the generated consensus genome, and assign samples SARS-CoV-2 lineage and clade types as outlined in the Titan_ClearLabs data workflow below.

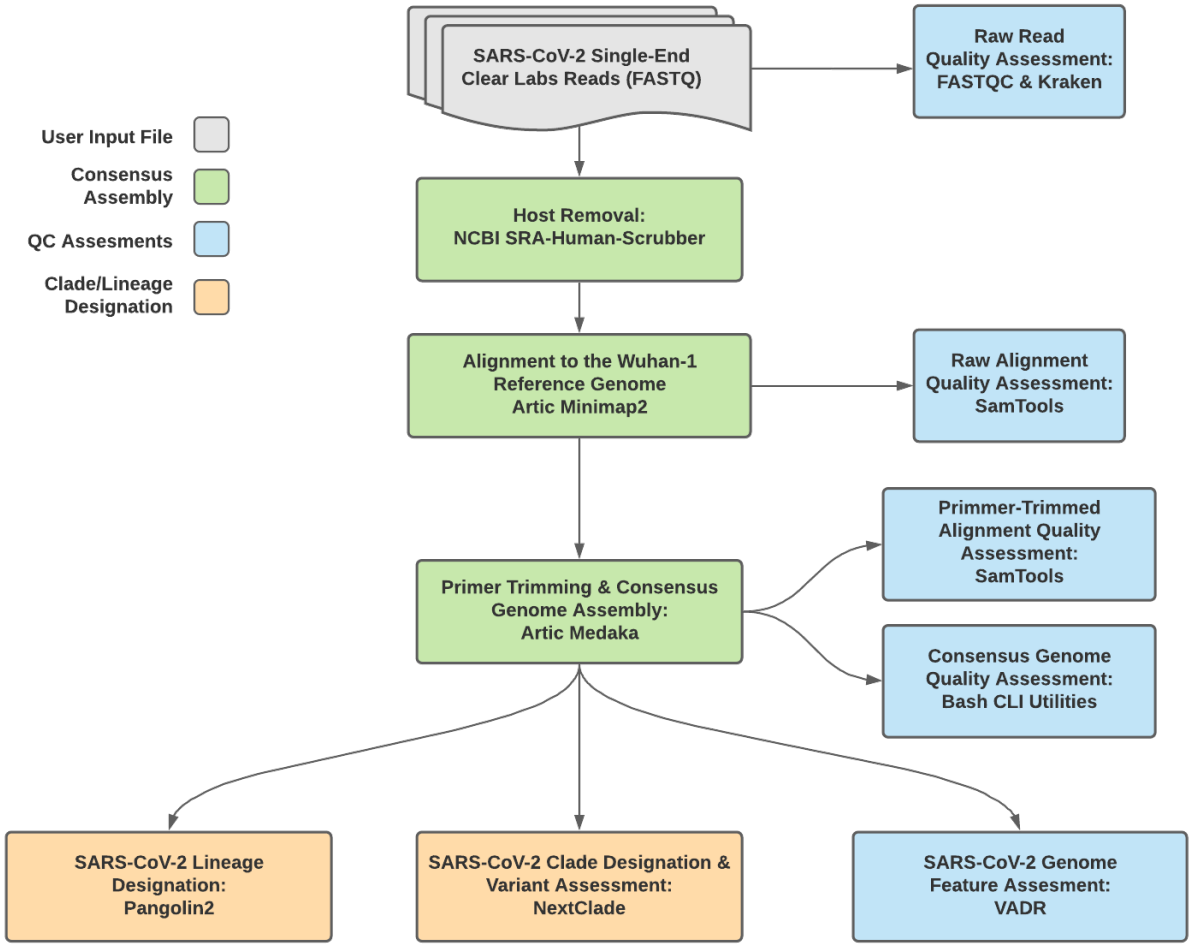

Fig. 3: **Titan_ClearLabs v1.4.4 Data Workflow**

Consensus genome assembly with the Titan_ClearLabs workflow is performed by first de-hosting read data with the NCBI SRA-Human-Scrubber tool then following the *Artic nCoV-2019 novel coronavirs bioinformatics protocol <https://artic.network/ncov-2019/ncov2019-bioinformatics-sop.html>*. Briefly, input reads are aligned to the Wuhan-1 reference genome with minimap2 to generate a Binary Alignment Mapping (BAM) file. Primer sequences are then removed from the BAM file and a consensus assembly file is generated using the Artic medaka command. This assembly is then used to assign lineage and clade designations with Pangolin and NextClade. NCBI'S VADR tool is also employed to screen for potentially errant features (e.g. erroneous frame-shift mutations) in the consensus assembly.

Note: Read-trimming is performed on raw read data generated on the ClearLabs instrument and thus not a required step in the Titan_ClearLabs workflow.

More information on required user inputs, optional user inputs, default tool parameters and the outputs generated by Titan_CLearLabs are outlined below.

Required User Inputs

Download CSV: `Titan_ClearLabs_required_inputs.csv`

Task	Input Variable	Data Type	Description
titan_clearlabs	clear_lab_fastq	File	Clear Labs FASTQ read files
titan_clearlabs	samplename	String	Name of the sample being analyzed

Optional User Inputs

Download CSV: `Titan_ClearLabs_optional_inputs.csv`

Task	Variable Name	Data Type	Description	Default
bedtools_cov	primer_bed	String	Path to the primer sequence coordinates of the PCR scheme utilized in BED file format	/artic-ncov2019/primer_schemes/nCoV-2019/V3/nCoV-2019_amplicon.bed
bedtools_cov	fail_threshold	String	Minimum coverage threshold to determin amplicon sequencing failture	20x
consensus	cpu	Int	CPU resources allocated to the Artric Medaka task runtime environment	8
fastqc_se_raw	cpus	Int	CPU resources allocated to the FastQC task runtime environment for asessing raw read data	
fastqc_se_raw	read1_name	String	Name of the sample being analyzed	Inferred from the input read file
kraken2_raw	cpus	Int	CPU resources allocated to the Kraken task runtime environment for asessing raw read data	4
kraken2_raw	kraken2_db	String	Path to the reference genome within the staphb/kraken2:2.0.8-beta_hv Docker container	/kraken2-db
kraken2_raw	read2	File	Optional input file for the Kraken task that is not applicable to this workflow	None
nextclade_one_sample	ref_sequence	File	Custom reference sequence file for NextClade	None
nextclade_one_sample	qc_config_json	File	Custom QC configuraiton file for NextClade	None
nextclade_one_sample	pcr_primers_csv	File	Custom PCR primers file for NextClade	None
nextclade_one_sample	gene_annotations_json	File	Custom gene annotation file for	None

Outputs

Download CSV: `Titan_ClearLabs_default_outputs.csv`

Output Name	Data Type	Description
aligned_bai	File	Index companion file to the bam file generated during the consensus assembly process
aligned_bam	File	Primer-trimmed BAM file; generated during conensus assembly process
artic_version	String	Version of the Artic software utilized for read trimming and conesnsus genome assembly
assembly_fasta	File	Consensus genome assembly
assembly_length_unambiguous	Int	Number of unambiguous basecalls within the SC2 consensus assembly
assembly_mean_coverage	Float	Mean sequencing depth throughout the conesnsus assembly generated after performing primer trimming–calculated using the SAMtools coverage command
assembly_method	String	Method employed to generate consensus assembly
auspice_json	File	Auspice-compatable JSON output generated from NextClade analysis that includes the NextClade default samples for clade-typing and the single sample placed on this tree
consensus_flagstat	File	Output from the SAMtools flagstat command to assess quality of the alignment file (BAM)
consensus_stats	File	Output from the SAMtools stats command to assess quality of the alignment file (BAM)
dehosted_reads	File	Dehosted reads; suggested read file for SRA submission
fastqc_clean	Int	Number of reads after dehosting as determined by FastQC
fastqc_raw	Int	Number of raw input reads as determined by FastQC
fastqc_version	String	Version of the FastQC version used
kraken_human	Float	Percent of human read data detected using the Kraken2 software
kraken_human_dehosted	Float	Percent of human read data detected using the Kraken2 software after host removal
kraken_report	String	Full Kraken report
kraken_report_dehosted	File	Full Kraken report after host removal
kraken_sc2	Float	Percent of SARS-CoV-2 read data detected using the Kraken2 software
kraken_sc2_dehosted	Float	Percent of SARS-CoV-2 read data detected using the Kraken2 software after host removal
kraken_version	String	Version of Kraken software used
meanbaseq_trim	Float	Mean quality of the nucleotide basecalls aligned to the reference genome after primer trimming
meanmapq_trim	Float	Mean quality of the mapped reads to the reference genome after primer trimming
nextclade_aa_dels	String	Amino-acid deletions as detected by NextClade
nextclade_aa_subs	String	Amino-acid substitutions as detected by NextClade
nextclade_clade	String	NextClade clade designation
nextclade_json	File	NexClade output in JSON file format
nextclade_tsv	File	NextClade output in TSV file format

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Table 5 – continued from previous page

Output Name	Data Type	Description
nextclade_version	String	Version of NextClade software used
number_Degenerate	Int	Number of degenerate basecalls within the consensus assembly
number_N	Int	Number of fully ambiguous basecalls within the consensus assembly
number_Total	Int	Total number of nucleotides within the consensus assembly
pango_lineage	String	Pango lineage as detremined by Pangolin
pango_lineage_report	File	Full Pango lineage report generated by Pangolin
pangolin_conflicts	String	Number of lineage conflicts as deteremed by Pangolin
pangolin_docker	String	Docker image used to run Pangolin
pangolin_notes	String	Lineage notes as deteremined by Pangolin
pangolin_version	String	Pangolin and PangoLEARN versions used
percent_reference_coverage	Float	Percent coverage of the reference genome after performing primer trimming; calculated as assembly_length_unambiguous / length of reference genome (SC2: 29,903) x 100
pool1_percent	Float	Percentage of aligned read data assocaited with the pool1 amplicons
pool2_percent	Float	Percentage of aligned read data assocaited with the pool 2 amplicons
samtools_version	String	Version of SAMtools used to sort and index the alignment file
seq_platform	String	Description of the sequencing methodology used to generate the input read data
titan_clearlabs_analysis_date	String	Date of analysis
titan_clearlabs_version	String	Version of the Public Health Viral Genomics (PHVG) repository used
vadr_alerts_list	File	File containing all of the fatal alerts as determined by VADR
vadr_docker	String	Docker image used to run VADR
vadr_num_alerts	String	Number of fatal alerts as determined by VADR
variants_from_ref_vcf	File	Number of variants relative to the reference genome

Titan_ONT

The Titan_ONT workflow was written to process basecalled and demultiplexed Oxford Nanopore Technology (ONT) read data. IInput reads are assumed to be the product of sequencing Artic V3 tiled PCR-amplicons designed for the SARS-CoV-2 genome.

Note: As of May 2021, alternative primer schemes are not currently supported for the Titan_ONT workflow, but active development us underway to allow for such analysis in the near future.

Upon initiating a Titan_ONT run, input ONT read data provided for each sample will be processed to perform consensus genome assembly, infer the quality of both raw read data and the generated consensus genome, and assign samples SARS-CoV-2 lineage and clade types as outlined in the Titan_ONT data workflow below.

Consensus genome assembly with the Titan_ONT workflow is performed performed by first de-hosting read data with the NCBI SRA-Human-Scrubber tool then following then following *Artic nCoV-2019 novel coronavirs bioinformatics protocol <https://artic.network/ncov-2019/ncov2019-bioinformatics-sop.html>*. Briefly, input reads are filtered by size (min-length: 400bp; max-length: 700bp) with the Aritc guppyplex command. These size-selected read data are aligned to the Wuhan-1 reference genome with minimap2 to generate a Binary Alignment Mapping (BAM) file.

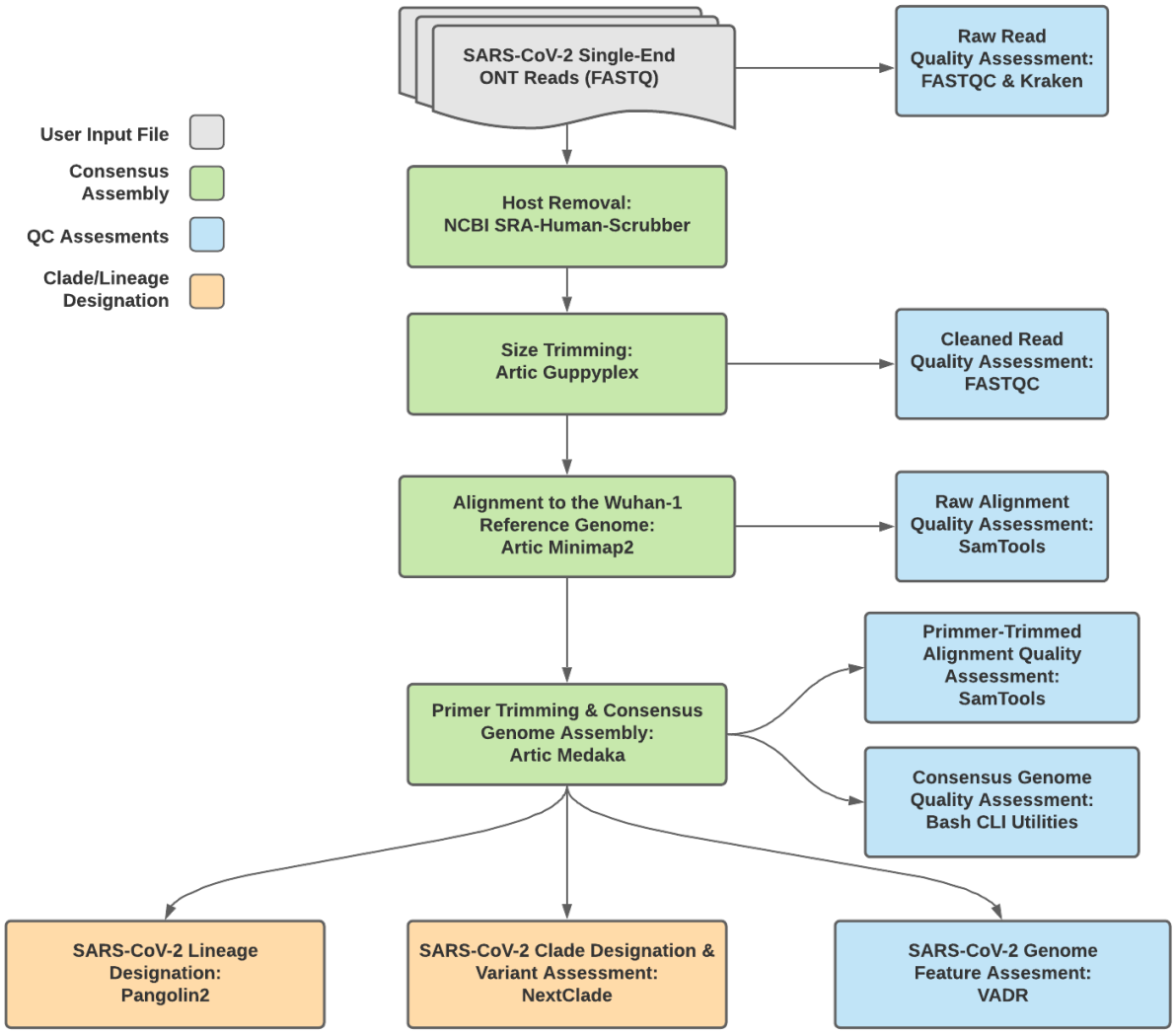

Fig. 4: **Titan_ONT v1.4.4 Data Workflow**

Primer sequences are then removed from the BAM file and a consensus assembly file is generated using the Artic medaka command. This assembly is then used to assign lineage and clade designations with Pangolin and NextClade. NCBI'S VADR tool is also employed to screen for potentially errant features (e.g. erroneous frame-shift mutations) in the consensus assembly.

More information on required user inputs, optional user inputs, default tool parameters and the outputs generated by Titan_ONT are outlined below.

Required User Inputs

Download CSV: `Titan_ONT_required_inputs.csv`

Task	Input Variable	Data Type	Description
titan_ont	demulti-plexed_reads	File	Basecalled and demultiplexed ONT read data (single FASTQ file per sample)
titan_ont	samplename	String	Name of the sample being analyzed

Optional User Inputs

Download CSV: `Titan_ONT_optional_inputs.csv`

Task	Variable Name	Data Type	Description	Default
bedtools_cov	primer_bed	String	Path to the primer sequence coordinates of the PCR scheme utilized in BED file format	/artic-ncov2019/primer_schemes/nCoV-2019/V3/nCoV-2019_amplicon.bed
bedtools_cov	fail_threshold	String	Minimum coverage threshold to determin amplicon sequencing failture	20x
consensus	cpu	Int	CPU resources allocated to the Artric Medaka task runtime environment	8
fastqc_se_clean	cpus	Int	CPU resources allocated to the FastQC task runtime environment for asessing size-selected read data	2

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Table 6 – continued from previous page

Task	Variable Name	Data Type	Description	Default
fastqc_se_clean	read1_name	String	Name of the sample being analyzed	Inferred from the input read file
fastqc_se_raw	cpus	Int	CPU resources allocated to the FastQC task runtime environment for asessing raw read data	
fastqc_se_raw	read1_name	String	Name of the sample being analyzed	Inferred from the input read file
kraken2_raw	cpus	Int	CPU resources allocated to the Kraken task runtime environment for asessing raw read data	4
kraken2_raw	kraken2_db	String	Path to the reference genome within the staphb/kraken2:2.0.8-beta_hv Docker container	/kraken2-db
kraken2_raw	read2	File	Optional input file for the Kraken task that is not applicable to this workflow	None
nextclade_one_sample	dataset_sequence	File	Custom reference sequence file for NextClade	None
nextclade_one_sample	qc_config_json	File	Custom QC configuraiton file for NextClade	None
nextclade_one_sample	pcr_primers_csv	File	Custom PCR primers file for NextClade	None
nextclade_one_sample	gene_annotations_json	File	Custom gene annotation file for NextClade	None
nextclade_one_sample	docker	String	Docker tag used for running NextClade	neherlab/nextclade:0.14.2
nextclade_one_sample	phylogeny_reference_tree_json	File	Custom reference tree file for NextClade	None

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Table 6 – continued from previous page

Task	Variable Name	Data Type	Description	Default
pangolin3	inference_engine	String	pangolin inference engine for lineage designations (usher or pangolarn)	usher
pangolin3	min_length	Int	Minimum query length allowed for pangolin to attempt assignment	10000
pangolin3	max_ambig	Float	Maximum proportion of Ns allowed for pangolin to attempt assignment	0.5
read_filtering	cpu	Int	CPU resources allocated to the read filtering task (Artic guppypled) runtime environment	8
read_filtering	max_length	Int	Maximum sequence length	700
read_filtering	min_length	Int	Minimum sequence length	400
read_filtering	run_prefix	String	Run name	artic_ncov2019
titan_ont	artic_primer_version	String	Version of the Artic PCR protocol used to generate input read data	V3
titan_ont	normalise	Int	Value to normalize read counts	200
titan_ont	seq_method	String	Description of the sequencing methodology used to generate the input read data	ONT
titan_ont	pangolin_docker_image	String	Docker tag used for running Pangolin	staphb/pangolin:2.4.2-pangolearn-2021-05-19
vadr	docker	String	Docker tag used for running VADR	staphb/vadr:1.2.1

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Table 6 – continued from previous page

Task	Variable Name	Data Type	Description	Default
vadr	maxlen	Int	Maximum length for the fasta-trim-terminal-ambigs.pl VADR script	30000
vadr	minlen	Int	Minimum length subsequence to possibly replace Ns for the fasta-trim-terminal-ambigs.pl VADR script	50
vadr	vadr_opts	String	Options for the v-annotate.pl VADR script	–glsearch -s -r –nomisc –mkey sarscov2 –alt_fail lowscore,fstukcnf,insertnn,deletinn –mdir /opt/vadr/vadr-models/
vadr	skip_length	Int	Minimum assembly length (unambiguous) to run vadr	10000
version_capture	timezone	String	User time zone in valid Unix TZ string (e.g. America/New_York)	None

Outputs

Download CSV: `Titan_ONT_default_outputs.csv`

Output Name	Data Type	Description
aligned_bai	File	Index companion file to the bam file generated during the consensus assembly process
aligned_bam	File	Primer-trimmed BAM file; generated during conensus assembly process
amp_coverage	File	Sequence coverage per amplicon
artic_version	String	Version of the Artic software utilized for read trimming and conesnsus genome assembly
assembly_fasta	File	Consensus genome assembly
assembly_length_unambiguous	Int	Number of unambiguous basecalls within the SC2 consensus assembly
assembly_mean_coverage	Float	Mean sequencing depth throughout the conesnsus assembly generated after performing primer trimming–calculated using the SAMtools coverage command

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Table 7 – continued from previous page

Output Name	Data Type	Description
assembly_method	String	Method employed to generate consensus assembly
auspice_json	File	Auspice-compatable JSON output generated from NextClade analysis that includes the NextClade default samples for clade-typing and the single sample placed on this tree
bedtools_version	String	bedtools version utilized when calculating amplicon read coverage
consensus_flagstat	File	Output from the SAMtools flagstat command to assess quality of the alignment file (BAM)
consensus_stats	File	Output from the SAMtools stats command to assess quality of the alignment file (BAM)
dehosted_reads	File	Dehosted reads; suggested read file for SRA submission
fastqc_clean	Int	Number of reads after size filttering and dehosting as determined by FastQC
fastqc_raw	Int	Number of raw reads input reads as determined by FastQC
fastqc_version	String	Version of the FastQC version used
kraken_human	Float	Percent of human read data detected using the Kraken2 software
kraken_human_dehosted	Float	Percent of human read data detected using the Kraken2 software after host removal
kraken_report	File	Full Kraken report
kraken_report_dehosted	File	Full Kraken report after host removal
kraken_sc2	Float	Percent of SARS-CoV-2 read data detected using the Kraken2 software
kraken_sc2_dehosted	Float	Percent of SARS-CoV-2 read data detected using the Kraken2 software after host removal
kraken_version	String	Version of Kraken software used
meanbaseq_trim	Float	Mean quality of the nucleotide basecalls aligned to the reference genome after primer trimming
meanmapq_trim	Float	Mean quality of the mapped reads to the reference genome after primer trimming
nextclade_aa_dels	String	Amino-acid deletions as detected by NextClade
nextclade_aa_subs	String	Amino-acid substitutions as detected by NextClade
nextclade_clade	String	NextClade clade designation
nextclade_json	File	NexClade output in JSON file format
nextclade_tsv	File	NextClade output in TSV file format
nextclade_version	String	Version of NextClade software used
number_Degenerate	Int	Number of degenerate basecalls within the consensus assembly
number_N	Int	Number of fully ambiguous basecalls within the consensus assembly
number_Total	Int	Total number of nucleotides within the consensus assembly
pango_lineage	String	Pango lineage as detremined by Pangolin
pango_lineage_report	File	Full Pango lineage report generated by Pangolin
pangolin_conflicts	String	Number of lineage conflicts as deteremed by Pangolin
pangolin_docker	String	Docker image used to run Pangolin
pangolin_notes	String	Lineage notes as deteremined by Pangolin
pangolin_version	String	Pangolin and PangoLEARN versions used
percent_reference_coverage	Float	Percent coverage of the reference genome after performing primer trimming; calculated as assembly_length_unambiguous / length of reference genome (SC2: 29,903) x 100
pool1_percent	Float	Percentage of aligned read data assocaited with the pool1 amplicons
pool2_percent	Float	Percentage of aligned read data assocaited with the pool 2 amplicons
samtools_version	String	Version of SAMtools used to sort and index the alignment file

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Table 7 – continued from previous page

Output Name	Data Type	Description
seq_platform	String	Description of the sequencing methodology used to generate the input read data
titan_ont_analysis_date	String	Date of analysis
titan_ont_version	String	Version of the Public Health Viral Genomics (PHVG) repository used
vadr_alerts_list	File	File containing all of the fatal alerts as determined by VADR
vadr_docker	String	Docker image used to run VADR
vadr_num_alerts	String	Number of fatal alerts as determined by VADR
variants_from_ref_vcf	File	Number of variants relative to the reference genome

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